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14. ABSTRACT The United States Air Force (USAF) and Navy (USN) use a battery of tests to quantify depth perception, including the Armed Forces Vision Tester (AFVT) stereopsis test, AO Vectograph, Verhoeff, and Howard-Dolman (HD). Most of these tests are tests of stereopsis, such as the AFVT and AO Vectograph. Others evaluate depth perception with stereo as a contributor to performance, such as the HD. The USAF and USN maintain depth perception standards for pilots and other aircrew with scanner duty (e.g., aerial refueling operators, aircrew responsible for clearing aircraft during landing, etc.). However, very little research has been carried out to establish quantitative relationships between clinical tests of vision and operational aircrew performance, including clinical tests for depth perception, which is the goal of the USAF Operational Based Vision Assessment program. While the need for stereo vision for tasks involving distance estimation seems intuitive, research examining the role of stereo vision and/or stereo displays often fails to show a clear relationship. Further, the results of different depth perception tests often differ substantially. Thus, any research examining the importance of stereo vision must also take into consideration the adequacy of the screening test. This paper provides a review of the research on the role of depth perception in performance as well as different methods of assessing stereo acuity. Research plans at the USAF 711 th Human Performance Wing, U.S. Naval Aerospace Medicine Research Unit, and DSO National Laboratories involving depth perception and stereo acuity test methods are described.					
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OPERATIONAL BASED VISION ASSESSMENT RESEARCH: DEPTH PERCEPTION

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INTRODUCTION

The purpose of the United States Air Force (USAF) School of Aerospace Medicine (USAFSAM) Operational Based Vision Assessment (OBVA) Laboratory is ultimately to provide quantitative data identifying the visual performance capability that will indeed prove useful during air combat, contribute to the success of the mission, and help ensure survivability. Depth perception has become a topic of particular interest recently due to the introduction of remote view aerial refueling, concerns about the applicability of existing depth perception standards, and costs involved in tracking the performance of aircrew granted stereopsis waivers throughout their careers. The origin of U.S. military aviation standards for stereopsis can be traced back to recommendations of the Armed Forces National Research Council Vision Committee in the late 1940s.¹ However, the three branches of the U.S. military now maintain somewhat different standards. Unique mission demands and recruitment constraints may have influenced changes in policy over time. Aeromedical policy changes may have also been driven by mishaps. For example, Air Force policy was modified to require all aircrew members who perform scanning duties (e.g., clearing wingtips) to meet stereopsis standards after a mid-air collision between two HH-60 helicopters.² To address questions concerning depth perception standards, the USAFSAM Aerospace Ophthalmology Branch, Naval Medical Research Unit-Dayton (NAMRU-D), and DSO National Laboratories

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ABSTRACT

The United States Air Force (USAF) and Navy (USN) use a battery of tests to quantify depth perception, including the Armed Forces Vision Tester (AFVT) stereopsis test, AO Vectograph, Verhoeff, and Howard-Dolman (HD). Most of these tests are tests of stereopsis, such as the AFVT and AO Vectograph. Others evaluate depth perception with stereo as a contributor to performance, such as the HD. The USAF and USN maintain depth perception standards for pilots and other aircrew with scanner duty (e.g., aerial refueling operators, aircrew responsible for clearing aircraft during landing, etc.). However, very little research has been carried out to establish quantitative relationships between clinical tests of vision and operational aircrew performance, including clinical tests for depth perception, which is the goal of the USAF Operational Based Vision Assessment program. While the need for stereo vision for tasks involving distance estimation seems intuitive, research examining the role of stereo vision and/or stereo displays often fails to show a clear relationship. Further, the results of different depth perception tests often differ substantially. Thus, any research examining the importance of stereo vision must also take into consideration the adequacy of the screening test. This paper provides a review of the research on the role of depth perception in performance as well as different methods of assessing stereo acuity. Research plans at the USAF 711th Human Performance Wing, U.S. Naval Aerospace Medicine Research Unit, and DSO National Laboratories involving depth perception and stereo acuity test methods are described.

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have conducted a thorough literature review. There are many excellent reviews available concerning stereopsis³⁻⁵ and stereo displays.⁶ However, this review focuses more specifically on aeromedical concerns, test methods, and vision standards.

DEPTH PERCEPTION IN AVIATION

Spatial awareness, or the ability to relate one's position to surrounding objects, is generally considered essential for military aviation. While there are many cues to orient to the environment, including proprioceptive and vestibular, interpretation of the visual environment is considered the strongest.⁷ Depth perception is of particular importance, as many military aviation maneuvers, such as formation flight, initiation of flare, aerial refueling, obstacle/object avoidance, etc., rely on accurate judgment of distance to be performed with proficiency.

