VESTIBULAR UPDATE

EVALUATION OF VISUAL VESTIBULAR INTERACTION WITH THE DYNAMIC VISUAL ACUITY TEST

by

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Abstract

Interaction of the vestibular system with the other vision stabilizing visual vestibular interaction (VVI) systems is essential for retinal image stability during movement to optimize visual performance. Dynamic visual acuity (DVA) is the threshold of visual resolution achieved during relative motion, and is a performance measure of VVI. Dynamic visual acuity has been correlated with athletic abilities, aviator spatial orientation, and driving frequency in the elderly.

A computerized Dynamic Visual Acuity Test (DVAT) developed by Micromedical Technologies, Inc. using the VORTEQÒ system uses active head movements to trigger a computer generated eye chart. The computerized Dynamic Visual Acuity Test (DVAT) overcomes limitations of the Dynamic Illegible E (DIE) test, a bedside test with a handheld chart. The computerized DVAT can quantify a wide range of head velocities, can store multiple eye charts, and takes only 8 - 10 minutes. Visual acuity is scored using the log Mean Angle Resolvable (log MAR) scale, allowing visual performance to be precisely quantified. The DVAT has been used in 1) normal subjects, 2) divers (exposed to high intensity low frequency waterborne sound), 3) aviators (with recurrent or disabling spatial disorientation, difficulty with instrument flying, or refractory airsickness), and 4) patients (with neurological and/ or vestibular complaints).

The healthy subjects were comprised of 30 male U.S. Navy divers with mean age 33 years old (S.D. 5.9 years) ranging from 22 - 45 years old. The clinical patient population consisted of the 37 cases, ranging from 21 to 51 years old, whose average age was 33 years old (S.D. 8.6 years). Several DVAT performance patterns were identified based on the magnitude of decreased visual acuity and spectrum of head velocity of visual acuity deficit. These patterns include 1) Low/ high head velocity DVA deficit pattern, 2) Severe low/ high head velocity DVA deficit pattern, 3) High head velocity DVA deficit pattern, 4) Zero, low and high head velocity DVA deficit (subphysiologic) pattern, and the 5) Supraphysiologic Pattern. The Dynamic Visual Acuity Test (DVAT) can assist in diagnosis and r-management of patients with vestibular disorders and can aid the in evaluation of fitness for special duty, such as divers or flight personnel.

Introduction

Stabilization of the retinal image during movement is necessary for optimal visual performance of an ambulatory human. Visual tracking (pursuit), proprioception, motor preprogramming (efference copy), prediction, and mental set (non visual parametric adjustment) interact synergistically to optimize the gain (eye velocity divided by head velocity) of the vestibulo-ocular reflex (VOR) to stabilize the retina during head movements and are collectively termed visual vestibular interaction (VVI) [7]. Patients with a deficient vestibular system often compensate with other VVI mechanisms. These mechanisms are insufficient for optimal vision at higher rotational frequencies and velocities, and often give rise to symptoms of oscillopsia (apparent motion of objects in the visual field). Loss of VVI function is described as like viewing a video camera image recorded while walking, with the image bouncing around.

Dynamic visual acuity (DVA) is the threshold of visual resolution achieved during relative motion of either the visual targets or the observer and is a performance measure of VVI. Visual functions that decline with age include dynamic visual acuity, and the implications of these age-related changes in visual performance are great [10]. Dynamic visual acuity was significantly associated with driving frequency in the elderly [14]. Dynamic visual acuity has been correlated with athletic abilities and may be trainable [8,11]. Interaction of the vestibular system with the other vision stabilizing VVI systems is essential for an aviator to succeed in the complex visual motion flight environment and enhances a flyer's ability to maintain situation awareness and spatial orientation [3].

For flyers, different VVI functions are prioritized depending on operational needs. The Visual Vestibular Ocular Reflex (VVOR) is required to track a stationary (earth fixed) target while turning. Pursuit (slow eye movement) is essential to track and identify slowly moving objects, and the saccade (fast eye movement) is necessary to acquire objects detected in the peripheral visual field. Visually induced optokinetic nystagmus (OKN) occurs in a moving visual background, contributing to optical flow and the sense of speed over terrain. Suppression of the Vestibular Ocular Reflex (VOR-S) is required when tracking a head fixed target (such as a helmet mounted visual display) while turning. VOR gain and retinal instability may be significantly altered by viewing through a movable telescopic sight (optical targeting device).

