Head-Mounted Dynamic Visual Acuity for G-Transition Effects During Interplanetary Spaceflight: Technology Development and Results from an Early Validation Study

Ethan Waisberg; Joshua Ong; Nasif Zaman; Sharif Amit Kamran; Andrew G. Lee; Alireza Tavakkoli

INTRODUCTION: Dynamic visual acuity (DVA) refers to the ability of the eye to discern detail in a moving object and plays an important role whenever rapid physical responses to environmental changes are required, such as while performing tasks onboard a space shuttle. A significant decrease in DVA has previously been noted after astronauts returned from long-duration spaceflight (0.75 eye chart lines, 24 h after returning from space). As part of a NASA-funded, head-mounted multimodal visual assessment system for monitoring vision changes in spaceflight, we elaborate upon the technical development and engineering of dynamic visual acuity assessments with virtual reality (VR) technology as the first step in assessing astronaut performance when undergoing G-transitional effects. We also report results from an early validation study comparing VR DVA assessment with traditional computer based DVA assessment.

METHODS: Various VR/AR headsets have been utilized to implement DVA tests. These headsets include HTC Vive Pro Eye system. Epic's game engine UnrealEngine 4 Version 4.24 was used to build the framework and SteamVR was used to experience virtual reality content. Eye tracking technology was used to maintain fixation of the participant. An early validation study with five participants was conducted comparing this technology versus traditional DVA with a laptop.

RESULTS: The head-mounted technology developed for assessing DVA changes during G-transitions is fully functional. The results from the early validation study demonstrated that the two DVA tests (laptop-based and VR) indicated a strong association between both methods (Pearson correlation coefficient of 0.91). A Bland-Altman plot was employed to assess levels of agreement, with all data points falling within the limits of agreement.

DISCUSSION: The results from this early validation study indicate that head-mounted DVA assessment performs similarly to traditional laptop-based methods and is a promising method for assessing DVA during spaceflight, particularly in G-transitions. Future studies are required for further assessment of validation and reliability of this technology. With its ease of use, accessibility, and portable design, VR DVA has the potential in the near-future to replace conventional methods of assessing DVA. The technology will likely be an important aspect to help monitor functionality and safety during interplanetary missions where astronauts are exposed to G-transitions.

KEYWORDS: dynamic visual acuity assessment, long duration spaceflight, ocular monitoring.

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Dynamic visual acuity (DVA) refers to the ability of the eye to visually discern detail in a moving object. DVA plays an important role whenever rapid physical responses to environmental changes are required, from playing sports to performing tasks onboard a space shuttle. DVA depends on several factors including: the vestibulo-ocular reflex (**Fig. 1**), catch-up saccades, and possibly visual motion processing.[13] One day after astronauts returned from long-duration spaceflight, a decrease in DVA of approximately 0.75 eyechart lines has been observed, with some astronauts having a reduction in DVA similar to a group of vestibular-impaired

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From the University College Dublin School of Medicine, Dublin, Ireland.

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Address correspondence to: Ethan Waisberg, M.B. B.Ch.; School of Medicine, University College of Dublin, Belfield, 4, Dublin, Ireland; ethan.waisberg@ucdconnect.ie.

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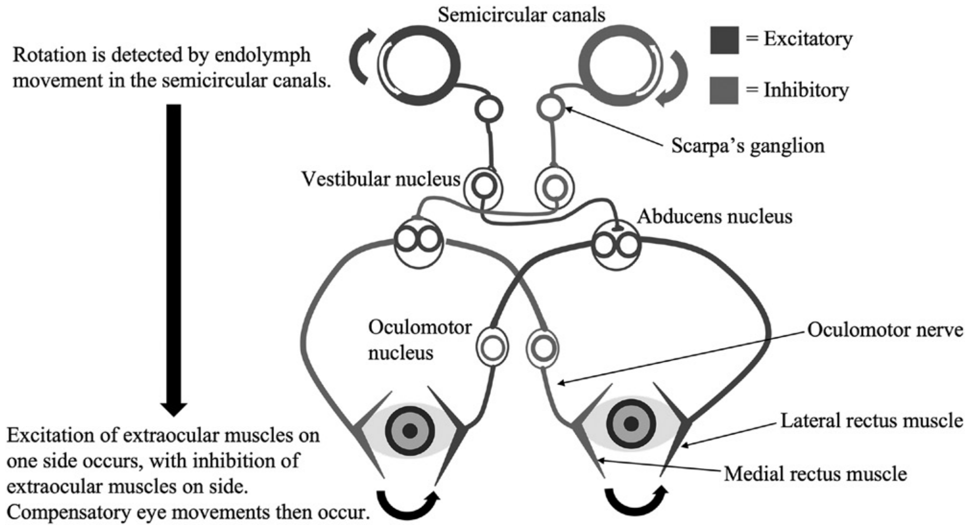

