Linear Acceleration Perception on a Moving VR Environment

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Understanding how people perceive linear acceleration is crucial for creating more realistic and immersive virtual environments. This thesis investigates how people perceive linear acceleration on a moving platform while in virtual reality (VR). The objective is the identify the Just Noticeable Difference (JND), which represents the smallest detectable change in stimuli that users can perceive. The study integrates a physically moving platform with a VR environment, employing a staircase method to determine upper and lower perception bounds. By focusing on human sensitivity to acceleration, the research aims to bridge the gap between physical and virtual motion experiences, a key motivator for enhancing VR realism.

The results demonstrate that at low accelerations, there is an distinguishable upper and lower bound of acceleration perception. These findings, validated through statistical methods including t-tests, offer insights into how people perceive changes in acceleration. However, unexpected trends, such as increased variability at lower accelerations, suggest further investigation is needed to confirm the applicability of Weber's Law in this context.

The research also highlights practical applications, such as space conservation in VR motion systems, by leveraging the lower acceleration JND to shorten track distances without compromising perceived realism. Limitations, including sample size and equipment constraints, are acknowledged, and future work is proposed to explore higher speeds, angular acceleration, and alternative experimental conditions. By advancing our understanding of linear acceleration perception, this study provides a foundation for improving VR systems used in training, entertainment, and rehabilitation, ensuring they balance realism, comfort, and practicality.

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Dedication

This is dedicated to my friends and family.

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Chapter 1

Introduction

The concept of virtual reality dates back to 1935 when author Stanley Weinbaum first introduced the idea in his short story "Pygmalion's Spectacles," [2] where he described goggles that allowed the user to experience movies through sight and other senses [3] [4] [5]. This imaginative concept would take nearly three decades to materialize when Dr. Ivan Sutherland developed the first virtual reality head-mounted display, known as the "Sword of Damocles," in 1968 [6]. This device was the earliest attempt to create an immersive 3D experience through a head-mounted display, albeit with very primitive technology [4] [7] [8].

While VR was primarily confined to research labs for many years, significant advancements were made in the 1980s and 1990s, albeit the technology remained largely experimental due to the limited computing power and graphics capabilities of the time. The broader public first became aware of VR when Oculus released its Oculus Rift VR headset in 2012, marking a turning point in the accessibility and popularity of virtual reality [9] [8]. Since then, VR has moved beyond research labs and into mainstream consumer markets.

The release of Oculus Rift spurred several technology giants, including Amazon, Apple, Facebook, Google, and Samsung, to develop their own VR devices [10] [11]. These companies are leveraging VR for a multitude of applications, such as training materials for employees, teaching children how to safely cross roads [12] [13], and enhancing understanding of the impacts of perception and visual immersion [14] [15]. These devices provide users with visual cues that can significantly alter their perception, leading to unique interactions across various applications [16]. One of the critical applications this research project seeks to investigate further is the effect of visual cues and environments on the perception of acceleration and motion.

As VR technology matured, its applications extended beyond entertainment and gaming, which were among the first industries to embrace VR's immersive potential. Today, VR is used in various fields, such as education, healthcare, architecture, manufacturing, and social interaction [17] [18] [19].

In education and training, VR creates immersive experiences that allow students to explore environments and scenarios otherwise inaccessible. For example, medical students can practice surgeries in a risk-free virtual environment [10]. In healthcare, VR has been employed in pain management, rehabilitation, and mental health therapy, including treating PTSD through controlled exposure to traumatic memories [11]. In architecture and design, VR allows architects to create and explore 3D models of buildings and spaces, facilitating a more interactive design process [12]. In manufacturing and engineering, VR is used for prototyping and testing products before they are physically built, allowing engineers to simulate assembly processes and test ergonomics in a virtual environment [13]. VR is also paving the way for new forms of social interaction, with platforms like VRChat enabling users to interact in virtual spaces in ways that are not possible through traditional social media [14].

Virtual Reality has also emerged as a powerful tool for simulating a wide range of motion-based experiences, including driving, flight, and walking [20][21][22]. By creating immersive environments, VR allows users to experience realistic scenarios without leaving the physical space. One of the key aspects of these experiences is the sensation of acceleration, which is critical for delivering an authentic experience, whether the user is flying an aircraft, driving a car, or walking through a virtual landscape [20][21]. In real-world motion, the human body constantly senses acceleration, primarily through the vestibular system, which is responsible for detecting changes in movement and maintaining balance[23]. However, simulating this sensation accurately in VR environments presents significant challenges, particularly when the physical movement of the user does not align with the visual cues presented in the virtual environment[24][25].

In typical VR applications, such as those used for gaming or general motion simulation, users often rely on input devices like trackpads, joysticks, or controllers to navigate the virtual environment[26] [27] [28]. While these methods are effective for controlling movement, they do not provide the sensation of acceleration, which can limit the user's sense of immersion and perception. When using a joystick or trackpad to move in a virtual world, the visual cues indicate motion, but the user's body does not feel the accompanying forces. This lack of physical sensation can affect user performance and immersion, as the brain expects to receive feedback from the vestibular system when motion is perceived visually. Studies have shown that this disconnect between visual and physical feedback can impair performance in tasks that rely on motion perception, as users are less likely to react as

they would in real-world scenarios without the sensation of acceleration [24] [29] [22] [30] [31].

One of the primary challenges of movement in VR is the issue of space [32]. Many VR experiences, especially those that involve walking or driving, require large physical areas for the user to move in. If a VR environment is set inside a basketball arena, then the physical space to fully interact with the environment would need to be the same size as the arena. This presents a problem for most use cases, as large-scale motion simulators or 1-to-1 scale VR setups are often impractical in homes or small spaces. To address this, developers have explored a variety of methods to reduce the physical space needed for motion simulation. Techniques such as omnidirectional treadmills allow users to walk in place while navigating a large virtual environment, effectively reducing the need for a large physical space [20] [15] [14]. These treadmills enable full 360-degree movement, allowing users to walk in any direction without leaving a confined area. While omnidirectional treadmills offer a solution to the space problem, they are often expensive and require complex setups, limiting their accessibility for everyday users [33] [19]. Furthermore, they are only limited to walking applications, and cannot be used for other uses of VR environment navigation, such as driving or flying.

For VR systems that are used for training and educational purposes, such as flight simulators or driving simulators, the perception of acceleration is essential for creating a realistic experience. For instance, when a pilot accelerates during takeoff or makes sharp turns, the sensation of acceleration helps the pilot respond appropriately[24] [20] [29]. Without this feedback, the pilot may not fully experience the forces they would encounter in a real aircraft[24]. Similarly, in driving simulators, the lack of physical acceleration feedback could lead to a reduction in training effectiveness, as drivers may not fully appreciate the forces involved in accelerating, braking, or cornering[16] [29]. Simulating acceleration in these training environments is not just about making the experience more immersive; it also directly impacts the effectiveness of the training by helping users develop muscle memory and other critical responses that are essential in real-world scenarios.

