Dangers of Highly-Immersive Virtual Reality Displays

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ABSTRACT

Although rare, anomalous responses to highly immersive virtual reality (~~VR~~V.R.~~).R.~~), augmented reality (A.R.) or mixed reality (M.R.) displays can pose users challenges with disastrous consequences, especially when operating motor vehicles/military platforms. Anomalous responses manifest frequently as unusual visual-vestibular or vestibular-spinal, perceptual-motor effects to include non-veridical sensations of motion~~,~~ and balance disturbances. Examples include driving off the road following a long session in an aircraft simulator or prolonged balance dysfunction after strong vection experiences similar to the rare but often prolonged mal de debarquement (MdD) balance issues following sea voyages.

To investigate adverse effects on balance coordination associated with adaptation to a motion-based environment, subjects were seated in a ~~20~~ 20~~-~~foot diameter rotating room that was slowly rotated while subjects performed controlled head movements in pitch and roll once per minute for periods of time varying from 10 to 30 minutes. When compared to baseline balance performance on the Equitest balance device all subjects demonstrated reduced performance scores following 20 minutes of exposure on the rotating room.

Since the anomalous reactions are rare events, individual but well documented cases become important. The lead author exposed an individual to a highly compelling vection illusion as part of a demonstration of whole-field vection inside a rotating sphere. Shortly after exiting the sphere, the subject experienced balance dysfunction which was thereafter readily experienced with large field visual displays and only dissipated slightly over the following several years.

Both the motion-based adaptation experiment and the controlled full-field vection experience produced visual-vestibular conflict adaptation issues that will become increasingly important especially as V.R.~~R~~/A.R./M.R.~~R~~ devices become more visually compelling and are integrated with motion-based devices or involve self-motion of the user.

Based on lessons learned from adaptation to motion-based devices there are techniques that should be recommended to V.R.~~R~~/A.R./M.R.~~ER~~ software developers to reduce the frequency of potentially dangerous physiological and perceptual anomalous responses.

ABOUT THE AUTHORS

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INTRODUCTION

Motion sickness (M.S.) can be defined as a maladaptive response to real or apparent motion (Cheung, 2000). By including apparent motion in the definition, M.S. can be applied to non-motion simulators, virtual reality displays, augmented reality displays, large screen theaters or any device that can provide the sensation of movement. Recent engineering advances in video cards, higher speed chips, and screen displays have resulted in wide field-of-view, head-mounted virtual reality devices such as Vive, Oculus Rift, and Varjo that can provide realistic, high fidelity simulation environments. It has been argued that the incidence of simulator sickness has increased over time as simulations become more compellingly realistic (Kennedy, Hettinger, & Lilienthal, 1990).

The aftereffects of motion sickness are generally short-lived and dissipate quickly when the motion or apparent motion ceases. However, there are many instances in which people experience prolonged postural and perceptual aftereffects that can continue for weeks, months, or years. A familiar example of a generally short-lived after effect is Mal de Debarquement: a condition of persistent unsteadiness triggered by traveling on boats, aircraft, or automobiles, usually for at least a few hours. The sensations of rocking back and forth usually dissipate after a few minutes to hours. If the balance symptoms persist for prolonged periods, the condition is then referred to as Mal de Debarquement Syndrome (MdDS) (Cha, 2009). Long-lasting balance or sensory aftereffects are now included in a condition known as Persistent Postural-Perceptual Dizziness (PPPD or 3PD). The disease classification of PPPD was introduced in 2017 by the Bárány Society and is now included in the International Classification of Disease version 11 (ICD-11) which took effect internationally January 2022.

The Bárány Society Criteria for the diagnosis of PPPD (Stab, 2017) includes several components which must be present to warrant classification as PPPD. The dizziness, unsteadiness, or non-spinning vertigo symptoms must be present on most days for three months but need not be present throughout the day, can wax and wane and may occur without provocation but are often exacerbated by exposure to moving visual stimuli or complex visual patterns. Active or passive motion especially while standing may precipitate PPPD sympsoms which may cause significant distress and functional impairment.

This paper will examine a clinical case history of PPPD induced by whole field-of-view vection as can occur with large field-of-view VR/AR displays. We consider the possible pathophysiology from the perspective of adaptation to rearranged visual-motor responses in novel sensory environments.

