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Motion Sick in Cyberspace

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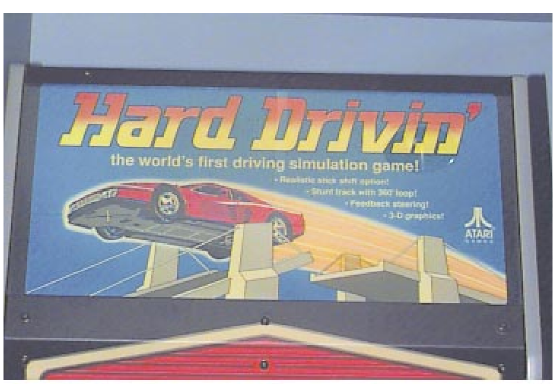
I used to love roller coasters as a kid. But today's rides, with their high-speed loops and turns, are too much for me. Small planes in bumpy skies or small boats in choppy water also set me off. Over-the-counter remedies help, but I'm resigned to the fact that, like many others, I get motion sick.

It never occurred to me that this had anything to do with computer graphics. Then, about eight years ago, I sat down to play Atari's new "Hard Drivin'" video arcade game, one of the first of the now familiar real-time racecourse driving simulations (see Figure 1). After a while, to my great surprise, I got motion sick. Later, I discovered that even watching someone else play the game could make me queasy. But how can you get motion sick if you aren't moving?

As a graphics old-timer it pains me to admit that some computer displays can make me ill. But I am not alone. The problem, first noticed in flight simulators, became known as "simulation sickness." It now affects many more people due to the availability of immersive VR systems and video arcade games. I personally do OK with helmet-style VR systems, but I have problems if the display motion is poorly matched to my head motion or if I move around too fast or in extreme ways. My first time in a CAVE I was fine, but as soon as someone else controlled the motion, I got dizzy. Then, a year or so ago I downloaded a demo version of Microsoft's "Monster Truck Madness" game for Windows (Figure 2). I was having great fun, but after about 10 minutes, wow, I got the same thing and had to quit. It was a scary thought that even my personal computer display could make me sick.

Turns out it's a common phenomenon, although very subjective and hard to measure accurately. Published estimates suggest that 10 to 60 percent of the population experiences some adverse effects from computer displays of motion. This has serious implications for the ultimate applicability of VR. Some problems result from technical shortcomings such as low frame rates, flicker, or time lag. But even if VR displays are perfected, the eyes still may see a world that's moving in ways the body knows it's not. This means that sickness caused by moving displays may be a fundamental, insurmountable problem for certain kinds of VR.

With our field's big investment in VR, it may not be popular to call attention to this problem. Though perceptual psychologists are studying the phenomenon, it is hard to find many computer graphics people seriously addressing it. But there's a very real danger that motion sickness might keep VR from being a truly universal display technology.



1 **Atari's "Hard Drivin'" video arcade game, introduced in 1989, billed itself as "the world's first driving simulation game." It was followed by a succession of increasingly sophisticated simulated motion arcade attractions.**

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What to call it?

Many motion-related illnesses have similar but varying causes, with many names in common use. Motion sickness is a widely experienced malady in the general population, along with its variants seasickness, car sickness, and airsickness. When flight simulators first appeared in the late 1950s and made pilot trainees ill, they described their affliction as motion sickness. But while some flight simulators included physical motion, many fixed-platform systems also made subjects ill. To distinguish this apparently visually induced illness from the traditional motion-induced one, the terms "simulation sickness" or "simulator sickness"—or sometimes "simsickness"—were introduced.

2 Microsoft's "Monster Truck Madness" very effectively invokes sensory conflict by perturbing the perceived sense of vertical as the trucks tilt and bounce realistically over the uneven terrain.