Depth perception is often considered to be a combination of monocular and binocular cues. Monocular cues such as retinal image size, linear perspective, motion parallax, and occlusion are frequently characterized as learned skills based on life experiences, but also prone to illusion.^{8,9} Stereopsis is a binocular cue that results from fusion of two disparate retinal images, producing perception of stereo depth, or what Wheatstone referred to as "seeing in solid."¹⁰ However, it is important to note that stereopsis provides relative depth information rather than information about absolute distance. Additionally, the process of distance scaling of disparity information is important, because the disparity cues for two objects separated by the same distance differ depending on the viewing distance.⁶

Stereopsis develops early in life and is relatively immune to misinterpretation.¹¹⁻¹³ Monocular cues provide indirect information on depth that may be influenced

by environmental or intrinsic factors. However, Gibson (1955) presents a much different perspective concerning the perception of depth. He argued persuasively that optic flow is a rich source of information available to any organism that locomotes to guide egomotion, and that classically defined, static cues to depth were not sufficient for the control of egomotion. According to Gibson, egomotion, including depth, is specified by the interaction of the observer with the environment as optical invariants. He went on to identify several flight tasks that could be guided by the optical flow field: control of glide slope, initiation of flare, helicopter landing, avoiding obstacles, and pursuit maneuvers.¹⁴

The role of depth perception and stereopsis in flying has been a topic of interest since the birth of aviation medicine. In 1919, Wilmer and Berens¹⁵ noted "the value of stereoscopic vision...is of great value in judging distance and landing... The importance of this qualification seems to grow greater as our experience increases." Howard (1919) stated, "It is error in judgment of distance in landing a plane that has caused the great majority of deaths among cadet aviators."¹⁶ More recently, however, some researchers have concluded that stereopsis is not required for flight safety, and that other cues to depth are sufficient.^{17,18} Other authors have also commented that, given the large distances typically involved in aviation, there may not be sufficient reason to maintain a depth perception standard in aviation.¹⁹

Historically, there is some anecdotal evidence that suggests that monocular aviators might possess sufficient depth perception for safe control of aircraft.²⁰ However, in nearly every case, these aviators were already very highly experienced prior to their injury and highly motivated to continue flying. History has also presented evidence that flying without the perception of stereoscopic cues can result in mishap. Wilmer and Berens (1920) reported two cases of crashes during landing due to binocular disorders of the pilot. In the first event, the pilot suffered from paralysis of the superior oblique muscle in one eye and reported intermittent diplopia and difficulty judging distances while landing. The second example was due to a temporary disruption of the binocular system due to hypoxic exposure while flying at 15,000 feet. During an emergency landing, the pilot initiated a flare maneuver when he judged his plane to be about 1 foot above the ground, when in reality he was about 15 feet; the plane stalled and crashed.¹⁵ More recently, the National Transportation Safety Board concluded that the probable cause of the crash of a Delta MD-88 on approach to LaGuardia airport in 1996 "...was the inability of the captain, because of his use of monovision contact lenses (one eye corrected for far, one eye corrected for near), to overcome his misperception of the airplane's position relative to the runway during the visual portion of the approach."²¹ A post-accident examination revealed the pilot had substantially reduced stereopsis and was likely relying on monocular cues to judge distances. Although the pilot had flown with monovision contact lenses for 6 years before the mishap and had an exemplary record, the circumstances during the mishap flight may have reduced the utility of monocular cues to depth (poor visibility; approach over water, which offers fewer cues for judging altitude than would be available with detailed terrain; and lights on the runway spaced at 150 feet apart, rather than a standard 200 feet).

Numerous studies have evaluated the role of stereopsis in landing performance by comparing binocular landings to landings performed under occlusive conditions. In 1935, Jongbloed²² reported that he could find no differences in landings performed by experienced aviators under monocular and binocular conditions, although subjects reported a high level of apprehension when performing the task with one eye. A study involving experienced Naval flight instructors flying a standard biplane trainer used bi-nasal occlusion to eliminate the binocular stereoscopic field, while maintaining the full visual