To address the limitations of VR systems that lack physical motion feedback, a variety of motion platforms have been developed to simulate the sensation of acceleration. These platforms, such as Stewart platforms (also known as hexapod platforms)[24] [20], use mechanical actuators to move the user in multiple directions, thereby creating the physical forces that correspond with visual motion cues in the VR environment. Stewart platforms are commonly used in flight simulators, where they can replicate the sensation of takeoff, turbulence, and other maneuvers by tilting and accelerating in sync with the visual cues from the VR headset[24] [20]. These platforms help solve the problem of missing physical feedback by giving users a more realistic experience that includes the sensation of

acceleration, thereby improving performance and immersion [29] [34].

Another approach to simulating acceleration in VR is through the use of tilt mechanisms. Tilt-based simulators, such as those used in driving and flight training, can simulate acceleration by tilting the chair in the direction of motion, creating the illusion of acceleration without requiring large movements [34]. By tilting the user's body, these simulators engage the vestibular system, tricking the brain into perceiving motion even when the platform is stationary. This method allows for the creation of realistic motion experiences within a smaller physical space, which is a key advantage in environments where space is limited [34] [33]. Tilt mechanisms, however, can only simulate a portion of the forces experienced in real-world acceleration, as they do not fully replicate the dynamic range of forces encountered in activities like driving or flying.

This research aims to explore the Just Noticeable Difference (JND) in linear motion perception within VR, particularly the threshold at which users detect discrepancies between physical and virtual linear acceleration cues. The concept of JND, rooted in psychophysics, pertains to the smallest difference in stimulus intensity that a person can detect [24] [21] [22] [30] [31]. Determining the JND in motion perception in VR involves understanding the sensitivity of users to differences between visual and physical acceleration. Understanding the JND is crucial for creating realistic and immersive experiences in applications involving motion, such as virtual reality, driving simulators, and flight training environments [35]. The JND represents the threshold at which users can perceive a change in a stimulus, in this case, acceleration. By identifying this threshold, designers and developers can better align virtual cues with human sensory expectations, ensuring that users remain immersed without being overwhelmed or disoriented by the environment [36] [37]. By gradually varying physical acceleration while maintaining a constant visual acceleration (or vice versa), we can identify the threshold at which users begin to notice a difference. This data is crucial for optimizing VR experiences, ensuring that the alignment between visual and physical aspects of motion enhances realism and immersion [38].

One of the most significant JND implications of this research lies in its potential application for conserving physical space in commercial settings, particularly in industries like entertainment and training. The findings related to the lower acceleration JND threshold offer valuable insights into how virtual environments can replicate motion experiences while reducing the physical space required.

In traditional 1:1 physical applications, such as go-kart tracks, a large amount of space is necessary to accommodate the full range of motion. Lets say for instance that there is a lower acceleration JND bound set at 0.5 times the base acceleration. By utilizing the lower JND bound, the physical acceleration can be subtly reduced below the baseline

while maintaining the illusion of continuous motion. This approach minimizes the need for expansive tracks and allows for a more compact setup, ideal for commercial spaces such as malls, theme parks, or VR arcades.

For instance, a drag racing simulator could employ a shortened track where the initial acceleration matches the visual cues provided in the VR environment. As the user progresses, the system can reduce the physical acceleration just above the JND lower threshold, ensuring the motion remains imperceptibly consistent with the visual cues. This reduction translates to a shorter physical track while preserving the immersive experience of high-speed racing. Similarly, in go-kart racing, the lower JND bound could allow for smaller, more compact tracks that deliver the sensation of a full-scale racecourse.

Take for example, in a traditional drag race, where cars attempt to drive 400 meters as quickly as possible. Using a classic drag race vehicle as reference like a 2023 Dodge Challenger SXT [39], which can travel a distance of 400 meters in 14 seconds. Now, traditionally, you would need a 400 meter track for a 1:1 recreation. However, when we apply the lower JND bound of 0.5 times the base acceleration the space gets reduced by 50% to 200 meters.

$$d = v_0 + \frac{1}{2}at^2$$

This is because the reduction in physical space required for motion simulations is directly proportional to the lower JND threshold of 0.5 times the baseline acceleration, as acceleration is fundamentally constrained by time in these scenarios. Note that constant velocity is assumed once the vehicle finishes accelerating.

To the best of our knowledge, this research is the first to combine the concept of JND with a physically moving environment to study the perception of linear acceleration. While previous studies have examined JND in visual or stationary setups, no prior research has tested acceleration perception using a mobile platform such as a go-kart integrated with VR. This novel approach bridges the gap between purely visual studies and real-world motion experiences, offering unique insights into how physical and virtual motion interact to influence perception.

In the following chapters, this thesis will explore the Just Noticeable Difference in the detection of linear acceleration in a Virtual Reality environment. Chapter 2 will review the relevant background concepts necessary for understanding this research, including foundational principles of VR, acceleration, motion perception, and the JND framework. Chapter 3 details the methods used in the study, covering the development of the VR environment,

the experimental setup, and the mobile platform (Go-Kart) used for testing the participants' perception of acceleration. Chapter 4 focuses on the data collection and processing, presenting the analysis that led to the determination of the upper and lower bounds of acceleration for JND. The results of the study will be discussed in detail, along with their potential applications and broader implications in VR technology and motion simulation. Finally, in Chapter 5 we conclude the thesis by summarizing the key findings and offering insights into current limitations and potential directions for future research.

Chapter 2

Background

2.1 Acceleration Perception

Of the many ways humans can perceive motion, acceleration plays a large part in our perception. It plays a key role in how people navigate and interact with the physical world [10] [11]. It is primarily affected by the vestibular system, located in the inner ear, which detects changes in motion, orientation, and balance [40] [37]. The vestibular system is responsible for sensing linear acceleration (forward, backward, upward, or downward) and angular acceleration (rotational movements). This system works in conjunction with other sensory inputs, including visual cues and proprioception (the awareness of the body's position in space), to provide a cohesive perception of motion [40] [37].

2.1.1 The Vestibular System and Acceleration Detection

The vestibular system is composed of two main structures: the otolith organs (the utricle and saccule) and the semicircular canals [6]. The otolith organs detect linear acceleration and gravitational forces, while the semicircular canals sense angular acceleration. When the head moves, fluid within the semicircular canals shifts, stimulating hair cells that send signals to the brain about the direction and magnitude of rotational movement. Similarly, the otolith organs detect shifts in head position during linear movements, providing the brain with information about changes in speed and direction [6].

The brain integrates these signals from the vestibular system with visual information and proprioceptive feedback to form a complete picture of motion [6] [41]. For instance,

when driving a car, the vestibular system detects acceleration as the car speeds up, while visual cues from the environment provide information about movement relative to objects outside the vehicle. Proprioception helps maintain posture and balance in response to these changes in motion. Together, these systems allow for accurate perception of movement, enabling humans to respond to changes in speed, direction, and orientation [41].

2.1.2 Perception of Acceleration and Jerk

Humans are particularly sensitive to changes in acceleration due to the way our vestibular system is structured to detect variations in motion. This sensitivity is critical for maintaining balance, spatial orientation, and reacting to dynamic environments[41] [2]. The human body is equipped to notice even small changes in speed or direction, particularly when there is a rapid alteration in movement. The concept of jerk, which refers to the rate of change of acceleration, plays a central role in how these changes are perceived [2].