A clinical test of dynamic visual acuity (DVA) is the Dynamic Illegible E (DIE) test, which was developed to assess patients for aminoglycoside ototoxicity at the bedside using a specially designed visual acuity chart of E's of different sizes [12]. The DIE test measures static visual acuity (head held still) then the head is moved passively back and forth once per second and the change in visual acuity is recorded. The decline in acuity during head movement with the DIE test correlated with reduced caloric response [12]. Normal subjects making head movements dropped no more than one row while reading the DIE chart, while decline in acuity more than two rows with head movement was considered abnormal [13].

The change in visual acuity with head movement can be used to monitor patients for medication related vestibulotoxicity, however VOR compensation, shown by the DIE test, did not always coincide with onset of vestibular dysfunction, possibly due to individual variability in compensatory mechanisms [13]. The relationship between oscillopsia and DVA or rotation testing is not always established, and many patients with bilateral vestibular loss deny oscillopsia [1]. The relative changes in VOR rather than the absolute VOR loss may be responsible for oscillopsia [1]. Dynamic visual acuity has been measured experimentally using a computer-controlled projection system during sinusoidal motion either of the eye chart letters or the subject [5]. In normal persons, the VOR functions adequately during head movements to limit retinal image motion. DVA for both letter (target) and head motion was degraded when the retinal image velocity exceeded 2 degrees per second. Dynamic visual acuity during imposed head motion is a quantitative measure of oscillopsia.

Dynamic visual acuity for head motion was measured unaided and with telescopic spectacles (plus lenses). Normal subjects wearing telescopic spectacles experience artificial experimental oscillopsia. Telescopic spectacles are used as aids for the visually impaired in order to increase visual acuity. Static visual acuity improved with increasing telescopic spectacle power, but DVA progressively worsened with head motion as telescopic spectacle power increased [6]. Reduced acuity with head motion while wearing telescopic spectacles is due to retinal image slip. The adverse effect of head motion on DVA while wearing telescopic spectacles diminishes their value in low vision patients and may be reduced by VOR adaptation, which reduces visual-vestibular conflict [6].

The Visual Vestibular Ocular Reflex (VVOR) or visual enhanced VOR, maintains ocular stability during head motion by generating compensatory eye movement opposite to head movement, and is a major component of visual vestibular interaction (VVI). The gain of the Visual Vestibular Ocular Reflex is higher (more accurate) than VOR gain. VVOR can be tested with conventional rotational chair methods or with active head rotation techniques. Rotational chairs generate movement from .01 Hz up to about 1 Hz, while active head rotation systems test from 1 to 8 Hz. Dynamic Visual Acuity is a performance measure of VVOR function. Micromedical Technologies developed a research computerized software version of the Dynamic Visual Acuity Test (DVAT) using the VORTEQÒ system hardware. The Micromedical Technologies DVAT system uses active head movements to trigger a computer generated eye chart.

This system has been used in the U.S. Navy and U.S. Army Aeromedical Research Laboratories in a program to evaluate a screening test to rapidly assess visual vestibular performance [9]. The basis for this program resulted from the case of a 24-year-old student aviator in advanced jet training evaluated for recurrent in flight spatial disorientation (SD) during instrument flight training [3]. He had done well in his flight training except in cloudy weather conditions, where he could no longer see the instrument panel that oscillated during turbulence, and could not pass his instrument check ride. On exam he had a substantial drop in visual acuity with horizontal or vertical head movements, minimal caloric response bilaterally, and absent VOR gain on rotational testing. He had a history of severe vertigo, nausea, and vomiting for 3 days at age 13 years, which resolved, and he denied oscillopsia. He was disqualified from aviation despite considerable investment in training costs, and a program was instituted to develop a screening test for vestibular function in Navy flight personnel.

Clinical Evaluation of Visual Vestibular Interaction

A clinical Dynamic Visual Acuity Test (DVAT), the Dynamic Illegible E (DIE) test, can be performed to assess Visual Vestibular Interaction at the bedside. Static acuity (no head movements) is tested then the patient reads the visual acuity chart while they rotate their head from side to side at 1-2 cycles per second. An abnormal response, indicating vestibular dysfunction, is suggested if there is a decrement of more than 2 lines on the visual acuity chart. There are several limitations of the bedside Dynamic Illegible E (DIE) test. The eye chart can be memorized during the test or on repeat testing and the letters are present even when the head is not moving, allowing the subject to view them and memorize them. The conventional eye charts are scored as the visual acuity line. For example if a subject can see most of the 20 / 20 line, but missed 2 letters (incorrect), their score would be 20 / 20 minus 2 letters. This is very difficult to score and analyze statistically. Eye charts used at close distance may invoke discongugate eye movements. Velocity and frequency are not always well controlled or quantified with either passive (operator generated) or active (subject generated) head movements.