field.²³ In this study, the removal of the binocular field created a tendency to flare too high and resulted in "missed" landings on 6 of 13 attempts versus misses on 1 of 12 attempts without occlusion. A National Aeronautics and Space Administration study²⁴ involving experienced test pilots flying a T-33A jet trainer compared landing performance under binocular and monocular (using an occlusive patch) conditions. No differences in either lateral or longitudinal accuracy were observed; however, monocular approaches were flown with a greater rate of descent (i.e., steeper) and occluded subjects reported a greater cognitive workload. A limitation cited for all of these studies was the fact that subjects were highly experienced pilots who might be expected to overcome unusual conditions. Several studies evaluated landing performance of low-hour civilian pilots flying a single-engine general aviation aircraft with and without occlusion. One reported a statistically significant improvement in landing accuracy under monocular conditions, although the authors could not offer any satisfactory explanation for this finding.²⁵ In contrast to prior studies, there were no observed differences in the manner in which monocular approaches were flown, although pilots did report increased workload when performing monocularly. Another reported no differences in landing accuracy under monocular conditions, although monocular approaches were flown higher and steeper and were rated as more difficult by the subject pilots.²⁶ The authors of these studies have generally concluded that the judgment of distance while landing is a combination of both monocular and binocular cues due to the fact that, although landings could be performed under monocular conditions, the landing strategy was modified and subjects had to exert more cognitive effort to compensate for the loss of binocular input.

While the studies of landing under occlusive conditions provide some insight regarding the role of stereopsis when flying, they are only partially applicable to the interests of this paper for several reasons. First, these studies involved normal subjects deprived of binocular vision with little time to develop adaptive strategies. For example, although subjects with normal stereo acuity are generally found to perform better in tests of fine motor skills, there is some evidence for adaptation to the absence of stereovision.²⁷ Second, subjects were typically deprived of the full visual field, which has been shown to play a role in altitude maintenance during flight simulations.²⁸ Additionally, individuals with reduced ("defective") stereopsis often exhibit monofixation syndrome. This condition is characterized by a central suppression scotoma, which may be constant or intermittent, with peripheral fusion.^{29,30} Cover testing may reveal orthophoria, a well-compensated phoria, a partially compensated phoria, or a small angle tropia (up to 8 prism diopters). Thus, additional factors may affect the performance of individuals with defective stereopsis that would not be evident in studies involving normal subjects with one eye occluded.

Several studies have compared pilot training outcomes between stereo normal and stereo defective subjects. In a 1993 retrospective study of attrition rates from USAF Undergraduate Pilot Training (UPT) based on stereoscopic visual status, three groups of subjects were identified: (1) applicants who passed the Vision Test Apparatus (VTA) (the USAF aeromedical standard for stereopsis), implying distant stereopsis of 25 arcsec or better; (2) applicants who failed the VTA, but passed the Verhoeff near stereopsis test at 16 arcsec; or (3) applicants who passed the Verhoeff test with unknown results on the VTA due to lack of documentation in medical records. However, no significant differences in attrition rates were identified between any of the groups.³¹

A second study compared UPT performance of 96 individuals waived into USAF pilot training for defective stereopsis versus 8,907 subjects who met the stereopsis standard (25 arcsec or better on the Armed Forces Vision Tester). The make-up of the defective stereopsis group was not specified; however, based on USAF waiver policy, these subjects demonstrated monofixation

syndrome or a horizontal microtropia not exceeding 8 prism diopters. They also must have scored 60 arcsec on the AO Vectograph (a distance task that uses polarized targets to provide disparate images to the two eyes), or scored 120 arcsec on the AO Vectograph and 30 mm or less (better than 11 arcsec) on the Howard-Dolman (HD) depth perception test. UPT performance was based on six formation flight maneuvers that occur within a distance of 600 feet or closer. Five of the six maneuvers showed a small, but statistically significant, difference between populations, with defective stereopsis subjects demonstrating inferior performance.³² A third study compared stereo defectives (12 subjects) versus a control group of stereo normals (100 subjects) on an extended trail maneuver. This task requires the subject pilot to follow a lead plane through a series of aerobatic maneuvers at a distance of 500 to 1,000 feet behind the lead plane, and thus is considered to be a non-stereoscopic-dependent task. No statistical differences between populations were observed.³³ The results of these studies led USAF aeromedical policy makers to conclude that waiver criteria related to defective stereopsis were appropriate. In another recent study, UPT graduation rates for trainees with normal stereopsis versus those who had been admitted to training on a stereopsis waiver were examined. Scores from the spatial subtest portion of the Multidimensional Aptitude Battery, which involves recognition of two-dimensional rotated objects, were also included as a second independent variable. Analysis of stereopsis status alone did not show any significant differences in UPT graduation rate. However, subjects who scored below the 5th percentile on the spatial subtest and also received a waiver to attend UPT with defective stereopsis were over four times more likely to fail UPT versus normal subjects. This was a statistically significant finding; however, there were only three subjects with defective stereopsis and poor spatial sub-score.³⁴

For non-pilot tasks involving depth perception, very little data are available demonstrating a relationship between vision and performance. Research involving estimation of height above terrain for helicopter pilots, a task also performed by non-pilot aircrew such as tail gunners and flight engineers, indicates that performance is highly variable.³⁵ It has also been shown that the use of stereo displays in an aerial refueling simulation improves estimates of receiver aircraft distance relative to the refueling boom.³⁶

Another issue that is a particular concern for the aeromedical community given the demanding nature of the combat aviation environment, is the effect of fatigue and sleep deprivation on performance. The USAF in particular has specific policies addressing, for example, microtropia, that may become decompensated due to fatigue and may impair depth perception, potentially increasing operational risk³⁶. However, very little research is available that examines the effect of fatigue on depth perception and the performance of tasks that may depend on fine stereo acuity.