Jerk $\vec{j}$ is the derivative of acceleration with respect to time and describes how quickly acceleration itself is changing.

$$\vec{r} = position, \vec{j} = \frac{d^3\vec{r}}{dt^3}$$

It is important because the vestibular system responds more strongly to changes in acceleration (jerk) than to constant acceleration [2]. When a body moves with a constant acceleration, the otolith organs in the vestibular system quickly adapt to the continuous force, resulting in a decreased perception of motion over time. However, when there is a sudden change in acceleration—such as when a car brakes or accelerates sharply—the vestibular system detects this change immediately, creating a strong perception of motion [2] [42].

Jerk is what makes a smooth takeoff on an airplane or the rapid braking of a vehicle more noticeable than steady movement. A person may feel comfortable during the constant speed of a plane flying at cruising altitude, but the rapid changes during takeoff and landing, where jerk is high, create a more intense experience of motion [2] [42].

In the context of virtual reality and motion simulation, jerk plays a significant role in creating realistic sensations of movement. Sudden or high levels of jerk can be immediately noticeable to users, potentially disrupting the immersion and triggering discomfort or motion sickness. Conversely, smooth transitions with controlled jerk can enhance the believability of acceleration and deceleration, aligning with the natural dynamics of real-world motion [43].

Jerk has a profound impact on acceleration perception, particularly during the transition from a stationary state to motion, as it defines how smoothly acceleration is applied. When accelerating from zero, the sudden onset of motion accompanied by a high jerk value can create a sharp, noticeable sensation that stands out more than the acceleration itself [43]. This is because the human vestibular system is highly sensitive to changes in motion, with jerk amplifying the perception of acceleration transitions. In the context of this research, high jerk levels during the initial phase of movement could influence participants' ability to discern changes in acceleration accurately.

Once the body is exposed to constant acceleration or velocity, it begins to adapt to the motion relatively quickly [44] [45]. This process of adaptation usually occurs within seconds to a few minutes, depending on the intensity and type of motion. As the vestibular system adapts, the perception of motion diminishes, and the sensation becomes less noticeable. For example, when a person is in a car that accelerates to a constant speed, the initial acceleration is strongly felt, but after the car reaches a constant speed, the sensation of movement fades, and the person may feel as if they are not moving at all unless they visually reference their surroundings.

The vestibular system adapts to these constant forces because it is primarily designed to detect changes in velocity and acceleration, not constant velocity and acceleration. However, if the motion is prolonged, such as during long-duration acceleration, the body may gradually adapt, leading to reduced awareness of movement [44] [45]. In this research, our focus is on the perception of acceleration, and not jerk. Therefore, we will want to minimize the affect of jerk in our investigation. This will be expanded upon in Section 3.4.3.

2.1.3 The Role of Visual Cues in Acceleration Perception

Visual cues play a fundamental role in helping humans perceive acceleration and understand changes in motion [46]. While the vestibular system in the inner ear is responsible for detecting physical forces such as acceleration and angular movement, visual information significantly enhances the brain's ability to interpret and react to these changes [41] [46]. The integration of visual and vestibular signals allows for a more complete and accurate perception of motion, particularly in environments where both physical movement and visual cues are present.

One of the most important visual mechanisms involved in the perception of acceleration is optic flow, which refers to the pattern of apparent motion of objects, surfaces, and edges in a scene caused by the relative motion between the observer and the environment [47].

As a person moves through an environment—whether by walking, driving, or riding in a vehicle—objects in their field of vision move in the opposite direction, and their speed of motion increases with proximity to the observer. This visual flow provides critical information about the speed and direction of the movement. For example, when driving a car, the observer perceives objects near the road (such as roadside signs) moving past at a faster rate than distant objects, like mountains or the sky. The brain uses this optic flow information to infer not only the speed of movement but also any changes in acceleration [47]. When acceleration increases, the rate of optic flow also increases, reinforcing the vestibular system's perception of a change in velocity. Similarly, when decelerating, the slowing optic flow helps the brain interpret the reduction in speed. Optic flow is an intuitive and powerful tool for understanding acceleration, and it operates automatically during real-world movement.

Depth perception is another key visual component that aids in understanding acceleration [48]. Humans use binocular vision, where the slightly different images received by each eye are combined by the brain to estimate the distance of objects. This ability to gauge distance is crucial when moving through the environment because it helps predict how fast objects will approach and how changes in speed will affect their proximity [48]. For example, as a person accelerates toward an object, their perception of the object's size and proximity changes. This visual feedback is used to adjust movement, such as slowing down before reaching an obstacle, in addition to proving additional information about the relative speed and acceleration. The brain's ability to use depth perception to estimate distance also plays an important role in understanding how fast one is moving, allowing individuals to make decisions about their speed and relative movement.

Visual cues also help predict changes in acceleration before the vestibular system even detects them [49]. For instance, when a person in a car sees the brake lights of the car in front of them or notices the narrowing of lanes on a highway, they can anticipate the need to decelerate before the physical forces are felt [49]. Similarly, visual cues such as the sharp turn of a road ahead or approaching traffic lights can signal the need for acceleration changes. These anticipatory visual cues allow the brain to prepare for the upcoming motion, enabling smoother transitions in speed and reducing the risk of discomfort or disorientation. Visual cues can provide valuable foreknowledge of changes in motion, allowing the body to preemptively adjust and respond to acceleration forces [49].

In natural settings, visual cues can even override vestibular cues in certain circumstance [49]. For instance, if an individual is seated in a moving train, their vestibular system detects acceleration as the train starts, but if they look outside the window and see the landscape moving past them, the visual cues reinforce their understanding of the direction and speed of movement. Similarly, if an individual looks inside the train where everything

is relatively stationary, the lack of optic flow may reduce the perceived intensity of motion, even though the vestibular system continues to detect acceleration. In another example, if a person is moving in a straight line but their vestibular system senses a slight deviation, the brain may prioritize the visual cues from the environment that suggest continuous forward movement [49] [50]. This visual dominance ensures that people can maintain a coherent perception of motion even in situations where vestibular signals are ambiguous or unreliable.

Immersive VR environments effectively address the challenges of sensory conflicts in acceleration perception by providing highly synchronized and detailed visual cues that dominate the user's sensory input [51]. Unlike real-world scenarios where sensory conflicts between the vestibular and visual systems might arise due to limited or inconsistent feedback, immersive VR systems can be designed to present coherent and precisely timed visual stimuli. These stimuli are engineered to align with the perceived motion, reducing the mismatch that typically causes disorientation or discomfort. By immersing participants in a controlled environment where visual cues are crafted to simulate realistic acceleration, VR can trick the brain into resolving conflicts between what is seen and what is physically experienced [51].

2.2 Virtual Reality

Virtual Reality refers to the use of computer technology to create a simulated environment in which users can immerse themselves and interact with virtual objects and settings[3]. VR is distinct from traditional screen-based experiences because it relies on head-mounted displays, motion tracking, and 3D rendering to produce an environment that mimics physical spaces, allowing users to feel as if they are "inside" the virtual world.

2.2.1 Software Movement in Virtual Reality

One of the most critical aspects of virtual reality is the simulation of movement. In the real world, movement is experienced through a combination of physical motion, visual cues, and the sense of balance provided by the vestibular system [50] [9]. In VR, replicating the sensation of movement is key to maintaining immersion and convincing the user that they are navigating through a virtual space. However, simulating movement in VR is complex because it often requires tricking the brain into believing that movement is happening without the body actually moving.