Computerized Dynamic Visual Acuity Test (DVAT) Methodology

The computerized Dynamic Visual Acuity Test (DVAT) is a rapid screening test of the visual-vestibular ocular reflex (VVOR) which uses active (subject generated) head movements. It overcomes some of the limitations of the bedside test with a handheld chart. The computerized DVAT displays the visual acuity chart only when the head velocity exceeds a preset threshold, which can be quantified over a wide range of velocities. The computer can store multiple eye charts of the same size to prevent memorization. The Dynamic Visual Acuity Test (DVAT) test equipment used in this series of studies included a Micromedical Technologies VORTEQÒ system 386SX computer and 13 inch color monitor (VGA). The visual acuity chart is calibrated to the monitor screen by adjusting horizontal and vertical gain of the monitor to ensure the proper size according to the Dynamic Visual Acuity Test (DVAT) calibration scale (Table 1). The DVAT takes 8 - 10 minutes to perform, with setup and subject preparation (1 minute), test performance (5 - 7 minutes), and analysis time (2 minutes) and is routinely done by basic technician level trained personnel such as corpsmen. The subject wears a yaw axis angular rate sensor secured on a headband and reads a computer generated eye chart at a 10-foot (3-meter) distance while turning head side to side at specific head velocities and frequencies. The 10-foot test distance can be performed in most exam rooms. The operator sets the threshold velocity and frequency.

The threshold velocity determines when the computer-generated eye chart appears and the frequency determines when the audible metronome beep occurs. Head movements are coordinated with the metronome beep, with each beep the head should be at maximum deviation. The computer-generated eye chart is displayed only when the subject turns their head at or above the selected velocity. The subject attempts to read the smallest visual acuity chart while the operator encourages best visual acuity from subject. DVAT scores are compared to static (no head movement) acuity. The 5 test conditions used here were static (0 velocity), 0.7 Hz (70 deg/sec), 1.0 Hz (100 deg/sec), 1.4 Hz (140 deg/sec), and 2.0 Hz (200 deg/sec). Head movement sequence started at the slower frequency (velocity) and got progressively faster with each trial. Each test condition took 20 - 40 seconds to administer.

Baseline acuity is the smallest line of letters the subject can read for which the majority of letters were correctly identified. The visual acuity score used is the log Mean Angle Resolvable (log MAR) scale, which allows visual performance scores to be precisely quantified and statistically analyzed, unlike the 20 / 20 visual acuity score method. Each eye chart line has a logMAR score based on letter size. The acuity chart changes letter size scale in 0.1 logMAR increments (20% optotype size change), and there are 5 letters per line in a vertical column on the displayed eye chart (except for the very largest letters which exceed the monitor size).

The scoring convention is calculated for each letter missed from the baseline. For every letter missed add (+0.02 logMAR) to the logMAR score for that visual acuity size. If the subject can see all letters on a line the next smaller line is tested. A log Mean Angle Resolvable (logMAR) scale of zero (0.0) is equal to 20 / 20, and a log Mean Angle Resolvable (log MAR) scale of one (1.0) is equal to 20 / 200. The larger the logMAR score the worse the vision. Negative scores represent visual acuity that is better than 20 / 20 and most people have a best corrected visual acuity better than 20 / 20 (logMAR score of 0). It is important to obtain best visual acuity and not just stop at 20 / 20 because decrements will be more precisely detected when starting from best visual acuity. Faster head movements are challenging to make and may be very difficult if the subject has a stiff neck. The patient must have the motor strength and cognitive ability to understand and perform the test. The logMAR scores at the different head velocities are compared with normative data and/ or prior studies done on same subject.

Log MAR	Visual Angle (minutes of arc)	Visual Acuity	Size (inches) at 20 feet	Size (inches) at 10 feet
- 0.3	.50	20 / 10	0.18	0.09
- 0.2	.63	20 / 13	0.22	0.11
- 0.1	.79	20 / 15	0.28	0.14
0.0	1.0	20 / 20	0.35	0.17
+ 0.1	1.26	20 / 26	0.44	0.22
+ 0.2	16.0	20 / 32	0.56	0.28
+ 0.3	2.0	20 / 40	0.70	0.35
+ 0.4	2.51	20 / 50	0.88	0.44
+ 0.5	3.2	20 / 62	1.12	0.56
+ 0.6	4.0	20 / 80	1.40	0.70
+ 0.7	5.0	20 / 100	1.75	0.87
+ 0.8	6.4	20 / 130	2.24	1.12
+ 0.9	7.9	20 / 160	2.75	1.38
+ 1.0	10	20 / 200	3.50	1.75