In summary, although a large number of research studies have examined the role of stereo acuity/depth perception on the performance of various tasks over many years, the results are often conflicting, and so the importance of stereopsis continues to be a subject of much debate.

DEPTH PERCEPTION STANDARDS AND TEST METHODS

The U.S. military maintains standards for stereopsis as well as binocular alignment for pilots and other aircrew. In addition to pilots, the USAF maintains depth perception standards for non-pilot aircrew with scanner duties, which involves tasks that are likely to depend on good depth perception such as aerial refueling, clearing aircraft for landing, clearing aircraft during taxiing, and clearing aircraft during formation flight. U.S. Navy (USN) aviation depth perception and binocular alignment standards also apply to most of the Class II and some of the Class III aviation personnel. Class II includes Naval Flight

Officers, Naval Aerospace Medical personnel (e.g., flight surgeons), and Naval Aircrew Rotary Wing. These individuals operate in a wide range of tactical tasks such as anti-submarine, mine hunting, and search and rescue missions while onboard Navy fixed or rotary wing aircraft (e.g., SH-60R). Among Air and Space Interoperability Council nations, all but Australia test for stereo acuity. However, although Canada tests stereo acuity, a minimum standard has not been established, and the United Kingdom allows a stereo acuity score of up to 120 arcsec.³⁷ Table 1 below summarizes current USAF, USN, and US Army standards.

Table 1. USAF, USN, and US Army stereo acuity and oculomotor standards (¹Unmanned Aerial Vehicle, ²Armed Forces Vision Tester).

		USAF (Air Force Waiver Guide)	USN (NAVMED P-117)	USA (Army Regulation 40-501)
		FCI/IA/II/III (Scanners)	FCIII Class I, Class II (except Fixed Wing Aircrew), Class III (including UAV Operators, Critical Flight Deck Personnel)	Class 1/2/2F/3/4
Stereo-acuity (Arc Second)		≤25	N/A VTA-DP or OVT (≤25) or Randot or Titmus (≤40) or Verhoeff: 8/8 on 1 st trial; or 16/16 on the 2 nd and 3 rd trials	≤40
Phoria	Eso	<10 PD	<15 PD	<6
	Exp	<6	<8	<6
	Hyper	<1.5	<2	<1.5
Tropia		0	<15	0

The USAF uses a variety of methods to assess stereopsis and ocular alignment. All USAF pilots and aircrew with scanner duty are administered the stereo acuity and phoria tests using the Stereo-Optical Armed Forces Vision Tester (AFVT, see Figure 1). Aircrew must score 25 arcsec or better on the AFVT stereo test and must meet the minimum standards for phorias as summarized in Table 1. However, aircrew may receive a stereopsis waiver if they score at least 60 arcsec (4/4) on the AO Vectograph test of stereo acuity (see Figure 1) or, failing that, at least 120 arcsec on the AO Vectograph and obtain a score of 30 mm or better on the HD (Figure 2) depth test.³⁸ The USN Class I, Class II (except fixed wing aircrew), and some of the Class III (e.g., UAV operators, critical flight deck personnel) are required to pass the oculomotor requirements and score at least 25 arcsec on the AFVT stereo test or 40 arcsec on Titmus or Randot stereo test or score 8/8 on the first trial or 16/16 on the combined second and third trials on Verhoeff Stereoptor tested at a 1-meter distance (Figure 3). In general, there is no waiver recommended for any Class I aircrew ("duty involving actual control of aircraft").³⁹

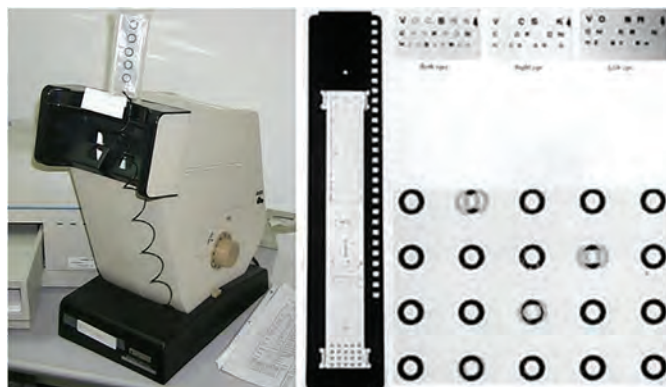


Figure 1. Stereo-Optical Vision Tester used by the USAF to administer stereo acuity and phoria tests (left). AO Vectograph slide (right).