There are three (3) common methods for simulating movement in VR:

1. Trackpad and Joystick Movement: In many VR systems, users move through the virtual environment by manipulating handheld controllers equipped with trackpads or joysticks. The user physically remains stationary, but the virtual world moves around them based on their input. While this method is simple and widely used in VR gaming, it lacks any physical motion or acceleration cues, which can create a disconnect between what the user sees and what their body feels. This often results in motion sickness, as the vestibular system does not register any actual movement [26] [27] [28].

2. Room-Scale VR: This approach allows users to physically move within a confined area tracked by external sensors, creating the sensation of movement in the virtual world. While room-scale VR is more immersive than joystick or trackpad movement, it is limited by the size of the physical space available. Users can walk around a predefined area, but once they reach the boundaries of the space, further movement must be simulated using other techniques, such as teleportation. This method still does not simulate acceleration in a way that matches real-world experiences [26] [27] [28].

3. Teleportation: To navigate larger virtual environments without causing motion sickness, many VR applications use teleportation. In this method, users point to a location in the virtual world and instantly "jump" to that location. Teleportation is effective at preventing discomfort because it avoids continuous movement, which can confuse the vestibular system. However, it can break the sense of immersion, as the instantaneous movement does not replicate the smooth transitions of walking or driving in the real world [26] [27] [28].

The primary limitation of these movement methods is the lack of physical feedback (apart from room-scale VR). Movement solutions like trackpad navigation, joystick walking, and teleportation are entirely virtual and visual in nature, relying on the manipulation of the user's perspective within the virtual environment. Without corresponding real-world acceleration or motion to reinforce these visual cues, the brain is forced to resolve the discrepancy between what it sees and what it feels through the vestibular system [27] [52] [17]. This disconnect often results in sensory conflicts, as the visual system signals motion while the vestibular system and proprioceptive inputs indicate a stationary state. Such conflicts can cause discomfort, disorientation, and in many cases, motion sickness, reducing the effectiveness and immersion of the VR experience.

The lack of physical feedback also diminishes the sense of presence and realism. When users cannot feel the forces or physical sensations associated with movement—such as acceleration, deceleration, or changes in direction—their brain is less likely to accept the virtual environment as authentic [52] [17]. For example, in scenarios that involve rapid changes in speed or direction, like driving simulators or flight training, the absence of physical motion prevents users from fully engaging with the experience, as critical sensory inputs are missing. This limitation is particularly pronounced in applications that depend on accurate spatial orientation or dynamic interactions, where physical feedback plays a vital role in decision-making and motor responses. While room-scale VR mitigates this issue by allowing users to physically move within a defined space, it is constrained by the size of the physical environment.

Without additional hardware, such as motion platforms or haptic devices, these movement methods fail to provide the physical cues necessary for a fully immersive and convincing experience [53] [54]. Thus, the lack of physical feedback remains a significant challenge in VR, underscoring the importance of developing integrated solutions that combine visual and physical motion cues to enhance user engagement and reduce sensory conflicts.

2.2.2 Acceleration in Virtual Reality

Acceleration in VR is more challenging to simulate than basic movement because it requires the user to perceive changes in velocity. In a virtual environment, where the user remains stationary for the vast majority of time, this physical feedback is absent, which can lead to discrepancies between the visual cues of motion and the user's sense of physical motion [50] [55].

In the real world, when a person accelerates—whether in a vehicle or while walking—their body detects the change in velocity through both visual and vestibular cues. When accelerating in a car, the vestibular system detects the physical force of acceleration, while the visual system perceives objects moving past the car more quickly. These cues are synchronized, allowing the brain to interpret the change in speed accurately.

Because of the physical movement needed, virtual environments aren't typically able to provide acceleration stimulation apart from visual cues [50] [55]. The visual cues of acceleration are provided without corresponding physical forces. For example, in a VR driving simulation, the user may see the environment moving faster as the virtual car accelerates, but their body does not feel the acceleration [30] [31]. This disconnect between what is seen and what is felt can lead to disorientation or motion sickness, as the brain struggles to reconcile the visual information with the lack of physical sensation.

2.2.3 Hardware Movement Solutions in Virtual Reality

These techniques attempt to address the sensory mismatch by introducing physical motion that complements the virtual experience, or by creating more convincing visual illusions of movement. Some of the most common methods include:

- Omnidirectional Treadmills: An omnidirectional treadmill is a physical device that allows users to walk in any direction while remaining in a fixed position. The treadmill tracks the user's movements and translates them into the virtual world, providing a more natural walking experience compared to using joysticks or trackpads. Although these treadmills can create a convincing illusion of walking, they are often expensive, bulky, and not widely accessible for most VR users. Moreover, while they replicate walking, they do not provide any real acceleration or deceleration feedback, which limits their ability to simulate fast-paced movements, such as driving or flying [56].

- Motion Platforms: Motion platforms, such as Stewart platforms (hexapod platforms), use multiple degrees of freedom to tilt, rotate, or move the user in response to changes in the virtual environment. These platforms are commonly used in flight simulators, driving simulators, and roller coaster experiences to simulate the forces of acceleration and deceleration. By tilting the platform forward during acceleration or backward during deceleration, the platform provides physical feedback that mimics the sensations of real-world movement. While motion platforms can greatly enhance the sense of immersion by providing both visual and physical cues of acceleration, they are typically limited to specialized, high-end applications due to their size and cost [24] [20] [56]. Similar to motion platforms, tilting chairs or seats are another solution for providing physical feedback during acceleration. These chairs tilt in response to virtual acceleration, giving the user the sensation of movement without requiring them to leave their seat. Tilting chairs are often used in racing and flight simulators, where they can replicate the forces experienced during high-speed turns, takeoffs, or landings. While less complex than full motion platforms, tilting chairs still provide an additional layer of physical immersion that helps bridge the gap between virtual and physical acceleration cues [24] [20] [56]. An investigation demonstrated how tilt coordination can create convincing illusions of acceleration by tilting a user backward during forward acceleration, effectively mimicking the physical sensation of being pushed back into a seat [57]. This method showed promising effectiveness in applications such as roller coaster simulators and racing games, where brief but intense sensations of acceleration are required to enhance immersion.

- Haptic Feedback: Some VR systems use haptic feedback to simulate the sensations of movement and acceleration. Haptic devices, such as vests or gloves, can apply vibrations or pressure to specific parts of the body in response to virtual motion. While haptic feedback is not capable of fully replicating the forces of acceleration, it can provide subtle cues that enhance the user's sense of immersion. For example, a slight vibration in the chest or arms during acceleration can simulate the feeling of being pushed back into a seat, helping to create a more convincing experience [56] [58].

Each of these methods provides varying levels of realism and immersion, depending on the complexity of the setup and the type of motion being simulated. However, replicating acceleration remains a challenge, as most methods focus on simulating basic movement or providing limited physical feedback without the full range of forces experienced during real-world acceleration.