CLINICAL CASE STUDY

A visiting 62-year-old male engineer was provided a demonstration of whole field-of-view visual vection in 2006. As the lead engineer from a major supplier of motion actuators for simulators, he requested a demonstration of our novel full field of view display. The Visual Vestibular Sphere Device (VVSD), belonging to the Naval Aerospace Medical Research Laboratory (NAMRL) in Pensacola, Florida, was used to provide the visual vection stimulus (Figure 1 and Figure 2). Vection is a visual illusion of self-motion in the absence of physical motion of the observer. The VVSD is a ten-foot diameter sphere that can be rotated around a subject seated upright with their head located in the center of sphere rotation. Randomly placed dots cover the entire interior of the sphere when the small oval-shaped cover door, through which the subject enters the sphere, is in place. When the VVSD is used to provide demonstrations for visitors, the door is usually removed to provide the observer receiving the demonstration the opportunity to look down through the hole to terminate the vection experience by observing the stationary floor and outside structures.

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Figure 1. Visual Vestibular Sphere Device (VVSD) Exterior View

Figure 2. VVSD Interior View During Rotation

When rotated around the stationary subject, the random dot pattern in Figure 2 fills the subject's entire field of view, providing a compelling vection stimulus. A typical demonstration consists of an initial rotation at 10 rpm in the counterclockwise direction until the subject reports a sensation of rotation in the opposite clockwise direction. This demonstration has been provided to more than 1000 visitors, scientists, and experimental subjects prior to and following the engineer in question. All subjects experience vection by 15 seconds and most within 5 to 10 seconds. The subject is first instructed to look straight ahead. Then, they are requested to look down and towards the floor on their right side through the entry hole in the sphere. The operator times this request so the hole approaches the subject as they look down and towards the right side. The subject is then requested to direct their gaze to follow

the hole in the sphere, looking at the floor outside the sphere, and follow the hole around to his/her left side. For most people, the experience of self-rotation in the opposite direction ceases as soon as they see the stationary floor and the VVSD supporting frame underneath the sphere. However, approximately 25% of subjects report the vection experience of self-rotation continues even while observing the stationary floor below them. These individuals seem to be more sensitive to vection and experience it more quickly when the sphere begins to turn. The stimulus is provided in both directions if requested by the person receiving the demonstration and if they are not experiencing any symptoms of motion sickness.

A second demonstration involves utilizing a special feature of the sphere which permits the whole sphere to be rotated 90 degrees while the observer remains upright in the chair to provide a roll vection experience. In the roll vection stimulus, the typical response is to experience a roll in the opposite direction but rarely not beyond 60 degrees after which the observer may report the unusual situation of continuous roll motion while not displacing beyond 60 degrees of roll. This is an example of sensory discord between motion and displacement sensations.

The engineer observer was provided both horizontal yaw vection in counterclockwise and clockwise directions and also the roll rotation. With yaw rotation he experienced immediate vection and exclaimed, "You told me you were not going to rotate me." I assured him that the chair axis was not in the control loop for this demonstration of the vection illusion and that neither he or the chair was in motion. When asked to look down through the entrance opening to the sphere the engineer did not experience a break in the sensation of rotation even while he could see the stationary floor and supporting structures outside the sphere. The sensation of motion is similar to that experienced by most of us when we have stopped at an intersection waiting for the light to change and when the car beside us moves we mistakingly think we have moved. The intensity of the vection sensation is in the sphere is overwhelming since the whole visual world is moving.

After the demonstration I accompanied the engineer to the local aviation museum for lunch. While walking from the car to the museum which was approximately 150 yards from the parking lot, I told the engineer he was not feeling well, to which he replied he was just fine. I repeated the statement and he asked why I said he was not feeling well. I pointed out that he was unaware he was leaning on me for support while we were walking. He finally realized he was not steady and later after lunch while walking around the museum he experienced an episode of dizziness when he entered a display room that was designed to present a large field of view from an underwater perspective. He had to immediately exit the display area, sit down and spend a few minutes to recover from dizziness and nauseous sensations.

On returning to his home state the following day, he experienced dizziness whenever he was presented with large field of view displays including T.V., movie screens, and watching video games with his children and grandchildren. His solution was simply to close his eyes. On occasion while walking down aisles with busy visual scenes he would experience dizziness. The balance issues improved slightly but continue to the present day some 16 years later.