Fig. 1. The vestibulo-ocular reflex uses eye movement to stabilize images on the retina when movement of the head is detected about any axis (vertical, horizontal, torsional). Otoliths detect translation of the head, while semicircular canals detect rotation. Movement of the eyes then occurs from excitatory signals to extraocular muscles on one side, and inhibitory signals to extraocular muscles on the other side.

patients.[11] Although these results are significant, they may underestimate the impact of G-transitions on DVA as they were collected 24 h after landing. This decrease in DVA was believed to have occurred as a result of altered gaze control after exposure to microgravity.

During interplanetary space travel, multiple transitions between gravity levels will be anticipated, including transitions between microgravity, hypogravity, and hypergravity (e.g., upon re-entry to Earth). These gravitational transitions initiate compensatory physiological adaptations which can lead to space motion sickness, altered blood pressure regulation, and altered sensorimotor control.[4] Although many studies demonstrated that the sensorimotor function of humans can eventually adapt to hypogravity and hypergravity, the process of adaptation when transitioning to a new level of gravity is not fully understood. This is particularly concerning as gravitational transitions occur during the most critical phases of space missions, such as while approaching a new planet, in which peak astronaut performance of complex tasks is required. Potential inability to perform these tasks correctly may lead to mission failure.

Assessment of DVA traditionally involves moving the participant's head from left to right at a target velocity of 100°/s while the participant maintains their gaze on a screen.[12] Following correct responses, the optotypes shown on the screen become progressively smaller, and following incorrect responses, the optotypes become larger. Although this traditional method of assessing DVA is accurate, it is currently not performed in space. To perform this traditional DVA assessment during spaceflight would be relatively time-consuming process and requires specialized hardware that is bulky.

This lack of knowledge about DVA during spaceflight is due to the current difficulties in collecting data on astronauts in real time while entering new gravitational environments.[4] The terrestrial assessment of DVA has been largely conducted on stationary platforms with a laptop. While assessments of DVA have not occurred during spaceflight, this set-up may likely be optimized in time-sensitive moments such as immediately after landing in a new gravitational environment. The National Aeronautics and Space Administration (NASA) has identified altered sensorimotor/vestibular function as a potential risk for affecting critical mission tasks and has assigned this risk an elevated "Likelihood and Consequence" rating.[14] One of the tasks listed for this risk in the NASA Human Research Program is to develop and test countermeasures for symptoms during and following G-transitions to help crewmembers perform critical tasks (SM-202).[14] As part of a NASA-funded, head-mounted multimodal visual assessment system for monitoring vision changes in spaceflight, we report the development and engineering of dynamic visual acuity assessments with virtual reality (VR) technology as the first step in assessing astronaut performance when undergoing G-transitional effects (**Fig. 2**). We further discuss the current assessment design for terrestrial testing of this technology and future considerations.