2.2.4 Driving Simulation

Driving simulators are widely used for various applications, including driver training, research on driving behaviors, and vehicle testing [16] [24]. They provide a safe and controlled environment where users can practice driving skills, experience different road conditions, or test new vehicle designs without the risks associated with real-world driving. Driving simulators are valuable because they allow users to encounter complex or hazardous scenarios—such as adverse weather conditions, sudden obstacles, or mechanical failures—that would be difficult or dangerous to recreate in real life. However, while driving simulators are effective for visual and cognitive aspects of driving, they face significant limitations when it comes to simulating physical acceleration [24] [20]. Unlike real-world driving, where acceleration and deceleration are felt as changes in velocity exerting physical forces on the body, simulators are typically stationary [20]. The challenge lies in replicating the feeling of acceleration. To compensate, most driving simulators use motion platforms that tilt or shift to provide some degree of physical feedback [20] [29] [34], creating the illusion of movement during acceleration, braking, or cornering. However, these platforms have limitations: they can only simulate brief and partial forces [20] [29] [34]. They are unable to replicate the sustained sensations of acceleration, such as the pressing feeling against the seat during rapid speed increases or the forward jolt felt during sudden braking.

Kemeny and Panerai [59] also contributed significant findings to the field with their work on visual-vestibular interaction in driving simulators. They examined how combining both

visual cues and vestibular feedback (physical motion) could enhance a user's perception of acceleration, especially during dynamic driving scenarios like braking and cornering [5]. Their research showed that users are more immersed and exhibit better performance when even subtle physical cues are added to the visual experience, as it reduces the sensory conflict between what is seen and what is physically felt.

2.2.5 Motion Simulation

Motion simulators are similar to driving simulators, except they are designed to replicate the physical sensations of movement, such as acceleration, deceleration, and changes in direction, by creating physical feedback that aligns with virtual or visual experiences. The most advanced motion simulators utilize platforms with multiple degrees of freedom, such as Stewart platforms, which allow the platform to move in six different directions: pitch, roll, yaw, and linear translations [24] [20]. These platforms tilt, rotate, and shift in response to changes in the virtual environment, giving users a more realistic experience of the physical forces associated with movement, such as banking during flight or accelerating in a vehicle. While these simulators provide a much more immersive experience than purely visual systems, they are still limited in their ability to replicate sustained or high-intensity forces due to the physical constraints of the platform, similar to what was mentioned in 2.3 on driving simulators. What mainly limits motion simulators is their inability to sustain the feeling of continuous acceleration. Although they can replicate brief changes in direction or speed, such as the initial jolt of takeoff in an airplane or the sensation of turning a corner in a car, they cannot fully mimic the long-duration forces experienced during real-world movement, such as the sustained acceleration of a vehicle on a highway or the extended forces of a steep climb in a flight [24] [20]. This constraint arises because motion platforms have limited range of movement and must return to a neutral position to continue operating, making it difficult to maintain continuous forces.

Apart from the Stewart platform mentioned in 2.2.3, other research has focused on vibrotactile feedback as a low-cost alternative to motion platforms. In studies by Witmer and Singer [60], vibrotactile devices, such as vibrating chairs or wearable haptic devices, were used to simulate acceleration by providing subtle, localized vibrations to different parts of the body. Although these systems do not replicate acceleration as effectively as motion platforms, they can enhance the user's perception of motion by adding physical feedback to the visual experience. For example, slight vibrations in the seat during acceleration can simulate the feeling of a vehicle's engine revving or the bumps on a road, contributing to a more immersive experience.

Finally, research by Bülthoff conducted research on the psychological effects of motion simulation [61], specifically focusing on how sensory conflict between visual and vestibular inputs impacts user experience. Their work revealed that when the motion cues provided by simulators do not match the expectations set by visual stimuli and cues, users are more likely to experience motion sickness or disorientation [61].

2.3 Just Noticeable Difference (JND) in Motion Perception

The Just Noticeable Difference is a concept from psychophysics that defines the smallest detectable change in a stimulus that can be perceived by a human observer [62]. Understanding the JND is particularly significant in the context of virtual reality, flight simulators, and driving simulators, where a realistic and immersive experience depends on accurately simulating motion to match human perceptual thresholds. Establishing the JND helps developers optimize how acceleration is represented in these systems, ensuring the user perceives changes as they would in the real world, without overcompensating or under-representing motion cues. In the context of this thesis, the application of the JND concept diverges from its traditional use of reducing bandwidth by decreasing resolution on imperceptible details. Instead, the focus here is on determining perceptual thresholds for acceleration changes to optimize the realism and immersion of motion experiences in virtual reality and simulation environments. Understanding JND in this context is helpful because it allows developers to identify the minimum changes in acceleration that users can perceive. By doing so, they can ensure that motion cues in VR or simulator systems are neither excessively exaggerated nor under-represented, striking a balance that enhances realism without unnecessary computational or mechanical complexity. This ensures that users experience changes in motion in a way that feels natural and realistic, avoiding excessive exaggeration or insufficient representation of motion cues that could disrupt immersion or cause sensory conflicts.

In real-world environments, humans rely on a combination of visual, vestibular, and proprioceptive inputs to perceive motion. The vestibular system detects changes in head position and acceleration, while the eyes provide cues through optic flow and the motion of objects in the environment. In simulated/virtual environments, these systems need to work together seamlessly to create a convincing sense of motion. If the acceleration in a VR environment does not align with the user's real-world expectations—either by being too subtle or too exaggerated—the experience can feel unrealistic, leading to a break in immersion and even motion sickness [26] [58]. By determining the JND, developers

and researchers can better understand the thresholds at which users begin to perceive motion changes, allowing them to fine-tune simulations to maintain realism and comfort, in addition to reducing space requirements.

2.3.1 Previous Work on JND in Motion Perception

Previous research has investigated the JND for various forms of motion, rotational movement, and directional changes.

In the field of motion perception, Steinicke et al. [58] conducted a study that examined the JND for rotation and translation in a 360 degree video system. Their research revealed that users were not able to determine differences between physical rotation in the virtual environment and the virtual motion. They concluded a 5.8% lower bound and 9.7% upper bound JND for virtual and physical motion in a local environment.

Another important contribution was made by Pretto et al. [57], who explored the perceptual thresholds for forward tilt acceleration in flying motion simulators. They studied how small tilts could be used to simulate forward acceleration. Although their variability was high across trials, the general wide range of tilts were believable by their participants [57]. They concluded that the majority of participants saw the acceleration as realistic despite it being under vestibular canal thresholds in other reports [57].

Early foundational work by Weber and Fechner established that the JND for a stimulus is generally proportional to the intensity of the stimulus, a concept formalized in Weber's Law. Mathematically, Weber's Law is expressed as:

$$\frac{\Delta I}{I} = k$$

where:

ΔI is the smallest detectable change in the stimulus intensity

I is the baseline intensity of the stimulus

k is the Weber fraction, a constant for a given sensory modality under specific conditions.

In the context of motion perception, Weber's Law suggests that as the magnitude of acceleration increases, a proportionally larger change in acceleration is required for the difference to be perceptible [63]. For instance, detecting a change in acceleration from 0.5 m/s^2 might require a much smaller absolute difference compared to detecting a change

from 2.0 m/s^2. This principle has been extensively applied across sensory domains such as vision (e.g., changes in brightness) [64], hearing (e.g., changes in volume) [65], and touch (e.g., changes in pressure) [66], as well as in motion studies [63].