Beginning in the 1960s, "space sickness" was observed in the US and Soviet Union space programs, apparently caused by weightlessness and the resulting disorientation astronauts and cosmonauts experienced. The exact relationship to motion sickness is not clear but seems to involve discrepancies among the perceived visual cues and sense of orientation with the lack of corresponding physical sensation. Of course, the space program, with its training centrifuges and flight simulators, also induced much real motion sickness and simulation sickness as well. As a result, NASA and military organizations have performed a significant fraction of all the research to date into motion sickness in all its forms.

The widespread use of animated computer displays, including VR systems and certain video games, has led to many more people experiencing similar symptoms. Some of these systems involve actual motion, but many others do not. This has given rise to new terms like "cybersickness" and "virtual reality (or VR) sickness," but many researchers continue to refer to animated computer display illness as "simulation sickness," since it is not clear that it is fundamentally different.

To complicate matters, some research suggests that much of what people experience as motion sickness in moving vehicles may actually be visually induced and not really different from simulation sickness. Some debate whether visually induced and motion-induced effects are different at all; they simply refer to all forms as motion sickness. In reading the literature, you will find each of these terms in use and need to track them all.

What causes it?

The causes of motion sickness are not completely clear. The most broadly accepted theory, called *sensory conflict theory* or *cue conflict theory*, holds that inconsistent sensory information about body orientation and motion causes the ill effects. Motion is detected by the semicircular vestibular canals of the inner ear, which measure tilt and acceleration in six directions (roll, pitch, and yaw each in two directions). Body orientation is usually detected visually, but also by the internal muscular sensation of gravity's pull on the body.

Sensory conflict theory can explain many things about motion and simulation sickness and why they are closely related if not the same. If the eyes viewing a computer screen sense the world is moving while the body senses things are not moving, simulation sickness can result. Many people experience car sickness if reading or sitting in the back seat, as opposed to keeping their eyes focused on the outside scene which serves to keep visual cues and perceived motion in sync. The same goes for passengers below deck in boats or for airplane passengers not sitting next to a window. Travelers at night also have a greater susceptibility because they can't see the outside cues so well and their perception is dominated by the vehicle's apparently non-moving interior.

Other evidence supports mismatches between the visual and vestibular senses as a cause of motion sickness. In flight simulators that move, the maximum fore-aft or side-to-side tilt is about 30 degrees. When simulated motion exceeds this, such as in a barrel roll, the physical sensations suddenly become disconnected from the visual experience and can induce motion sickness.

Sensory conflict theory also holds that conflicting cues within a sense can cause illness. Certain visual displays with simultaneous contrary motion, or different visual displays for each eye in a head-mounted display, are known illness-inducers.

Many people (such as myself) report that they feel OK if they drive but not if others drive. The theory suggests that being able to control and anticipate motion reduces sensory conflict. The same concept applies to immersion in a VR environment such as a CAVE with someone else in control.

It also appears that some people can learn tolerance to motion sickness. For centuries sailors have known that over time they acquire "sea legs." Many people can adapt and ignore certain conflicting cues once the body learns they do not provide reliable information. Indeed, some people who have adapted then get seasick all over again when they get off the boat and back onto firm ground.

A cognitive explanation for sensory conflict theory, called the *rest frame hypothesis*, states that the brain uses sensory cues to form an internal model of what things are stationary, disruptions to which may cause motion sickness. As an example, people sitting in one stopped train alongside another find it disorienting when either train slowly begins to move because they are conflicted—if only momentarily—about who exactly is moving. According to this hypothesis, we need to mentally lock on to something stationary to accept a perceived motion relative to it.

The visual background is usually the dominant rest frame. Thus keeping your gaze fixed on the horizon in a pitching boat or looking out the window in a car or airplane often helps ease motion sickness. On earth the rest frame is primarily based on gravity and on the visual scene polarity—trees and houses are vertical, the sky is overhead, and so forth. Without gravity, astronauts variously lock on to the orientation of the spacecraft interior, the other crew members, or their own orientation, and these perceptions can induce multiple internal conflicts.