Table 1 Dynamic Visual Acuity Test (DVAT) Calibration Scale

Results

The DVAT has been used in 1) normal subjects, 2) divers (exposed to high intensity low frequency waterborne sound), 3) aviators (with recurrent or disabling spatial disorientation, difficulty with instrument flying, or refractory airsickness), and 4) patients (with neurological and / or vestibular complaints) in several U.S. Navy studies [2, 4, 16].
The DVAT was used to study clinical patients with general neurological diagnoses without vestibular symptoms, and diagnoses with vestibular complaints, such as vertigo and / or disequilibrium referred from neurologists, otolaryngologists, and internists for evaluation. The DVAT was used to assess flight personnel with recurrent severe airsickness or in-flight spatial disorientation (SD) referred from flight surgeons for evaluation (see Table 2).

Diagnosis		Number (%)	
Neurological (non vestibular)		10 (25%)	
	Headache		2 (5%)
	Closed head injury		2 (5%)
	Multiple Sclerosis		2 (5%)
	Brain Tumor		2 (5%)
	Heat stroke		2 (5%)
Vestibular		18 (51%)	
	Vertigo		8 (23%)
	Vertigo / Disequilibrium		7 (19%)
	Disequilibrium		3 (9%)
Flight related		9 (24%)	
	Air Sickness		5 (13%)
	Spatial Disorientation		4 (11%)
TOTAL		37 (100%)	

Table 2 DVAT Clinical Cases

The Dynamic Visual Acuity Test using active horizontal head movements was used to rapidly assess vestibular function before and after high intensity low frequency waterborne sound exposure in 30 divers with mean age 33 years old (S.D. 5.9 years) ranging from 22 - 45 years old [4, 16]. The necessity for this capability resulted when a diver exposed to high-intensity low frequency underwater sound (160 dB (re 1 m P) for 15 minutes) developed disequilibriurn and visual frame shift (oscillopsia) following sound exposure [15]. In a series of operational projects twenty-two divers underwent sound exposure in a wet hyperbaric chamber and 6 different divers received sound in open water at depths from 33 – 130 feet [4, 16]. Two other divers served as controls (dove without sound exposure) were also tested. Divers received 15 min cumulative exposure (100 seconds on / 100 seconds off) of 240-320 Hz underwater (U / W) sound at 160 dB (re 1 m P) each test day over 2 - 4 weeks with 8 - 10 exposures per diver. The Dynamic Visual Acuity Test detected transient vestibular effects immediately post sound exposure. The majority of divers were asymptomatic, however one diver had transient unsteadiness immediately post exposure and one diver developed transient visual frame shift and unsteadiness 24 hours post exposure. The Dynamic Visual Acuity Test and quantitative oculography were normal or improved in all divers at the conclusion of the study compared to pre-exposure baselines. The improvement in dynamic acuity function may be a training effect (subjects performed DVAT before and after each sound exposure for a total of 16 - 20 DVAT tests by completion of the study (Figure 1) [4, 16].