Traditional forms of assessing DVA require extensive instrumentation and equipment that would likely be prohibitive on the International Space Station (ISS). This VR-based method of assessing DVA overcomes these limitations and provides a portable, lightweight technique to monitor these changes. This assessment is one aspect of a NASA-funded head-mounted display, multimodal visual assessment system for long duration spaceflight. This novel mixed reality device will integrate static and DVA, contrast sensitivity, visual field, and metamorphopsia data to closely monitor functional vision.[9]

Assessment of visual function using VR tests has grown quickly in the past several years. To our knowledge, only two previous studies assessed dynamic visual acuity using a head-mounted device, and the first study required the head of the participant to be oscillated manually.[3] The second study involved testing DVA in vertical, horizontal, and no head motion conditions.[6] In this manuscript, we report the overarching

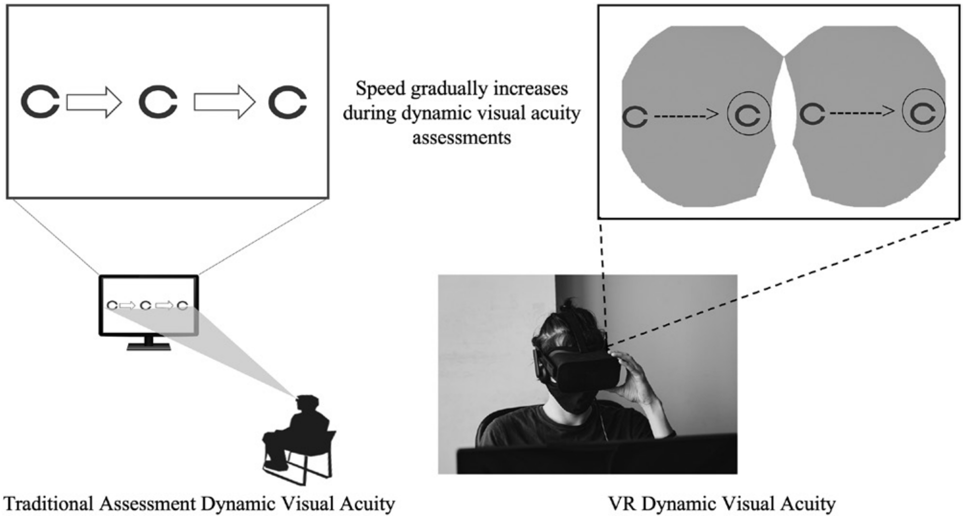

Fig. 2. Image illustration comparing between laptop and virtual reality dynamic visual acuity.

features of the head-mounted, multimodal assessment system and the DVA component for spaceflight and how it compares to a laptop-based method of DVA assessment.

METHODS

Equipment

Various VR/AR headsets have been utilized to implement DVA testing. These headsets include HTC Vive Pro Eye system (HTC, Xindian District, New Taipei City, Taiwan), which has a pixel density of 615 pixels per inch, per eye, and a field of view of 110°. The headset weighs only 555 grams and consists of an AMOLED screen with a band to fit comfortably over the head of a subject. Epic's game engine Unreal Engine 4 Version 4.24 (Epic Games, Cary, NC) was used to build the framework and Steam VR was used to experience virtual reality content (**Fig. 3**). Eye tracking technology was used to maintain fixation of the participant. If the gaze of the participant deviated significantly from the stimuli, the response was then discarded. Eye tracking accuracy was assessed on each participant in advance using an Unreal Engine plugin called "SRanipal" to determine if eye tracking was reliable. In the VR headset, text was displayed to help participants focus. Participants were assisted with calibration of the VR headset to ensure an appropriate pupil distance, focus distance, and to avoid lens rim artifact. The individualized adjustments made were then noted for each participant.

Procedure

In our experiment design, DVA is measured binocularly. A single Landolt C is displayed at a fixed distance of 6 m from the observer and moved horizontally across from left to right and right to left at an angular speed of 30°/s. In each presentation, the Landolt C can be oriented at any of the eight directions. The participants use the numpad keys to respond to the direction of the gap in the Landolt C. A staircase method is used to vary the size of the Landolt C after each response. If the participant responds correctly for the same-sized stimuli, the subsequent character size will be decreased logarithmically. Otherwise, it will be increased