The prior motion experience of this engineer is germaine to his experience. As the chief design engineer for a company providing motion-based devices for the North American entertainment industry he had experienced most rides at Disney, Universal and other venues since he and his company were responsible for the engineering design of many of these motion-based devices. Prior to the strong vection demonstration in the Navy VVSD he did not have any issues with motion devices and visual displays.

EXPERIMENTAL STUDY RELATED TO CAUSAL FACTORS OF SOME PPPD CASES

A pilot study was conducted to examine postural aftereffects of adaptation to a novel environment requiring visual adaptation or rearrangement to maintain a stable visual field and a change in postural stability reflexes to maintain normal balance and walking.

The U.S. Navy provided the funding for this line of research with the intention of developing an objective test of simulator sickness. When aviators experience and report simulator sickness symptoms they are grounded for 24 hours. Since aviators rarely, if ever, self-report simulator sickness issues, the training community was eager to develop objective balance tests to guide physiologists and flight surgeons concerning the grounding of aviators with symptoms of simulator sickness

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Commented [ar8R7]: Jennifer you are absolutely correct and I spent 2 hours at WPAFB last Wednesday morning describing this conecept of illusory position and motion (posimotion illusion) with sensory psychologists who had difficulty understanding unless they had been exposed to such an illusion which was only only two of the dozen psychologists present. I have a video clip I developed for presentations that helps to convery this illusion. I can't put it into a written paper unfortunately.

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Commented [ar12R11]: So neurologists and neurotologists who specialize in these type of symptoms do not have an explanation for PPPD. My personal opinion as to why this occurs is related to the experiement that follows in this paper. When our brain begins the adaptive process to deal with a new set of visual-vestibular conditions (such as in the rotating room, or space, or whole visual field movements) the "rewiring" that occurs does not readapt when we return to our old environment (i.e. get off the boat, return from space, leave the rotating roon, etc) and the nausea and sickness remains.

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Figure 3. Coriolis Acceleration Platform with 20-foot diameter rotating room.

This pilot study was not published but was presented at the 1993 Aerospace Medical Research conference (McGrath, Rupert & Ruck, 1993) and results were highlighted in a *Frontiers in Neurosciences* article (Lawson, Rupert, and McGrath, 2016). The goal was to identify the time course of sensory motor adaptation to sensory rearranged environments as measured with a modified balance protocol (McGrath, 93; Shepard, 1998). Although the following experiment demonstrated a novel new measurement tool, it was not used for simulator sickness Although the following experiment demonstrated a novel new measurement tool, it was not used for simulator sickness Although the following experiment demonstrated a novel new measurement tool, it was not used for simulator sickness Although
the following experiment demonstrated a novel new measurement tool, it was not used for simulator sickness but rather a closely related phenomenon – space motion sickness. The data resulted in a clinical test used by NASA flight surgeons in the evaluation of astronauts on their return from space to determine at what point in their sensory-motor recovery profile they could safely return to flying.

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Highlights of the Rotating Room Experiment:

Thirty-two Naval aviator candidates served as participants,subjects. All had passed the Navy flight aviation physical with no vestibular abnormalities. While seated in one of four chairs placed around the perimeter of the room (Figure 3) every 90 degrees, participants experienced rotation at 10 rpm for periods of 10 to 30 minutes. Participants performed a series of slow head movements with direction and cadence provided by recorded instructions. Subjects were instructed to: "tilt left ear to left shoulder, head upright, right ear to right shoulder, head upright, chin on chest, head upright, head tilted back and return to head upright." After each set of head movements, the participantt stood up and walked to the next chair and rested until the next set of head movement instructions which were started at one minute intervals.

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Although this appears to be a simple task, the participants are exposed to both linear Coriolis forces while walking and Coriolis Cross Coupling (CCC) forces when making head movements. For example, under non-rotating

conditions when the head is tilted from head upright to left ear on left shoulder, the information sent from the vestibular canals normally would signal roll information and the eye reflex would result in some counter-rolling of the eyes to maintain a stable image on the retina. However, while the room is rotating and the subject is experiencing CCC, the information from the canals signals a head tilted back position and elicits a reflex eyes-down position. Indeed, if the head movement to left ear on left shoulder and return to upright is made quickly, the eyes move down and up quickly with an associated retinal slip resulting in the subject seeing objects move up and down in their visual field. By performing the maneuver slowly, the brain can adjust the eyes to prevent retinal slip performing a modified response and begin to reprogram the 3 neuron reflex arc to keep the image in focus on the retina. Similarly, while walking from one chair to the next chair, participants experience a linear Coriolis effect which has to be compensated for by changing the pattern of walking movements/reflexes to accommodate for the new gravitoinertial force environment.