The rest frame hypothesis suggests that motion sickness isn't induced physically by conflicting motion signals but is induced mentally by conflicting rest frames deduced from the motion signals. The distinction is subtle but important. There may be a "motion" sickness caused by too much outright physical movement, but the rest frame hypothesis suggests that motion sickness (and certainly simulation sickness) results primarily from cognitive conflict. Some researchers make the definitional distinction that motion sickness is a perceived vestibular conflict whereas simulation sickness is a perceived visual conflict. The rest frame hypothesis suggests that these are nothing more than two sides of the same problem.

If correct, this hypothesis presents a serious problem for certain kinds of VR display technology. Unlike motion in a vehicle, the experience of watching a moving display inherently conflicts with a stationary observer. Indeed, the better the display and the more the observer can perceive a personal sense of presence in the scene, the worse the conflict with a nonmoving (or differently moving) physical reality.

University of Cincinnati psychologist Thomas Stoffregen proposed a variation on sensory conflict theory called *postural instability theory* or *ataxia* in 1991. This theory holds that the real problem is an instability in controlling posture caused by a loss of perceived vertical. Hence the specific sensory conflict causing motion sickness is one between the sensed vertical (detected either vestibularly, visually, or by sense of gravity) and the subjective or expected vertical (the mentally perceived rest frame).

Several lines of evidence support this postural instability variant. Some studies indicate that pitch and roll cause motion sickness more than yaw, the one motion that keeps the vertical upright. Ship passengers face more roll and pitch (and more vertical motion) than car or airplane passengers. If motion sickness results from a conflict between the sensed vertical and the subjective or expected vertical, seasickness would be the most common form—and indeed it is, as well as the oldest recorded form of motion sickness.

The EDS Virtual Reality Center in Detroit reports that their visitors find boat simulations the most unsettling VR displays. NASA centrifuge studies show that tilting your head under acceleration is a major motion sickness inducer. Others suggest that modern roller coasters became more nausea-invoking when they started turning people upside down. All of these observations imply that controlling one's sense of uprightness is a key to not getting sick.

Symptoms

I have always had a hard time describing to others exactly how my motion sickness makes me feel, but to me the sensation is unmistakable. My symptoms are like a bad form of headache, though different from either a normal headache or a migraine. Aspirin will cure my real headaches but has no effect on my motion sickness. The closest thing I can compare it to is a bad hangover. I almost feel like I've been poisoned, though I stop short of getting nauseous. I just want to avoid any further movement, lie down in a dark room, and wait for it to pass.

The literature makes clear the wide variety of motion sickness symptoms people experience. They fall into three broad categories of effects, on the mind, the eyes, or elsewhere in the body (see Table 1).

This broad list may represent the difficulty people have in describing the sensations. But it is clear that some people get many of these symptoms, while others only get specific ones. The effects appear to be both polysymptomatic (different possible symptoms) as well as polygenic (multiple causes). And it is important to remember that many people experience none of these symptoms—they just don't get motion sick.

Studies show that symptoms continue for anywhere from 30 minutes to 10 to 12 hours. There have also been reports of "flashbacks," where a strong recollection of the experience can occur hours or even days later, though this phenomenon has been disputed.

Another complication in sorting out symptoms is the imprecision in distinguishing simulation sickness from true motion sickness. Comparisons suggest that true motion sickness is more likely to cause nausea and vom-

Table 1. Symptoms of motion sickness.

Mental	Visual	Somatic
General discomfort	Blurred vision	Pallor
Apathy	Eye strain	General sweating
Drowsiness	Oculomotor discomfort	Sweaty palms
Headache	Difficulty focusing	Loss of skin color
Disorientation	Inward shift of focus	Salivation
Fatigue	Light sensitivity	Stomach awareness
Sleepiness		Nausea
Malaise		Vomiting
Fullness of head		
Lightheadedness		
Vertigo		
Dizziness eyes open		
Dizziness eyes closed		
Vection (self-motion)		

iting, whereas simulation sickness tends more toward fatigue, eye strain, and headaches. Otherwise, the two clearly have a broad overlap of symptoms.