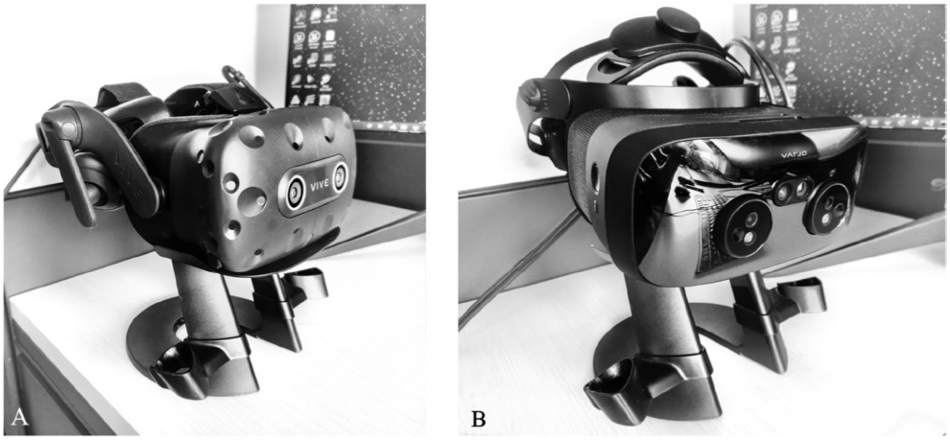

Fig. 3. Virtual reality headsets used for the current experiments in dynamic visual acuity assessment. Compared to the A) HTC Vive Pro Eye, the B) Varjo XR-3 has significantly higher pixel density and, therefore, can be more effective in detecting changes in dynamic visual acuity.

along the same logarithmic scale. This procedure was approved by the University of Nevada, Reno, Institutional Review Board and was in accordance with the tenets of the Declaration of Helsinki.

Subjects

An early validation study with five participants was conducted comparing this technology versus traditional DVA with a laptop. The laptop-based test was assessed on a 23-in monitor connected to a PC with Nvidia RTX 2080 GPU, 32 GB RAM and Intel Core-i7 8700. To minimize bias, both tests were conducted during the same session, on the same day, with Landolt ring optotypes.

Statistical Analysis

Descriptive statistical analysis was primarily conducted due to the nature of the early validation study with a relatively small number of participants. Future studies will likely have comparative statistics.

RESULTS

The mean age of participants in our study was 26.4 ± 1.5 yr and 4 of the 5 participants were men. All participants had a best correctable visual acuity of 20/20. Further information of participant demographics can be seen in **Table I**. DVA was plotted graphically using Excel version 16.44 (**Fig. 4A**). The Pearson correlation was greater than 0.9 (0.911), indicating a strong, positive association between both methods of DVA measurement. A Bland-Altman plot was also used to examine the level of agreement (**Fig. 4B**). All data points were within the limits of agreement, indicating that our head-mounted system is a promising method to assess DVA.

DISCUSSION

NASA's Human Research Program (HRP) identified "Risk of Altered Sensorimotor/Vestibular Function" as a potentially significant biomedical risk, with the greatest risk during and following gravitational transitions.[5] Gravitational transitions are a critical time for astronauts as they occur while entering and landing on a new planet, which is one of the most difficult spaceflight tasks. Risks during landing include potential loss of life, vehicular damage, or damage to other assets. Although all piloted spacecraft landings to date have been successful, the risk of failure during Mars missions is significantly higher due to the prolonged period in microgravity (6 mo), which will lead to more significant sensorimotor adaptations, and thus likely lead to a larger physiological response to the gravitational transition on entry to Mars.[1] The ability for astronauts to control complex systems in space requires a combination of cognitive function, visual acuity and spatial orientation perception, all of which have been shown to be impacted in microgravity.[1]

Table I. Subject Demographics and Results.

CHARACTERISTIC	SUBJECTS
Age (yr)	26.4 ± 1.5
Gender	
Male	4
Female	1
Ocular history	None
Best correctable visual acuity	20/20
History of seizures or vertigo	None
Any neurological or balancing disorder	None
Standard deviation (logMAR)	0.114
Average DVA (with laptop)	0.525
Average DVA (with headset)	0.485
Pearson correlation	0.911

It has previously been shown that DVA can be enhanced after participating in specialized training involving distinct eye movement patterns.[10] Currently, pre-spaceflight training and post-spaceflight rehabilitation protocols are not optimized to attenuate the changes on sensorimotor function and DVA after gravitational transitions.[4] Our VR dynamic visual framework can potentially serve as a countermeasure for astronauts entering another gravitational environment.