The test to measure balance performance was a modified version of the Neurocom Equitest Sensory Organization Test #5 (SOT5), illustrated in Figure 4. During the standard SOT5 procedure the participant stands with eyes closed on a platform that measures the participant's center-of-gravity and then tilts the platform fore or aft in the same direction that the participant's center-of-gravity is moving. This activity deprives the participant of much of the sensory skin-muscle-joint somatosensory information. The participant becomes more reliant on the vestibular system information to determine an appropriate response and the direction down. The SOT5 score is a measure of changes in center-of-gravity (sway) over time and whether the participant falls. The standard SOT5 is modified in this protocol by having the participant make pitch and roll head movements while performing the balance task.

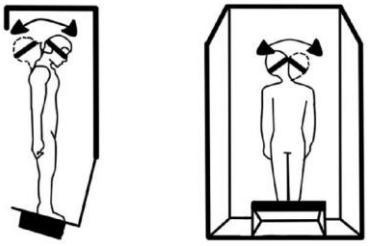

Fig. 4 Schematic of the modified Sensory Organization Test 5 (SOT5).

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In Sensory Organization test 5 the participant or patient makes controlled head movements in pitch or roll while maintaining balance without vision (eyes closed) and while the platform sways in concert with the participant's center of gravity, thus depriving the participants from accurate ankle and skin-muscle-joint information. This is a difficult task even without making a head movement. SOT scores for each condition are given in the range of 0-100, with higher scores representing better performance (less sway of the center of gravity) and participants swaying to the limits of stability receiving low scores. A fall is registered as a zero.

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Participants performed the SOT5 test three times (three trials in each test) to reach asymptotic performance before exposure to the rotating room. Following exposure to the rotating room the participants performed two sessions (3 trials each) of SOT5. As can be seen in Figure 5 the participantts performed significantly worse after exposure to the rotating room. If the subject had not made significant reflex changes to the balance system there would be no change in performance.

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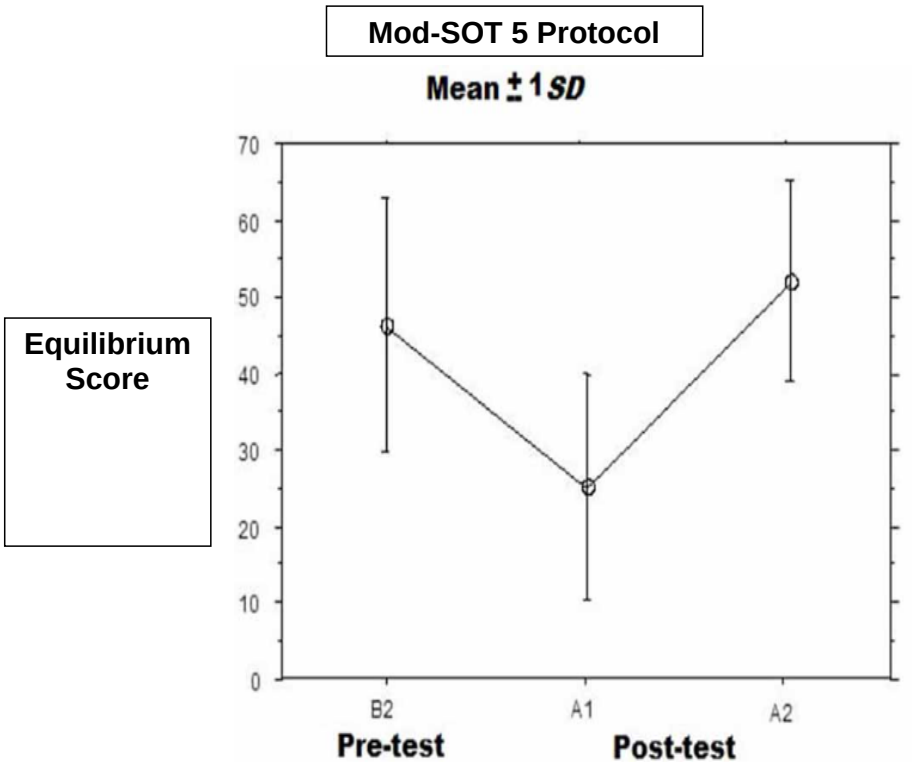

Figure 5. Mean modified SOT5 Equilibrium Scores Before (B2) and at two Intervals After (A1, A2) the Rotating Room Sessions.