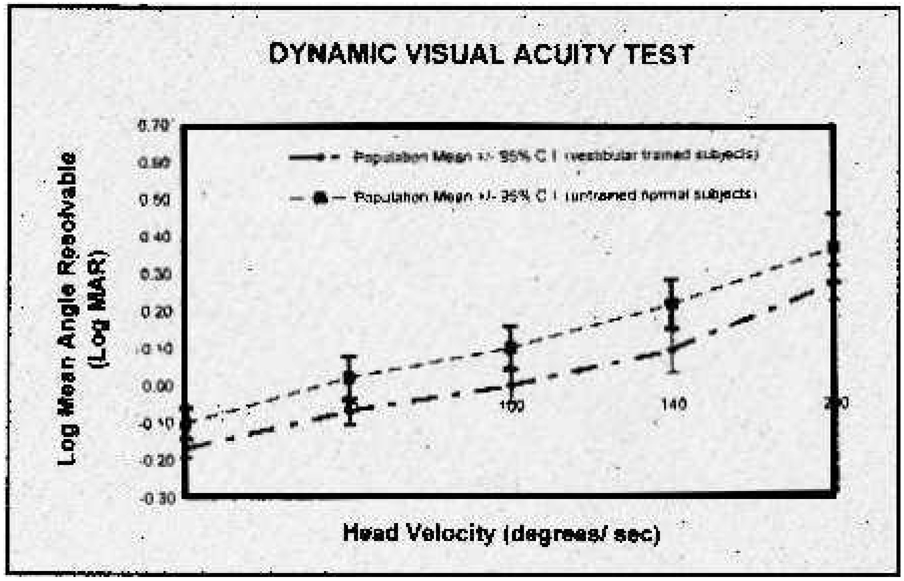

Figure 1

Normative data was analyzed for healthy subjects and clinical patients (Tables 3 and 4). The healthy subjects were comprised of 30 male U.S. Navy divers with mean age 33 years old (S.D. 5.9 years) ranging from 22 - 45 years old. The clinical patient population consisted of the 37 cases, whose average age was 33 years old (S.D. 8.6 years) with an age range from 21 to 51 years old.

Head Velocity	0	70	100	140	200
LogMAR Mean	-0.15	-0.02	0.05	0.15	0.34
LogMAR S.E.M.	0.01	0.02	0.02	0.02	0.02
LogMAR S.D.	0.07	0.09	0.09	0.11	0.13
LogMAR 95% C.I.	0.03	0.03	0.03	0.04	0.05

Table 3 Normative logMAR Dynamic Visual Acuity Data for healthy subjects (n=30 males, 22-45 years old, mean age 33 years)

Head Velocity	0	70	100	140	200
LogMAR Mean	-0.11	0.04	0.13	0.25	0.41
LogMAR S.E.M.	0.01	0.02	0.02	0.02	0.02
LogMAR S.D.	0.06	0.12	0.13	0.13	0.13
LogMAR 95% C.I.	0.02	0.04	0.04	0.04	0.04

Table 4 Normative logMAR Dynamic Visual Acuity Data for clinical patients (n=37, 21-51 years old, mean age 33 years)

DVAT Performance Patterns

The magnitude of decreased visual acuity and spectrum of head velocity of visual acuity deficit establish the various DVAT performance patterns.

Low l high head velocity DVA deficit pattern
Case 1 is a 28-year-old male with chronic episodic non-positional vertigo and disequilibrium, hearing loss and ear fullness for several years (possible Meniere's disease). He had DVA above normal at all frequencies (Figure 2). Rotational chair VOR gain was low normal, with phase lead and asymmetry and VVOR gain of 0.9. He denied oscillopsia.

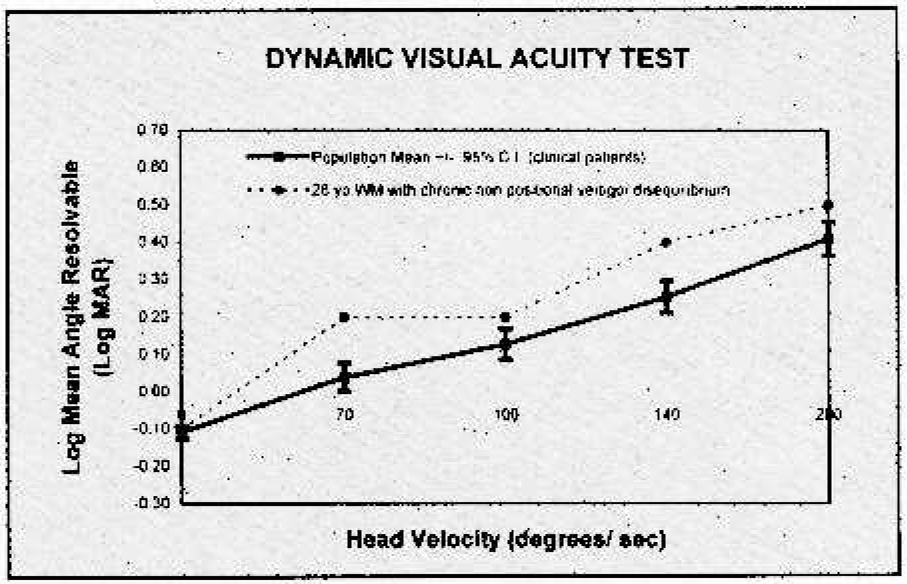

Figure 2 (Case 1)

Severe low l high head velocity DVA deficit pattern
Case 2 is a 48-year-old female who complained of severe oscillopsia and disequilibrium. She developed transient disequilibrium 1 week after each dose of carboplatinum for ovarian cancer. Her symptoms become constant when she received gentamycin for pneumonia she developed during chemotherapy. Her symptoms had progressively worsened, and her family nicknamed her "six pack". There was a strong family history of Meniere's disease. Dynamic visual acuity was significantly diminished at all frequencies tested (Figure 3). Rotational chair VOR gain was below normal, with a VVOR gain of 0.6.