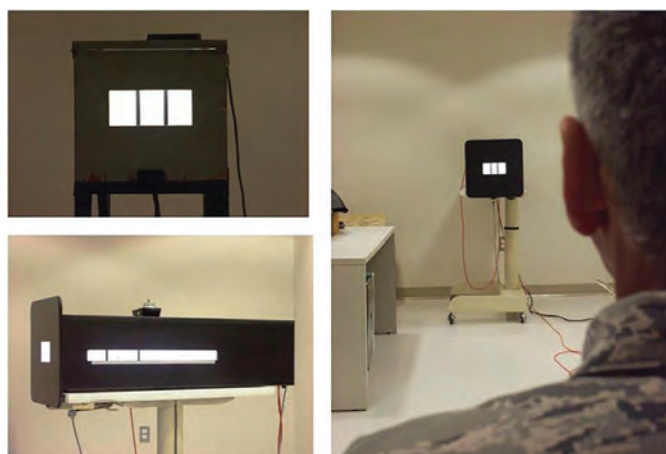


Figure 2. Howard-Dolman depth perception test.

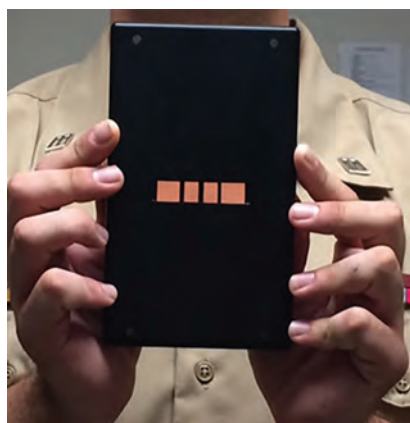


Figure 3. Verhoeff Stereoptor.

While existing aeromedical policy has been in place for many years, and is informed through feedback between operational squadrons and the aeromedical community, it is not clear that existing standards are predictive of operational performance. Figure 4 illustrates how current standards relate to data collected by Howard (1919).¹⁶ As shown in Figure 4, nearly everyone in Howard's test group would meet the existing USAF and USN standards.

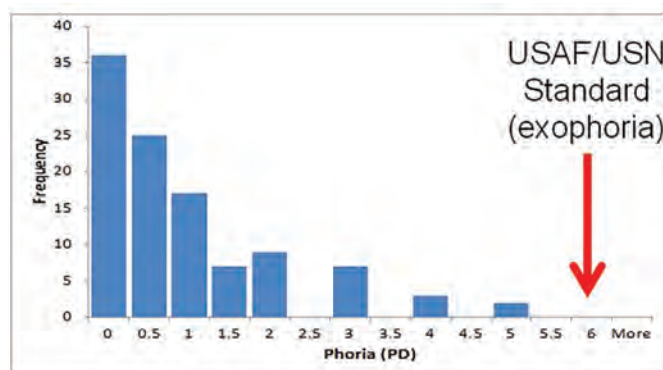
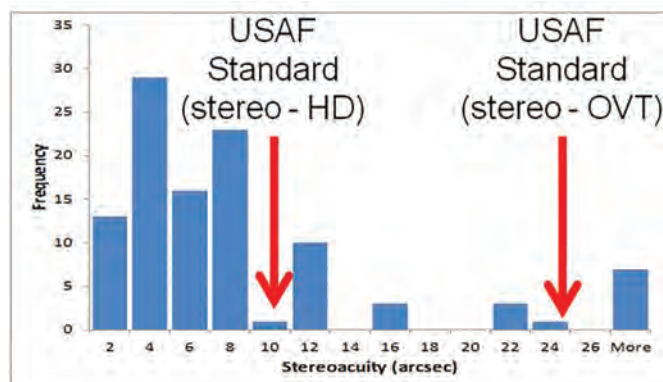


Figure 4. Howard's (1919) stereo acuity data (top) and phoria data (bottom) for 106 subjects. Current USAF and USN vision standards are shown for comparison.

The depth perception and stereo acuity tests still in use by the USAF and USN can be traced to the WWI and WWII era. These tests include the HD test, the AFVT stereo acuity test, Verhoeff Stereoptor,⁴⁰ and the AO Vectograph (see Figures 1-3). These tests are all manually administered and, although appropriate for rapid clinical screening, may result in fairly coarse estimates of stereo acuity. For example, the AFVT measures stereo acuity only to a level of 15 arcsec. However, for aircrew with good ocular health, stereo acuity thresholds are at the level of 3 to 10 arcsec.^{3,16,41} However, individuals differ widely in stereo acuity.^{16,42} The accuracy, test-retest reliability, and efficiency of stereo acuity testing could be improved with the development of computer-based tests. Further, with the introduction of new technologies, such as remote vision systems using stereoscopic displays viewed at a near distance, assessment of ocular alignment and stereovision may become more important and potentially require a different testing approach. Recent research has already demonstrated the feasibility of computer-based tests.^{43,44} Both of these studies showed that thresholds for stereopsis less than 5 arcsec could be quickly obtained using modern psychophysical procedures.