Developing a countermeasure for loss of DVA may be important as the inability to focus an image on the retina can create sensory conflict and cause motion sickness. Motion sickness is currently experienced by 60–80% of astronauts during their first 2 to 3 d in microgravity, which may impact their ability to perform critical tasks during gravitational transitions.[5] Although symptoms such as nausea and vomiting may seem relatively innocuous in a terrestrial environment, vomiting in an extra vehicular activity (EVA) suit could potentially be a life-threatening situation.[2]

Potential drawbacks of our study include not assessing the diagnostic utility of our proposed system as well as not determining the test-retest variability. In future studies, we plan on using a higher resolution VR headset, which will likely improve DVA values. The speed and direction of the stimuli may be varied in future studies to holistically quantify the nature of the deterioration in DVA.

Our early validation study showed that DVA can be measured in virtual reality with a similar level of accuracy as the traditional laptop-based method. There are several limitations to this technology and study. The main study limitation is the small sample size of this early validation study. Future studies will aim to test a larger sample size to increase reliability of this technology when compared to laptop-based methods. There are also technology limitations that can be improved upon. Future improvements from current developments include minimizing motion blur, which commonly occurs in OLED displays and can negatively impact dynamic visual acuity results. Our studies may also be limited by the VR device resolution of 13.09 pixels per degree, as well as minor variations in VR screen brightness at different battery levels. These limitations have been taken into consideration during this ongoing development and are actively being optimized as technological capabilities continue to expand.

In conclusion, with increased portability and accessibility, VR-based DVA assessment has promising potential to replace