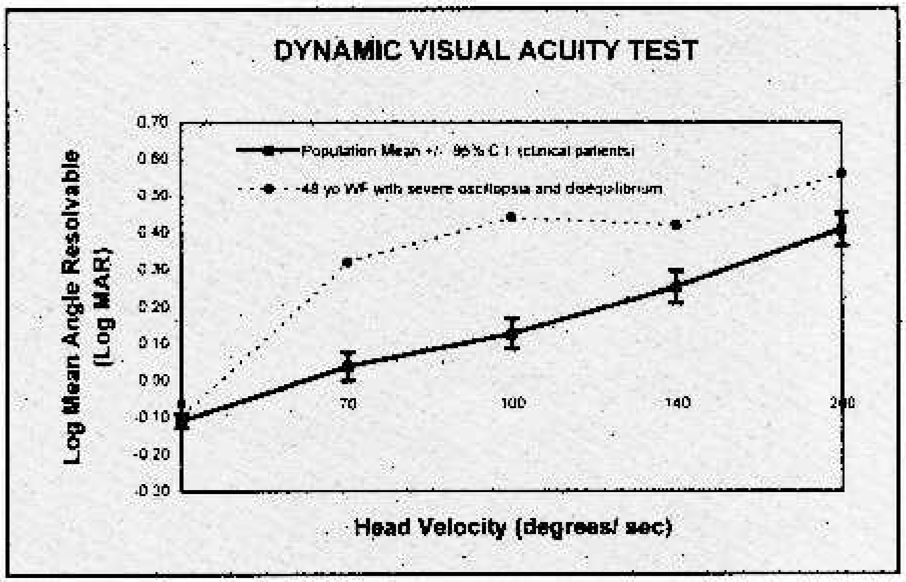

Figure 3 (Case 2)

High head velocity DVA deficit pattern
Case 3 is a 24-year-old student flyer with performance difficulty in basic phase of instrument training. He had recurrent SD, with difficulty interpreting flight instruments due to an inability to develop an efficient instrument scan pattern. DVAT testing showed decreased visual acuity at head velocities over 100 degrees per second (Figure 4). Quantitative oculography revealed saccade latency (time from target movement to eye movement) was markedly prolonged (mean 430 msec, max 680 msec) compared to normal controls (<230 msec), suggesting difficulty with instrument scan. Rotational chair VVOR gain was 0,61 to 0.78. This DVAT pattern was seen in 3 of 4 SD prone individuals screened with DVAT with delayed saccade latencies in 2 of the 4 individuals.

Case 4 is a 36-year-old male with possible Multiple Sclerosis (residual mild bilateral optic neuritis and neurogenic bladder) who had similar DVAT pattern with rotational chair VVOR gain of 0.8 (Figure 5). He denied oscillopsia. Saccades can contribute to ocular stabilization, particularly as eye position must rapidly change direction when the head direction changes at the end of its side to side excursion.

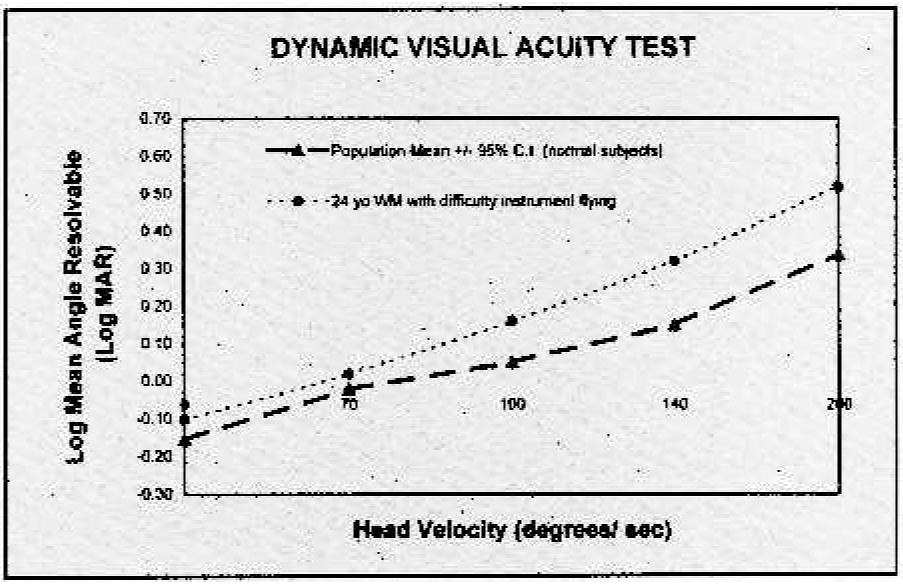

Figure 4 (Case 3)