Although no longer heavily relied upon for routine diagnosis and screening, the HD test, involving mechanically adjusted rods inside a wooden box viewed at 20 feet, is still in use at the USAF for depth perception testing, as noted above (Figure 2). The HD test is a variant on the original Howard (H) depth test dating to 1919. The HD test is more easily and quickly administered compared to the H depth test, which uses method of constant stimuli rather than direct adjustment by the patient. However, this method permits patients to use a bracketing technique that may allow them to reduce their error score even though they may actually have defective stereopsis. In fact, research has

shown that test scores based on the Howard and Howard-Dolman procedures were uncorrelated. Subjects with poor scores on the H test could still achieve low error scores on the HD test.⁴⁵ This is consistent with results observed in practice: patients can fail the AFVT and the AO Vectograph (with stereo acuity worse than 60 arcsec) but can still do better than 30 mm on the HD test. Verhoeff (1942) commented that “the basic principles of the test originally employed by Howard were sounder than those of the test now known as the Howard-Dolman test...”⁴⁰ An early comparison of the HD and Verhoeff⁴⁶ indicates that the two tests differ substantially in test outcome and that the HD in particular had low test-retest reliability. The use of a computer-based test and an adaptive threshold estimation procedure would enable highly accurate and repeatable thresholds to be obtained in a time frame comparable to existing methods.^{44,47-49}

Another concern for some existing tests of stereo acuity is that individuals with poor stereo acuity can potentially obtain passing scores. Stereo blind patients and patients with strabismus, or who may be recovering from surgery to correct strabismus, may often be classified as having some stereo capability after completing the Titmus or Randot tests.⁵⁰ This is because these tests contain monocular cues that may allow the patients to identify the targets in the first several rows of the test (score of 400 to 140 arcsec). In another study, 22% of 49 test subjects could complete at least 2 lines of the Titmus test and 4% could accurately complete all 9 lines of the Titmus test using monocular cues alone (i.e., 40 arcsec or better).⁵¹ In fact, the results from a number of additional studies indicate that several commonly available stereo acuity tests may not be adequate and that the results across different tests vary widely.⁵²⁻⁵⁵ Furthermore, these commonly used tests use crossed disparity only, and require only that patients detect whether something is different about one of the test items. In other words, depth discrimination is not required. In contrast, stereo tests that have demonstrated test-retest reliability^{16,40,44,46} or that have been shown to be resistant to the use of monocular cues require depth discrimination (i.e. require the observer to determine whether a target is in front of versus behind a reference). Reinforcing this point, vision science research concerning stereo acuity does not rely on tests involving crossed disparity only, but instead adopts procedures that require depth discrimination.^{41,42,56} In fact, Landers and Cormack note that crossed disparities were more quickly and accurately detected by most observers in their study. They also go on to suggest that disparity computation may be a multistep process, with disparity detection, disparity magnitude estimation, and disparity sign computation as separate steps in that process, the implication being that observer capability may vary as a function of the quality of processing at any one of those steps.⁵⁷ Thus, a test assessing crossed disparity only may not adequately assess stereo depth perception.

UTILITY OF STEREOPSIS

Although much is known about how stereopsis works, little is known about its actual utility.⁵⁸ The debate concerning the utility of depth perception has been ongoing since the early 1900s. Howard commented in 1919 that “some examiners have questioned the absolute necessity of binocular single vision as a preliminary requirement.”¹⁶ A number of studies have found that good stereo and/or the use of stereo displays may be important for athletics,^{59,60} walking,^{61,62} driving,⁶³⁻⁶⁵ catching,⁶⁶ distance estimation,³⁶ telerobotics,⁶⁷ virtual reality,⁶⁸ and in medical applications.⁶⁹ However, in recent reviews,^{70,71} the utility of stereo displays across a variety of studies was found to be highly variable, with some showing a benefit of stereo, but a surprisingly large number showing no benefit. In another review, the authors went so far as to conclude that stereo three-dimensional displays should be avoided altogether due to depth cue and sensory conflicts likely to be induced by such systems.⁷² In

fact, many studies have noted that stereoscopic displays present an unnatural viewing situation to the observer that may result in misperception of depth, asthenopia, and other problems.^{6,69,73-78} For the aeromedical community, these issues are important to be aware of since aircrew are increasingly likely to use remote vision technology and stereoscopic displays. Further, some individuals, including aircrew, may be more likely to experience eyestrain and discomfort than others, which may impact performance.^{77,79} Existing vision standards were not designed for this situation.