Finally, research done by Kemeny and Panerai [59] investigated driving simulation on a stewart platform and a large video display. They determined that visual cues played a large impact on the "believability" of the simulation. Accurate perception of speed and distances are largely dependent on a large field of view for visuals. Their JND results reinforced findings from previous research, which established that human sensitivity to changes in acceleration follows predictable patterns. These patterns often align with Weber's Law, which suggests that the detectability of a change is proportional to the initial intensity of the stimulus [58] [57] [59].

2.3.2 The Importance of JND

The concept of Just Noticeable Difference is central to this research because it defines the threshold at which participants can detect changes in linear acceleration [59]. Understanding this threshold is crucial for creating seamless and realistic VR environments that effectively integrate physical motion with virtual cues.

In this study, the JND is particularly significant because it provides a measurable way to determine the smallest acceleration difference that participants can perceive. By focusing on JND, the research aims to identify the boundaries where physical acceleration becomes distinguishable, ensuring that motion cues remain within perceptual limits. This is essential for aligning the physical and virtual experiences in VR, which directly impacts the realism and usability of such systems. For instance, in a driving simulation, a precise understanding of the JND can ensure that braking and acceleration cues feel natural, enhancing both training effectiveness and user satisfaction.

Moreover, the JND serves as a guide for determining the level of physical motion feedback necessary to achieve perceptual alignment with virtual environments. This research incorporates a mobile platform to simulate physical acceleration—a novel approach that directly links JND findings to real-world motion dynamics. By determining how participants perceive these changes, the research addresses key challenges in VR, such as mitigating motion sickness caused by sensory mismatches. Ensuring that acceleration cues remain within the perceptual thresholds defined by JND reduces the likelihood of such issues, improving overall comfort and immersion [57] [61].

JND is also critical for advancing the application of motion studies in VR systems. Previous research has explored JND in controlled environments without physical motion.

This study extends that work by integrating actual physical acceleration, filling a gap in existing knowledge. By focusing on how users perceive changes in acceleration on a moving platform, this research provides insights that can be directly applied to VR systems used in training, entertainment, and rehabilitation. Understanding the JND for acceleration in this context allows developers to fine-tune motion feedback systems, balancing realism and practicality while avoiding unnecessary hardware complexity or over-engineering.

Expanding on these findings, the concept of JND offers a unique opportunity to optimize VR systems for space-constrained environments, particularly in applications where physical motion is incorporated. By leveraging the lower JND bound, designers can significantly reduce the physical footprint of systems like driving simulators, amusement park attractions, and training platforms. This space-saving potential is especially relevant for industries where physical constraints are a primary concern. In urban settings or commercial environments, where space comes at a premium, understanding and applying JND thresholds allows for the creation of immersive VR experiences without requiring large, costly installations. For instance, a driving simulator designed with JND principles could simulate high-speed motion on a compact track, providing a realistic experience that is indistinguishable from larger-scale systems. Moreover, applying JND to space optimization aligns with broader trends in sustainable and efficient design. By minimizing the physical resources required to deliver immersive experiences, this approach not only conserves space but also reduces energy consumption and operational costs. This has implications for industries ranging from professional training to consumer entertainment, where balancing realism, practicality, and efficiency is paramount.

2.3.3 The Role of JND in Virtual Reality and Simulators

In virtual reality and motion simulators, the JND for acceleration plays a vital role in determining how users perceive and interact with motion. If the acceleration in a virtual environment does not fall within the user's JND, it can lead to a sense of disconnect between the visual and physical experiences, breaking the illusion of immersion. For example, if a user is in a VR driving simulation and the virtual car accelerates too quickly or too slowly compared to their real-world expectations, the discrepancy can make the simulation feel artificial or jarring. This not only disrupts immersion but can also induce motion sickness due to the sensory conflict.

Understanding JND allows developers and researchers to strike a balance between realism and comfort by calibrating the motion cues so that they are noticeable enough to feel realistic but not so extreme that they become uncomfortable or disorienting. For instance,

in a flight simulator, slight tilts and shifts can be used to mimic the forces of acceleration and deceleration.

Moreover, JND is crucial for cost efficiency in simulator design. Accurately simulating every possible physical sensation can be expensive and technically challenging, especially when it involves complex motion platforms. However, if developers understand the thresholds at which users begin to perceive motion discrepancies, they can optimize the design to simulate only those changes that fall within the JND. This allows for the development of more accessible, scalable, and cost-effective simulators that still provide a high level of immersion.

Research has also shown that managing JND can help mitigate motion sickness. In a study by Bülthoff et al. [61], it was found that users were less likely to experience discomfort when the motion cues in a virtual environment were fine-tuned to align with the JND. By avoiding abrupt changes that exceeded the user's perceptual threshold, developers could create smoother and more natural transitions in acceleration, which significantly reduced the likelihood of nausea.

Chapter 3

Methods

Chapter 3 provides a comprehensive overview of the University of Waterloo Ethics human factors approved methodologies used to investigate the Just Noticeable Difference (JND) in acceleration perception within a virtual reality environment. This chapter begins by describing the experimental setup, including the go-kart, accelerometer, VR headset, and Unity-based VR environment. It details how these components were integrated to create a seamless testing framework, with a focus on precision and reproducibility. The chapter also explains the rationale for the chosen experimental approach, including the application of the staircase method and statistical tools like the t-test. Additionally, it outlines the participant selection criteria, data collection processes, and data processing techniques, ensuring all aspects of the study align with the research objectives. This structured methodology aims to provide a robust foundation for understanding motion perception thresholds in VR.

3.1 Rationale

3.1.1 Hypothesis and Objective

The core objective of this research is to identify the JND in linear acceleration for users in a virtual reality environment while on a physical moving platform. To do this, we apply a staircase method to systematically adjust acceleration values and determine the point at which participants can detect a difference between physical and virtual acceleration cues [67].

To achieve the core objective, we designed an experimental framework using the staircase method. This method systematically increases or decreases physical acceleration values while maintaining a consistent virtual acceleration within the VR environment. Participants are asked to indicate whether they perceive a difference between the physical motion of the platform and the visual cues presented in VR.

The experiment is conducted in a controlled setting using a custom-built go-kart platform equipped with an accelerometer for precise motion tracking and a VR headset to deliver a consistent virtual experience. The testing procedure begins with a reference acceleration, where participants are exposed to a 1:1 correspondence between physical and virtual acceleration to establish a baseline. From this baseline, the staircase method adjusts physical acceleration values incrementally in either direction. Higher for the upper bound and lower for the lower bound, until participants indicate that they notice a difference from the reference.

Each participant completes multiple runs for both the upper and lower bounds to account for variability and ensure statistical reliability. The data collected includes accelerometer readings, participant responses, and the corresponding physical acceleration values at each staircase step. These are then analyzed using a one-sample t-test to validate the findings and confirm the significance of the observed JND thresholds.

Therefore, the hypothesis for the study is as follows:

- **Null Hypothesis (H_0)**: Participants cannot identify a JND difference between the physical and virtual acceleration.
- **Alternative Hypothesis (H_1)**: There is a significant point at which participants can detect a difference between the physical and virtual acceleration, provided that the change in physical acceleration values exceeds a JND threshold.

If the Null hypothesis is true, it would represent that participants have no point at which they would notice a difference between the visuals and physical acceleration. The JND would be effectively be zero, as participants would either not respond to a change (outlier) or randomly guess.