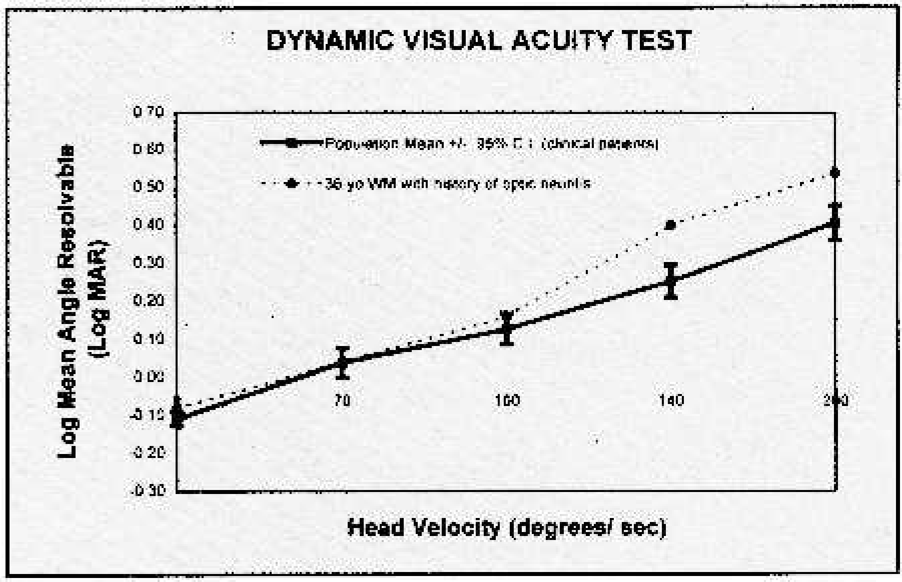

Figure 5 (Case 4)

Zero, low and high head velocity DVA deficit (subphysiologlc) pattern

Case 5 is a 50-year-old male with complaint of constant dizziness (swimming sensation) and unsteadiness lasting years. He had a long history of alcohol abuse but was in remission. Visual acuity was significantly diminished at all frequencies tested, including static (Figure 6). Rotational chair VOR gain was normal, and VVOR gain was 1.0. This pattern may represent less than optimal performance due to sub maximal effort. The slope of the patient's DVAT curve is the same as the normative data, with static vision starting below normal and shifting the curve upward. The normal VOR and VVOR gain also mitigates against a vestibular deficit as the cause of the DVA pattern.

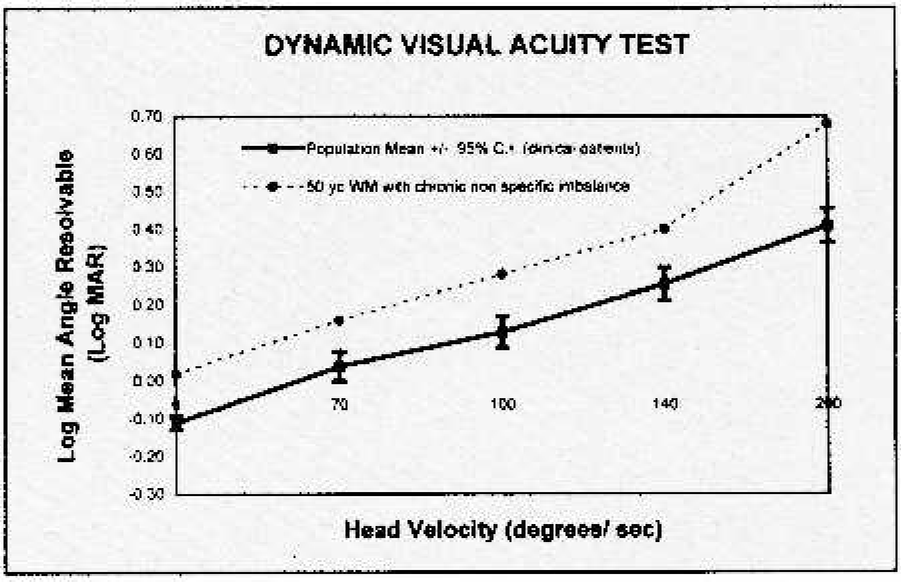

Figure 6 (Case 5)