Speculation as to the evolutionary or adaptive purpose of motion sickness and its symptoms is that the specific emetic responses such as nausea and vomiting are an evolutionary response to ingested toxins and poisons, with the body attempting to purge itself of these substances. Many neurotoxins affect balance and movement control, and motion sickness appears to trigger a similar response.

Who gets it?

Measuring how many people are susceptible to the various forms of motion or simulation sickness proves quite difficult. The exact phenomenon depends on the form of real or simulated motion and, in the case of simulation sickness, display characteristics. In addition, the basic research methodology is to put subjects through the test scenario, then have them respond to a questionnaire to assess the effects. Such subjective reports and linguistic characterizations are inherently hard to score and calibrate. For all these reasons, widely varying statistics appear in the literature. But it seems clear that the incidence is much higher than one might believe given the popularity of amusement parks, video game arcades, and VR systems.

Work by Eugenia Kolasinski at the US Army Research Institute, building on her 1990 University of Central Florida graduate thesis, represents one of the more systematic investigations into simulation sickness. She observes that susceptibility to simulation sickness is affected by simulator factors (display quality and other characteristics), task factors (what simulated situations are presented), and individual factors (susceptibility differences among subjects). Kolasinski states that 20 to 40 percent of pilots get simulator sickness, depending upon the situation.

As to individual factors, Kolasinski's studies suggest that motion sickness susceptibility decreases with age. Other researchers have noted this effect (though in my case I think it has gotten worse with age). Kolasinski speculates this could simply be the result of experience and learning to cope with the phenomenon.

Along these lines, simulation sickness is more likely among people familiar with the corresponding real environment. In other words, experienced pilots have more problems with flight simulators than do nonpilots, presumably because they are more attuned to the lack of correspondence with their real-world experience. Similarly, subjects experienced in using simulated environments are less likely to experience simulation sickness, suggesting again that tolerance can be learned.

Kolasinski's studies indicate that women are more likely than men to experience simulation sickness. However, she points out that because of the self-reporting nature of the experiments, this effect might be due to a male tendency to under-report vulnerability in these situations. Kolasinski also reports that motion sickness may be more common in Asians than other ethnic groups.

Illness, fatigue, sleep loss, hangover, stress, colds, or medications appear to increase susceptibility to simulator sickness. Also, perceptual studies indicate that subjects who are not good at mental rotation of 3D objects or at perceiving objects separate from their visual background field seem more prone to simulator sickness.

Other military studies have measured the overall incidence of motion sickness. A 1994 US Navy study found that 13.5 percent of all military flights have some sickness among passengers, with 5.9 percent experiencing nausea. Some 63 percent of flight students get sick on their first flight, though 15 to 30 percent never get airsick. Incidence appears to decline with age, and females report symptoms twice as often as males. Other studies by the Royal Air Force found 39 percent of flying students airsick at some stage of their training, with 15 percent experiencing symptoms bad enough to abandon flight.

The International Workshop on Motion Sickness was held in Marbella, Spain from May 26 to May 28, 1997. This conference attracted researchers from around the world, ranging from military and space researchers to perceptual psychologists studying all forms of motion sickness. An interesting collection of reports resulted:

- Research from international space programs indicates that space sickness is common, affecting half or more astronauts and cosmonauts. Russian scientists reported that 48 percent of cosmonauts experience "some space sickness effects," while a NASA study said that 70 to 80 percent of astronauts get some form of "space motion sickness and spatial orientation and motion perception disturbances." Symptoms usually subside after two to three days, presumably due to adaptation. Centrifuge studies on earth suggest that any non-earth gravity tends to evoke motion sickness, and head movements especially trigger symptoms, presumably due to the loss of subjective vertical.
- Studies from Sweden measured motion sickness on so-called "tilt trains." In designing trains to run at higher speeds on conventional railroad track, the technique of tilting rail cars as they round curves can lead to 25 to 30 percent higher speeds. The studies showed that 8 to 15 percent of passengers get motion sick in tilt trains (depending on degree of tilt). Evidently the tilts result in effects of gravity and centrifugal force at odds with the unfamiliar perception of rail car interiors not aligned to vertical.
- An extensive study spanning thousands of subjects by the Human Factors Research Unit at the University of Southampton, UK, compared several forms of commercial transportation for their motion sickness effects (see Table 2). They believed that long-distance bus passengers fare worse than car passengers because of poor forward visibility in buses.