The A1 sessions were performed immediately after the rotating room sessions ended, and the A2 evaluations were begun 15 minutes after A1.

Although we observed large variability in performance there was a significant difference between the mean baseline balance scores prior to rotation versus the first post-rotation test scores (*Wilcoxon Signed Rank Test: $p < 0.05$*).

Falls were common during the first post-test occurring in 25 of the 32 subjects on the first trial of the first post-rotating room test. This reflects the strong aftereffect of the adaptation to the rotating room. The effect was strong but short-lived and appeared to be stronger and longer-lasting (dose dependent) in the longer duration exposures to the rotating room.

Most interesting was that an exposure of ten minutes adaptation to the rotating room was sufficient to observe changes in the vestibular ocular reflex and coordinated walking movement that were appropriate for the rotating room environment. We were surprised that ten sets of head movements and ten short walks are sufficient for the brain to begin to adapt to this novel environment and produce measurable evidence of adaptation.

DISCUSSION

Commented [JM22]: Explain a little what these scores mean. What is "good" performance? Is it out of 100?

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The clinical case provides an example of an anomalous response to whole field-of-view motion that meets the criteria of PPPD diagnosis. The interesting question to be answered is, "What is the mechanism that resulted in this long-lasting relearned behavior and was there anything different about the engineer and possibly an increased susceptibility to motion."

A well-documented clinical case of a very high performing "top gun" instructor aviator developing PPPD following a single flight with acute intense intra-cockpit pressure changes has shown that there are many pathways to PPPD. Again, "How do abrupt pressure changes result in acute vestibular end-organ injury or possibly brain trauma leading to PPPD."

The rotating room study demonstrates that the brain is quite plastic and even 10 minutes is sufficient to demonstrate the beginning of postural adaptation to a novel altered force environment. The central nervous system control of eye movements to maintain a stable visual field in the rotating room involves changing the direction of response of a very basic three neuron arc from the vestibular end organ accelerometer to the brainstem vestibular nuclei (neuron one) to the oculomotor nuclei in the brainstem (neuron two) to the 6 eye muscles (neuron three). The brain begins the process to make correct responses in just minutes when there is consistent environmental pressure such that each sensory experience drives adaptation in a specific direction. The adaptation is a proper response to the new environment unlike the situation of PPPD, MdDS and motion sickness in which a maladaptation occurs.

The family history of the engineer is relevant to his vection susceptibility and motion sickness. On questioning family members it was found that there were two family members that are susceptible to large field-of-view motion displays and amusement park rides with significant acceleration. Just as motion sickness has an hereditary component (Hromatka, 2015) there may be a familial inheritance to susceptibility of whole field-of-motion induced postural instability.

The engineer in the VVSD was exposed to whole field displays that generated a visual perception of rotation that is normally tightly coupled with a concurrent vestibular stimulus of rotation and/or orientation. The response and confusion of conflicting sensations of rotation and orientation triggered what is referred to below as a vestibular crisis initiating the beginning of his PPPD.

PPPD frequently has psychological components that may sometimes precede and be considered causative or maybe a consequence of the maladaptation process. The below diagram (Popkirov, 2018) has been used by the originators of PPPD classification to illustrate the complex pathophysiology of PPPD.