3.1.2 Statistical Analysis Methods

To analyze the data collected during the experiment, this research employs statistical methods to test the hypotheses and validate the results. Among these, the t-test plays a

central role, as it is well-suited for comparing the means of two related datasets [1] [68] [69] and determining whether the observed differences are statistically significant.

The t-test is particularly appropriate for this study because:

- Small Sample Size: The limited number of participants in the experiment requires a statistical method that performs reliably with small datasets.
- Comparison of Paired Observations: Each participant undergoes multiple trials for both the upper and lower bounds of JND, making the paired t-test the ideal choice for comparing means within the same group of participants.
- Determining Statistical Significance: The t-test allows for rigorous evaluation of whether the observed differences in perception thresholds are significant or simply due to chance, ensuring the validity of the findings.

For both the upper and lower bounds of the JND, the one-sample t-test is used to determine whether there is a statistically significant difference between the upper and lower bounds of acceleration detection for each participant. This comparison is crucial to understanding whether participants are more sensitive to increases or decreases in acceleration.

The following is the process for t-test Implementation [1]

- Data Collection: Acceleration values corresponding to the upper and lower bounds for each participant are recorded during each trial. Multiple trials are conducted for each participant to ensure reliability, and the average of the values is used for analysis.
- Statistical Testing: Using the one-sample t-test, the goal is to determine whether the mean of a sample ($\overline{x}$) significantly differs from a known population mean (μ). The t-statistic is computed using the formula below

$$t = \frac{\overline{x} - \mu}{S/\sqrt{n}}$$

where

t = Calculated t-statistic

$\overline{x}$ = Sample Mean

μ = Assumed Mean

S = Sample Standard Deviation

n = number of samples

To verify the t-statistic, it is compared against the critical t-value derived from the Student's t-distribution, which is based on the degrees of freedom and the significance level (α). A significance level α of 0.05 is used. These critical values can be obtained from t-distribution tables. If the absolute value of the calculated t-statistic ($|t|$) exceeds the critical value, the null hypothesis (H_0) is rejected, indicating a statistically significant difference [70] [71].

Additionally, the p-value is evaluated to assess the strength of the evidence against H_0. The p-value represents the probability of observing a t-statistic as random chance under the assumption that H_0 is true. If $p < \alpha$ the result is considered statistically significant [72].

The t-test offers several advantages that make it particularly well-suited for this research. One of its primary benefits is its ability to precisely analyze differences between paired data, such as the upper and lower bounds of Just Noticeable Difference thresholds for each participant. By focusing on within-participant variability, the paired t-test minimizes the effects of individual differences, ensuring that the observed trends in the data are consistent and not skewed by outliers. This precision is essential in motion perception studies, where individual sensitivity to acceleration can vary significantly.

Another benefit of the t-test is its reliability with small sample sizes, which is often the case in specialized research like this. Since the study involves testing participants with specific criteria—such as experience in driving or VR—the ability of the t-test to yield meaningful results with limited data ensures that the study remains statistically robust.The t-test was originally developed by William Gosset [1] to address scenarios where sample sizes were too small to apply normal distribution methods reliably. It accounts for sample size through the degrees of freedom, ensuring accurate significance testing even with fewer data points.

In this research, the participant pool is inherently constrained by specific criteria—such as prior experience in driving simulators or VR—which naturally limits the sample size. A small sample size can lead to challenges in achieving statistical power with other methods, but the t-test's inherent design minimizes these limitations. By leveraging the Student's t-distribution, it adjusts for variability that is more pronounced in smaller samples, ensuring reliable conclusions without requiring large datasets [73] [74]. Additionally, the

t-test provides clear and interpretable results, such as the p-value, which directly indicates whether the differences observed are statistically significant or could have occurred by chance. These characteristics make it an indispensable tool for validating the hypotheses and providing insights into human motion perception.

The t-test contributes to the generalizability of the study's findings. By confirming statistically significant differences in perception thresholds, the results can be confidently applied to the design and optimization of VR systems and motion simulators. The ability to establish evidence-based guidelines for aligning physical and visual acceleration makes the t-test an invaluable part of the analysis, advancing the understanding of human sensory thresholds and their practical applications[75] [76] [71].

Despite its advantages, the t-test has limitations that need to be carefully considered in this study. One key assumption of the t-test is that the data follows a normal distribution. If the perception threshold data for acceleration does not meet this assumption, the validity of the test results may be compromised.

Another limitation of the t-test is its sensitivity to small sample sizes. Although it is designed to handle limited datasets, very small sample sizes can reduce the test's power, increasing the risk of failing to detect a true difference between the upper and lower bounds. This limitation emphasizes the importance of recruiting an adequate number of participants to ensure that the results are both reliable and representative [75].

Additionally, the t-test is most effective for simple comparisons between two groups or conditions. While this study primarily focuses on comparing the upper and lower bounds of JND, further investigations into subgroups—such as participants with differing VR or driving experience—may require more advanced statistical techniques, such as ANOVA [77] [78] or regression analysis [79] [80], to account for multiple variables simultaneously and smaller sample sizes [1] [81].

3.1.3 Staircase Method

The staircase method is integral to determining the JND in this study. The method is designed to adapt the acceleration values based on participant feedback. We start off by initially increasing the physical acceleration. When participants detect a difference in acceleration, the value is adjusted downward, and when they fail to notice a difference, the acceleration is increased [36]. This is then repeated three (3) times to narrow down the threshold at which the participant begins to perceive the difference.

Following this, we then test for the lower bound of acceleration perception by initially decreasing the physical acceleration. When participants detect a difference, the acceleration

is increased until they fail to distinguish and difference anymore. Once this point is reached, the acceleration is then decreased again. Similar to the upper bound, this procedure is repeated three times. This ensures that both upper and lower bounds of perception are captured through several iterations of acceleration changes [82] [83].

The data collection will occur in multiple phases, with each participant completing multiple trials to ensure that perception thresholds are consistent across different conditions [35] [36]. During each trial, acceleration data will be recorded using an accelerometer, and participant feedback will be noted in real-time to adjust the staircase sequence. The data from the accelerometer, along with participant responses, will be stored in a secure database for post-analysis.

3.1.4 Participant Selection

The participant list is restricted to those with both VR and driving experience to ensure the study's findings are highly relevant to the target applications. This focus is critical because participants with VR experience are likely to be accustomed to virtual environments, potentially influencing their sensitivity to discrepancies between physical and virtual acceleration cues. Similarly, individuals with driving experience may have a heightened awareness of physical acceleration, which could affect their ability to detect changes in motion. By limiting the participant pool to those with relevant experience, the study aims to produce consistent and meaningful results while reducing variability caused by unfamiliarity with either domain. This targeted selection ensures that the data collected reflects the nuances of acceleration perception among those who are most likely to benefit from advancements in VR and motion simulation technology. Additionally, as described in previous sections, we are assuming those with VR and driving experience have a smaller JND thresholds than the general public (Appendix D).

3.2 Equipment

In this study, several key pieces of equipment are used to deliver the necessary experimental conditions, provide accurate data collection, and simulate the virtual reality environment for participants. This section provides a detailed description of the Go-Kart used to simulate physical acceleration, the accelerometer employed to measure the real-time acceleration data, and the Oculus Rift VR headset used to immerse participants in the virtual environment.