As noted above, some researchers have concluded that stereopsis is not relevant for the landing of large aircraft and that there may not be sufficient reason to maintain a depth perception standard in aviation.¹⁷⁻¹⁹ Other researchers have even commented that it was their impression that many ophthalmologists and vision scientists secretly suspect that the utility of having a second eye is simply to have a spare in the event that one is injured.⁵² However, another set of studies conducted for the insurance industry in Canada found that commercial truck drivers with binocular vision problems were more likely to be involved in more severe crashes than normal drivers,⁶⁴ and taxi drivers with binocular vision problems were more likely to be involved in accidents.⁶⁵ In another driving study, driving characteristics between 10 stereo normal subjects and 10 subjects with defective or missing stereopsis (defined as either “no stereopsis” on the Titmus test or at most “fly positive”) were compared. Their results indicated that stereo normal subjects demonstrated superior performance on the slalom test, although no other differences in performance were identified.⁶³ Additionally, numerous studies have demonstrated that contrary to the “spare-eye” hypothesis, individuals who have lost one eye or suffer from amblyopia have significant difficulties with hand-eye coordination tasks and may have impairments in driving.⁸⁰

Because the disparity signal generated by two objects with a constant relative depth separation falls off approximately with the square of the distance of the objects from the observer, there is an ongoing debate concerning the distance over which stereopsis provides a useful cue to depth. It has often been assumed that stereopsis is not useful beyond about 6 meters (20 feet); however, other researchers have disagreed with this assertion.^{3,56} In an experiment to examine stereo acuity for viewing distances much larger than typically used in laboratory tests – up to 18 meters (60 feet), subjects were asked to make front/back discriminations for a large rod mounted on a motorized track relative to a reference panel (i.e., a super-sized Howard depth test). Binocular thresholds ranged from approximately 3 – 12 cm, corresponding to stereo acuities of approximately 5 – 10 arcsec. The authors concluded that stereopsis provides an effective cue for distances larger than typically assumed and go on to hypothesize that for individuals with 5 arcsec thresholds, it could remain an effective cue for distances as large as 1 km. In another experiment, errors in distance estimates for a boom operator task at a simulated distance of roughly 18 meters were consistent with stereo thresholds of approximately 5-10 arcsec.³⁶ Stereo thresholds were also in the range of 5 to 10 arcsec for an 18-meter viewing distance when display resolution and antialiasing were optimized in another experiment assessing factors that may affect boom operator training.⁸¹ According to USAF policy, stereopsis is assumed to be a useful cue for distances within 200 meters.³⁸

During the course of this literature review, it became apparent that many studies examining the utility of stereo and/or stereo displays do not assess individual differences in stereo acuity, rely on only very coarse measures, do not identify criteria for “normal” stereo, or simply group observers loosely into “good” versus “poor” stereovision groups, and then compare grouped performance. It probably should not be surprising that many studies have been unable to clearly demonstrate the utility of depth perception with what are often limited

measures of quality of binocular vision. Recently completed research provides support for this conclusion. A computer-based stereo acuity test designed by OBVA Lab personnel predicted performance on a depth placement task while a traditional stereo acuity test did not. All participants in this experiment would be classified as having "normal" or "good" stereopsis on the basis of having passed the Titmus test (i.e., 40 arcsec or better). However, only the threshold test was capable of revealing that differences in performance could be attributable to differences in stereo vision. Another potentially interesting result of this work was that measures of fusion range (which is not a standard screening test) were also predictive of performance, while phoria measures (which are standard tests) were not.⁴³

CONCLUSIONS

Based on the summary of the studies reviewed in this paper, it seems reasonable to conclude that stereopsis plays some role in judging depth in the course of performing aviation tasks. Landing studies under occluded conditions demonstrate that the maneuver can be accomplished by monocular cues alone. However, the fact that subjects modified their strategy (higher and steeper descents) and experienced an increase in cognitive load suggests that important visual information was missing. The 1996 mishap at LaGuardia also provides evidence that stereopsis may become particularly important under impoverished viewing conditions. Many other studies demonstrate that distance estimation at large distances, tasks involving hand-eye coordination, motor control, navigation, and vehicle control tasks may be dependent on good stereopsis. Furthermore, binocular viewing results in improved performance on many different task measures. A person without normal binocular function not only has the disadvantage of working without stereopsis, but also relies on monocular cues that are potentially diminished.^{82,83}