Table 2. Motion sickness from different types of commercial transportation.

Conveyance	Slightly Unwell	Vomiting	Quite Ill	Absolutely Dreadful
Oceangoing vessels	21%	7%	4%	4%
Long-distance buses	22%	1.7%	4%	2%
Airplanes	14%	0.5%	1.6%	0.4%

- The National Hospital for Neurology and Neurosurgery in London studied participants in a nine-month round-the-world yacht race. They found that female subjects reported seasickness for 28 percent of the days and male subjects for 7 percent of the days (again, perhaps reflecting reporting differences).

A number of VR and simulation sickness studies were presented at the conference. While they are hard to compare because of subjective reporting and varying experimental conditions, the overall impression is sobering:

- A joint study by researchers at NASA, University of Central Florida, and Essex Corp. found "at least one symptom clearly associated with motion sickness" in 20 to 60 percent of subjects using the "best" to "worst" flight simulators. Moreover, their study showed that head-mounted VR systems "appear to cause higher levels of sickness symptoms than those found in flight simulators and sea vessels."
- A study by Stoffregen at the University of Cincinnati found 29 percent of subjects having "mild motion sickness symptoms" in response to simple oscillating displays.
- A group from University of Nottingham, UK, had subjects move through a virtual environment and complete a variety of manipulative tasks. From 60 to 80 percent of subjects reported motion sickness symptoms during and post immersion.
- A study at the University of Southampton, UK, showed subjects visual displays based on others' walking motion. This induced motion sickness symptoms in fully 93 percent of subjects.

While it is hard to compare these numbers, it appears the incidence of simulation sickness may exceed that for true motion sickness. Computer displays can cause the purest form of sensory cue discrepancies, since the visual perception can be completely decoupled from physical motion, in addition to whatever effects might arise from technical quality problems.

Table 3. VR display factors contributing to motion sickness.

Head-mounted display time lag
Phosphor lag
Position tracking errors
Refresh rate (flicker)
Low update rate
Poor image quality
Poor resolution
Spatial stereo mismatches
Temporal stereo mismatches
Incorrect interpupillary distance
Narrow field of view
Excessive brightness
Excessive head movement
Excessive helmet weight
Motion controlled by others
Exaggerated scenes (high rates of linear or rotational acceleration, abrupt stops, flying backwards)

Prevention

Currently a debate rages between those who feel improved technology will reduce VR display sickness and those who feel the problems are insurmountable. Those who believe technology improvements will help point out that when TV (and later color TV) first appeared, the image quality, flicker, smearing, and other technical shortfalls caused discomfort in many people. As TV technology improved, the incidence of problems diminished. Researchers such as Mark Draper at the University of Washington and Eugenia Kolasinski have shown that almost every possible technical shortcoming in VR systems contributes to motion sickness (see Table 3). Perfecting VR display technology to eliminate these quality difficulties should mitigate their impact on VR sickness.

Others argue that the problem with VR sickness is inherent in the technology, and technical quality improvements won't eliminate it. As long as a mismatch exists between what is visually perceived and what is physically sensed, fixing the VR display properties does not address the root cause. Some even argue that perfecting VR displays will only convey any inherent mismatch more precisely to the user. Only perfect virtual environments limited to tracking actual user motions could completely avoid this difficulty.