Supraphysiologic Pattern

Another DVAT pattern is the supraphysiologic response, which is improved visual performance compared to normal. Two refractory severe airsickness cases had significantly better performance on DVAT. Case 6 is a 28-year-old navigator with recurrent severe airsickness who had significantly better performance on DVAT (Figure 7). He described that after looking outside at moving visual scenes while flying fast at low altitude, he was unable to see the instrument panel for many seconds. When he tried to fixate his vision on the instrument panel he would get airsick. Quantitative oculography revealed prolonged optokinetic stripe after nystagmus (OKAN) over 45 sec and prolonged vection illusion over 1 minute (sense of rotation in dark after OKN stripes were extinguished), suggesting excessive visual vestibular interaction.
The visual stimulus of the moving OKN stripes caused mild motion sickness and mimicked his in-flight sensation of visual blurring. Rotational chair VVOR gain was 1.06 -1.11. He denied oscillopsia.

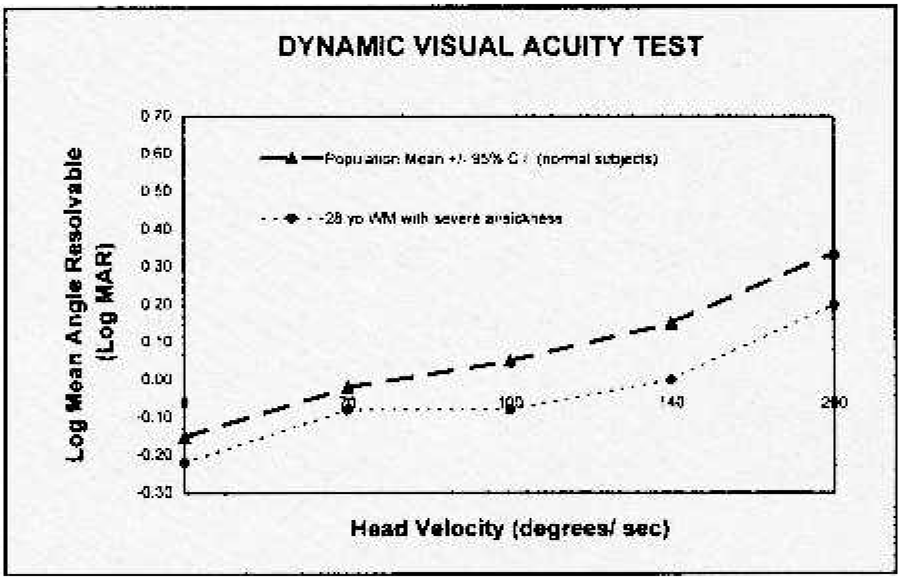

Figure 7 (Case 6)

Conclusions

A decrement in dynamic visual acuity (during head movement) suggests impaired visual vestibular interaction due to excessive retinal motion. The Dynamic Visual Acuity Test (DVAT) can assist in diagnosis and management of patients with vestibular disorders. The Dynamic Visual Acuity Test (DVAT) can aid in evaluation of fitness for special duty, such as divers or flight personnel. Resolution of transient vestibular dysfunction, as measured by the DVAT, aided in the timing of the decision to return aviators to flight status. Flyers with neurological complaints were returned to flight status only if they were asymptomatic and had normal visual vestibular interaction tests. Pathologic causes of spatial disorientation (SD) caused by specific oculomotor performance deficiencies may render a pilot more susceptible to recurrent or severe SD, and can be identified and screened with DVAT. Potential operational applications of the computerized DVAT include identifying medication that will adversely affect spatial orientation performance and determining when aircrew develops adequate adaptation to motion sickness desensitization and vestibular rehabilitation. The Dynamic Visual Acuity Test (DVAT) has potential for selecting future aircrew with optimal visual-vestibular function who can successfully operate advanced systems in complex motion environments.

Acknowledgments

Opinions and assertions expressed herein are those of the author and do not necessarily reflect the views of the Navy Medical Department, Department of the Navy**,** the Department of Defense, or NASA.

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Biography

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Jonathan B. Clark M.D., M.P.H. (CAPT MC USN) is a neurologist / flight surgeon recently assigned to NASA Johnson Space Center in Houston, TX. He was the former head of the Spatial Orientation Systems Department at the Naval Aerospace Medical Research Laboratory in Pensacola, FL, Principal Investigator on the Neurootologic Assessment, Naval Aviation Methodology Criteria Development, and Vestibular Effects of Low Frequency Waterborne Sound Projects. He is actively involved in clinical and operational medicine, research, teaching, diving, and flying.