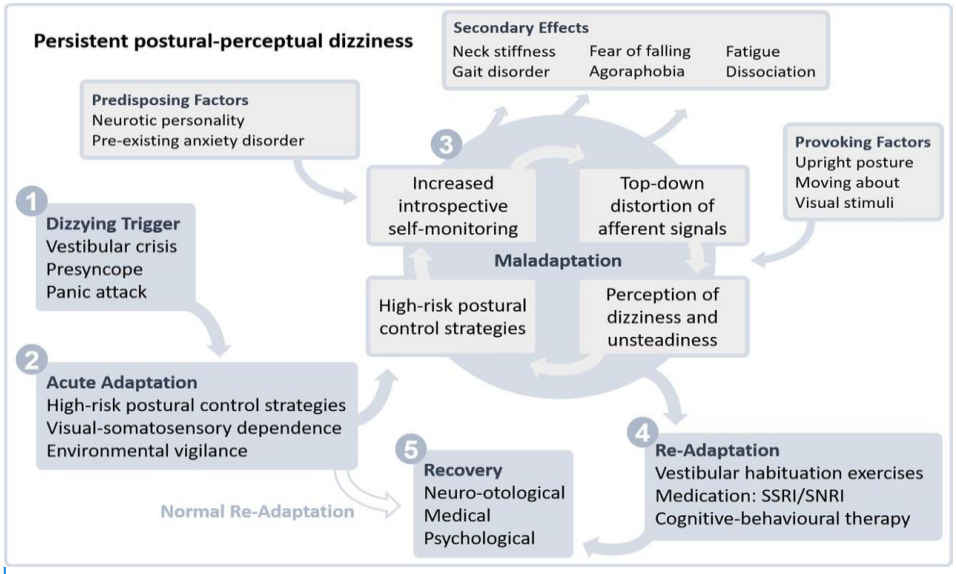

Figure 6. From Popkirov 2018. Factors associated with PPPD development and resolution.
The normal physiological reaction to strong dizziness or disequilibrium (1) is to activate alternative and additional systems of movement control (2) that do not rely on vestibular information. Once the acute trigger has subsided, instead of returning to normal function, a vicious cycle of maladaptation can arise (3), driven in part by excessive self-observation and anxiety. Somatosensory information about body position is thus amplified and distorted, which in turn produces subjective dizziness and leaves movement control on "red alert". Secondary effects like stiffening of gait, phobic avoidance and mental fatigue can develop. The aim of therapy (4) is to readapt the system to normal function by reducing anxiety and self-monitoring, habituating to provoking factors, and promoting automatic movement control until recovery (5) is achieved. SNRI, serotonin norepinephrine reuptake inhibitors, SSRI, selective serotonin reuptake inhibitors.

Just as prolonged ship motion can result in MdDS and prolonged visual vection can produce clinical PPPD so also can visual vection as produced by V.R. headsets when whole field of view displays are frequent or continuous for long periods. V.R. game designers are well aware that some stimuli produce high rates of motions sickness and so avoid scenes that provide strong visual vection for prolonged periods. However, when players have control over apparent motion, they may sometimes experience stimuli that can initiate symptoms similar to the clinical case of the engineer discussed earlier.

In November 2017 the Institute for Defense Analysis (IDA) and the Defense Advanced Research Project Agency (DARPA) held a combined conference (Dangers of Augmented Reality; DARE) to discuss the issues associated with the increased fidelity, faster refresh rates, and enlarged field of view of the latest head mounted displays (e.g., Oculus Rift, Vive, Microsoft HoloLens). It was recognized that it is difficult to estimate the prevalence of the anomalous response described in this paper. The lead author has seen only one such case in approximately 1500 demonstrations but has observed frequent, perhaps 100 instances, of similar visual-vection demonstrations that resulted in minor sickness for a few hours. One reason why it is difficult to estimate the incidence is that susceptible people learn very quickly to avoid such sensory experiences and often exhibit "one-trial learning" since such experiences are often accompanied by strong nausea. Even if the incidence is as low as one in ten thousand VR participants, there would still be 30 thousand people at risk of experiencing anomalous responses in the United States (population 330 million). VR and AR are anticipated to be in wide-spread use within both the military and civilian populations which will lead

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to the need for traditional or alternative methods of instruction for those who cannot tolerate the latest VR displays. Additionally, and/or alternatively, software programmers will need to optimize instructional programs to permit sensitive participants to use VR and AR displays safely and comfortably.

In summary the issue of probable PPPD caused by large or whole field-of-view displays is complex with genetic and psychological components but physiological maladaptation processes may be at the core of many types of motion sickness such as occurs in some PPPD patients, space motion sickness, aftereffects of VR/AR and other conditions involving real motion such as prolonged MdDS.

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ACKNOWLEDGEMENTS

The authors would like to thank the engineer described in this paper for agreeing to participate in the I/ITSEC presentation and receive questions from the 2022 I/ITSEC audience concerning his experience with the compelling whole field-of-view display he experienced in 2006 and which ultimately resulted in this paper.

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This paper was approved for public release; DISTRIBUTION A: Distribution Unlimited, Case 88ABW-2020-265.

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