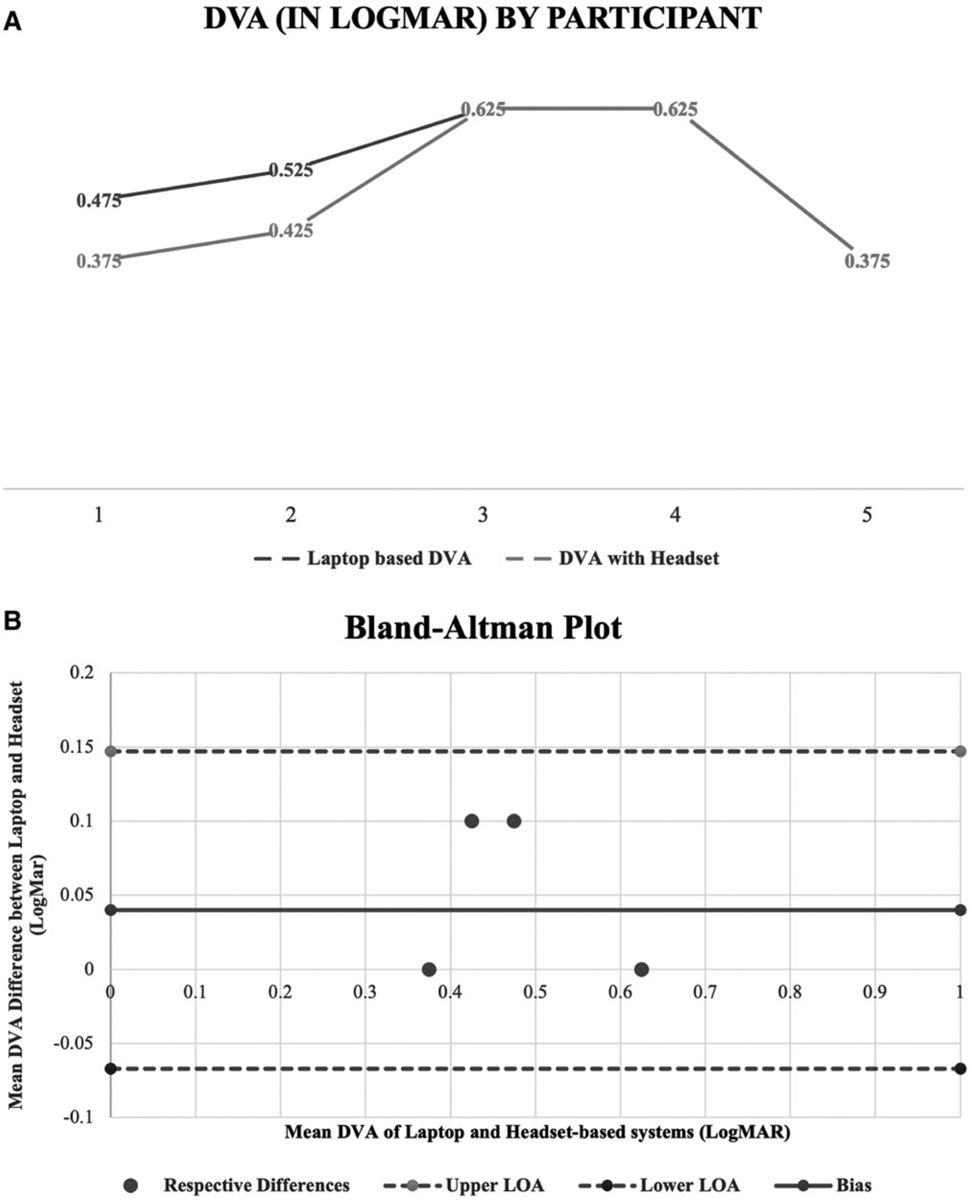

Fig. 4. A) Graphical comparison of our headset vs. a laptop-based DVA test. Note for the last three participants that the last three laptop-based test results cannot be seen as they were equal to the headset-based results. B) Bland-Altman plot showing a good correlation between our headset-based DVA assessment system with a laptop-based method. LOA: limits of agreement.

traditional laptop-based methods of assessing DVA. This technological advancement will be particularly important for astronauts undergoing G-transitions during interplanetary spaceflight missions.

Our group plans to conduct future studies with various other visual function assessments to map a multimodal assessment of visual function during spaceflight.[9] These forms of assessment include visual acuity, contrast sensitivity, Amsler grid metamorphopsia, foveal rendering and simulated daylight reading visual acuity.[8] These assessments are built around the various risks that astronauts may face during spaceflight including G-transitions and Spaceflight Associated Neuro-Ocular Syndrome (SANS), a group of neuro-ophthalmic findings observed in astronauts after long-duration spaceflight.[9] As a potential barrier to spaceflight, close monitoring SANS with consistent functional testing and imaging is of utmost importance for visual health during spaceflight.[7] Accurate extraterrestrial assessment of DVA will provide an additional metric for close monitoring of microgravity-induced visual acuity. Future directions of this research will also involve training using our VR-based DVA system to serve as a countermeasure for gravitational transitions during interplanetary travel. Our pilot study demonstrated the effectiveness of measuring DVA using a VR headset. Future studies are needed to evaluate for test-retest reliability, improve the accuracy of our DVA assessment framework and determine if training using our VR-based system can serve as a countermeasure during future long duration manned missions.

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Authors and Affiliations: Ethan Waisberg, University College Dublin School of Medicine, Belfield, Dublin, Ireland; Joshua Ong, M.D., University of Pittsburgh School of Medicine, Pittsburgh, PA, USA; Nasif Zaman, M.S., Sharif Amit Kamran, M.S., and Alireza Tavakkoli, Ph.D., Human-Machine Perception Laboratory, Department of Computer Science and Engineering, University of Nevada, Reno, Reno, NV, USA; and Andrew G. Lee, M.D., Department of Ophthalmology, Blanton Eye Institute, Houston Methodist Hospital, Houston, TX, Center for Space Medicine, Baylor College of Medicine, Houston, TX, The Houston Methodist Research Institute, Houston Methodist Hospital, Houston, TX, the Departments of Ophthalmology, Neurology, and Neurosurgery, Weill Cornell Medicine, New York, New York, the Department of Ophthalmology, University of Texas Medical Branch, Galveston, TX, University of Texas MD Anderson Cancer Center, Houston, TX, Texas A&M College of Medicine, TX, and the Department of Ophthalmology, The University of Iowa Hospitals and Clinics, Iowa City, IA, United States.

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