Just as there is poor agreement on the useful range of stereopsis, there is similar disagreement by international aviation governing bodies on what level of stereopsis is required to be considered "fit to fly." Currently, the USAF requires any aircrew involved in controlling or clearing the aircraft, out to 200 meters, to demonstrate 25 arcsec of stereo, although 60 arcsec is waiverable if the condition is considered to be stable. Aircrew can also potentially obtain a waiver if they score better than 120 arcsec on the AO Vectograph and pass the HD. The USN standard is 40 arcsec for aircrew in control of the craft with no allowance for waiver, while the U.S. Army requires 40 arcsec for all aircrew, regardless of crew position. Conversely, the Canadian Air Force³⁷ and the Federal Aviation Administration have no stereopsis requirements. Furthermore, the Federal Aviation Administration allows pilots of all classes who have lost an eye to return to flying pending a 6-month adaptation period.⁸⁴ Finally, although many different stereo acuity tests are available, it is not clear that existing tests provide sufficiently accurate and reliable estimates of stereo acuity for use in evaluating the relationship between stereopsis and operationally relevant performance.

PLANNED RESEARCH AND RECOMMENDATIONS

Based on the results of our literature review, due to questions concerning the practicality and cost of current aeromedical policy, and due to the introduction of aerial refueling operator (ARO) crew stations using remote view cameras and stereoscopic displays, we have developed a program of research to address gaps in our understanding of depth perception requirements:

- 1) Research and develop new tests of stereo acuity using adaptive threshold estimation procedures to improve accuracy and reliability, while reducing test time. As this review highlights, a "research grade" stereopsis test is needed as an initial step towards further

research. While most existing tests assess crossed disparities only, new test methods will require observers to discriminate crossed from uncrossed disparities. During the course of this research, we will compare the outcomes of different tests. New stereo tests will augment a battery of newly developed computer-based vision tests assessing color, contrast sensitivity, acuity, and motion perception. USAFSAM is working together with NAMRU, Battlespace Visualization Branch, and Singapore Ministry of Defence and DSO National Laboratories to conduct this research.

- 2) Evaluate relevance of existing vision standards for aerial refueling operators using remote view stereoscopic displays. The aerospace medical community has expressed concern that existing vision standards, designed for screening aircrew viewing real imagery at far distances, may not be adequate for screening AROs using this new technology.⁸⁵⁻⁸⁹ Additionally, much research has shown that use of stereoscopic displays leads to reports of eyestrain, headaches, and other discomfort,⁹⁰⁻⁹² and some individuals may be more susceptible to eyestrain and discomfort than others.^{77,79} Further, the effects of hyperstereo, a common feature of remote view systems, on performance are not well understood.⁹³⁻⁹⁷ USAFSAM has developed a simulation of an ARO crew station to evaluate the relationship between stereo acuity and performance and between measures of ocular alignment and user discomfort and fatigue over a long period of task performance (2 hours).
- 3) Evaluate applicability of depth perception standards for non-pilot aircrew. A research protocol has been developed to evaluate the relationship between measures of stereo acuity and performance on a simulated helicopter landing task under varying conditions of visibility. Participants in this simulation will be asked to estimate distance to the ground as the simulated aircraft descends. Participants' proficiency in avoiding ground obstacles will also be evaluated.
- 4) Evaluate effects of chronic sleep deprivation on depth perception. Sleep deprivation is known to result in an increase in pupillary response latency and a decrease in saccadic velocity. Additionally, pupillary response and saccadic velocity have been correlated with driving simulation crash rates.^{98,99} However, as noted previously, little is known about the effect of fatigue on depth perception. USAFSAM and NAMRU-D are collaborating on research to assess the effect of sleep deprivation fatigue and stimulants on cognitive and visual performance. USAFSAM's aerial refueling research will also examine whether fatigue may affect performance during the course of a 2-hour, operationally relevant, time period.

Although the research outlined above represents a large effort across several organizations, much more research is required to address the gaps in our understanding of depth perception summarized in this review. In aviation, and for other activities involving vehicular control, defective stereopsis can potentially lead to catastrophic consequences under some circumstances. Additional research establishing a quantitative relationship between depth perception and task performance would help reduce that risk. However, it is not clear that a restrictive depth perception standard is necessary for all aircrew. A better understanding of the relationship between depth perception and performance could also enlarge the eligible pool of candidates and reduce costs associated with medical screening and administration. Finally, although we focus here on aeromedical vision standards and the relationship between individual differences and visual task performance, more research is also needed to address the effect of system design variables on performance

and operational risk. With the proliferation of systems using remote vision, sensors, stereoscopic displays, and remotely controlled vehicles, vision science research, and human systems research more broadly, is becoming increasingly important.

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