Of particular interest are studies indicating that the weight of VR head-mounted displays may be in and of itself a contributing factor. The weight of VR helmets puts pressure on neck muscles and prevents natural motion and balance of the head, causing an unnatural sensation in response to movement and perhaps contributing to a perceived loss of posture control. (These arguments have even been applied to the debate over mandatory motorcycle helmet laws, though this topic is clearly controversial.)

The 1994 US Navy study reported that techniques such as biofeedback, relaxation training, and counseling had an estimated 40 to 85 percent success rate in helping reduce susceptibility to motion sickness. Drugs such as dimenhydrinate (Dramamine), meclizine HCl (Bonine), and scopolamine (Transderm Scop) reportedly reduce motion sickness by as much as 80 percent. But these drugs cause drowsiness in most subjects, and the military is not enthusiastic about their use among pilots. Also, these drugs all tend to be antiemetic, that is, they reduce nausea and vomiting. To the extent that simulation sickness has less emetic effects than true motion sickness, these drugs may prove less helpful.

Motion sickness drugs for the most part claim to prevent, not treat, motion sickness. It is not clear whether any medical remedy helps treat motion sickness once it starts, with the exception of medications that suppress the nausea and vomiting reflex. Again, these would seem less applicable to simulation sickness.

One study at the Marbella conference measured the effectiveness of wrist bands that stimulate an acupuncture point on the wrists. The results indicated that the bands do appear to reduce motion sickness. Again, this study measured true motion sickness, so the value for simulation sickness is unclear.

In summary, other than reducing the quality problems associated with VR displays, it is not clear what will help prevent or treat VR sickness as distinct from true motion sickness. Paradoxically, VR displays could play a role in preventing motion sickness. Reports at the Marbella conference and elsewhere suggest that motion sickness could be reduced in moving environments lacking an external view by providing a VR display that synthesized in real time an exact visual scene corresponding to the actual physical and inertial motion.

Implications for VR

What can we in the computer graphics field conclude from the preceding? Lessons include

1. The problem of VR sickness appears to be a real and serious issue.
2. While improvements in display quality and fidelity will eliminate some negative effects, VR displays may have an inherent problem affecting a significant percentage of the population.
3. VR systems that display simulated motion in the absence of actual user motion are especially problematic, and immersive VR systems that track real user motion or physically move the user must do so very well.
4. A number of factors may help reduce the problems associated with VR displays:
   - better VR display quality and fidelity
   - personal control
   - restricted motion
   - vertical stability
   - smaller field of view with a dominant stationary reference frame
   - lower helmet weight
5. If VR is inherently problematic for part of the population, its use should be optional.
6. If artificial motion is truly an inherent problem, perhaps more universally acceptable VR systems should focus less on motion as a created experience and more on other forms of virtual experience and dynamics.

To Explore Further

Eugenia M. Kolasinski, "Simulator Sickness in Virtual Environments," Technical Report 1027, US Army Research Institute, May 1995. This report is a comprehensive study of the causes and characteristics of simulator sickness, based on the author's 1990 graduate thesis at the University of Central Florida. Available at http://www.cyberedge.com/4a7a.html.

International Workshop on Motion Sickness, May 26-28, 1997, Marbella, Spain. This conference drew together a broad range of researchers who study motion and simulation sickness. An extensive set of abstracts and short papers is available at http://www.ion.bpmf.ac.uk/~dizzymrc/motsick.html.

"Can Your Eyes Make You Sick?: Investigating the Relationship Between the Vestibulo-ocular Reflex and Virtual Reality," April 1996, Capt. Mark H. Draper, USAF. Draper, working with other researchers in the Human Interface Technology Laboratory at the University of Washington, has published detailed studies of the perceptual basis for simulation sickness. This report is available at http://www.hitl.washington.edu/projects/vestibular/dis1.html.

The debate will continue into the implications of motion sickness for computer graphics. Clearly more research is needed to determine the extent of the problem and the potential solutions. Applying what we've learned so far will tell us more about how to make VR an effective technology for everyone. ■

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