3.2.1 Go-Kart

The primary vehicle for simulating real-world acceleration in this experiment is a custom-built 4-wheel Go-Kart developed by the University of Waterloo Ideas Clinic (Figure 3.1). The Go-Kart provided all of the needed equipment and access for a tailored, autonomous solution that met the project's low-speed requirements and could be fully integrated with the VR and data collection systems.

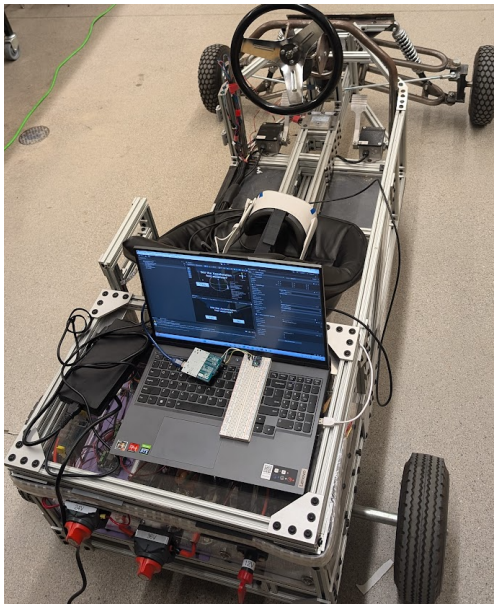


Figure 3.1: University of Waterloo Ideas Clinic Go-Kart

Technical Specifications of the Go-Kart

DC motor: The Go-Kart is powered by a 36V 3000 RPM DC Brushless motor connected to a rear-wheel-drive system, providing consistent and controllable acceleration.

Rear-wheel drive: The Go-Kart's DC motor powers the rear wheels via a 6:1 sprocket reduction mechanism, allowing for smooth, consistent acceleration during the trials.

Maximum speed: The Go-Kart is limited to a maximum speed of 2 m/s, ensuring safety and control during the experiment. This speed cap is in line with approvals from the University of Waterloo Safety and Ethics Boards (See Appendix A and C for documents), ensuring the vehicle's compliance with low-speed testing standards.

The Go-Kart is equipped with an Arduino UNO based autonomous control system, which removes the need for manual steering or pedal inputs. The system is pre-programmed to manage the Go-Kart's acceleration, deceleration, and stopping phases, ensuring consistent movement across all trials. Communication between the Arduino and the VR environment allows for precise synchronization of the physical motion and the visual stimuli participants experience, which is critical for maintaining experimental consistency.

The kart is equipped with a reinforced frame, safety harnesses, and an emergency stop feature, ensuring participant safety during all trials. Emergency stop protocols allow for immediate cessation of all motion if necessary, ensuring that participants are not exposed to unexpected risks.

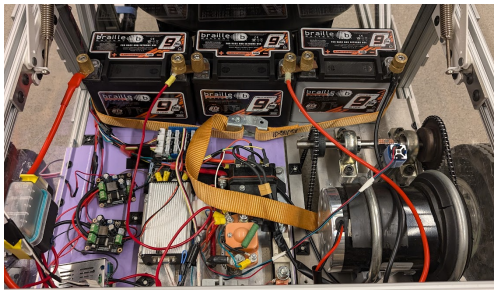


Figure 3.2: Go Kart Electronics

3.2.2 Arduino UNO R4 Minima

The Arduino UNO R4 Minima features an ARM Cortex-M4 processor, which provides a significant performance boost compared to previous Arduino models. This processor allows for faster computation and more complex control algorithms, ensuring that the Go-Kart's movements are precisely timed and synchronized with the VR environment. The board operates at 48 MHz, providing a good balance between power efficiency and processing speed, which is essential for real-time control of the Go-Kart.

The board includes 256 KB of flash memory and 32 KB of RAM, which is more than sufficient for the storage and execution of the control algorithms used in this experiment. Additionally, it supports both analog and digital inputs, making it versatile for sensor integration, including the accelerometer used to measure the Go-Kart's motion. The serial communication capabilities of the Arduino UNO R4 Minima allow for real-time data transfer between the Go-Kart and the Unity environment, ensuring that all motion commands are executed precisely.

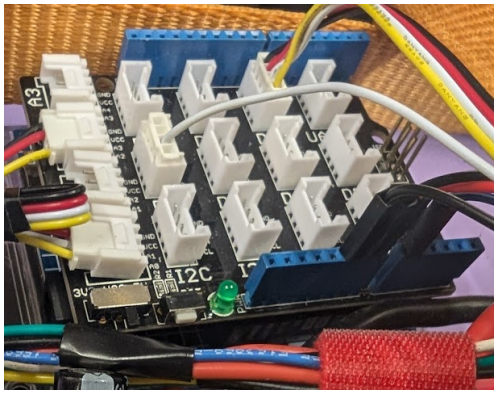


Figure 3.3: Arduino UNO R4 Minima with I2C Shield

3.2.3 Accelerometer (MPU 6050)

To accurately capture real-time data on the Go-Kart's motion, a MPU 6050 accelerometer is used. This accelerometer measures linear acceleration and is integral to tracking the Go-Kart during each test.

The MPU 6050 is a 6-axis accelerometer and gyroscope capable of detecting both linear acceleration and angular velocity across three axes. In this study, it is primarily used for measuring linear acceleration in the direction of the Go-Kart's motion. The accelerometer provides precise data, allowing for the detection of small changes in acceleration, which are critical when determining the upper and lower bounds of a participant's ability to perceive differences in acceleration. The accelerometer is connected to the Arduino microcontroller, allowing for real-time transmission of acceleration data. Updates are sent to the Unity Environment at a baud rate of 115200

The accelerometer is calibrated at the beginning of each session to ensure consistent readings across different participants. Given that participants' weight may affect the Go-Kart's behavior, the accelerometer ensures that the final data is normalized across trials. The accelerometer data will be used to create a ratio of the upper and lower bound acceleration versus perceived 1:1 acceleration, which will be analyzed in Chapter 4. This ratio helps quantify the relationship between the physical changes experienced by participants and their subjective perception of these changes.



Figure 3.4: MPU6050 Accelerometer

3.2.4 Virtual Reality Headset (Oculus Rift)

The visual component of the experiment is delivered through an Oculus Rift VR headset, chosen for its immersive capabilities and ability to provide high-quality visual cues that complement the Go-Kart's physical motion. The Oculus Rift allows participants to experience a pre-rendered virtual environment, synchronized with the physical acceleration of the Go-Kart.



Figure 3.5: Oculus Rift VR Headset

The Oculus Rift operates at 90Hz, reducing the latency of the virtual environment. This high refresh rate is critical for maintaining the immersive quality of the VR experience and for reducing motion sickness, which can occur when visual inputs are not smooth. The headset offers a 110-degree field of view, providing participants with a wide visual range in the virtual environment. The Oculus Rift is connected via a wired interface to the control

system. This ensures stable video playback and eliminates potential tracking issues caused by wireless latency. However, it should be noted that while the Oculus Rift typically uses base-station and camera tracking, tracking is disabled in this experiment because the Go-Kart's large-scale movement exceeds the system's tracking capabilities.



Figure 3.6: VR Headset with tape on the sensors (blue electrical tape)

VR Environment

The VR experience is built using the Unity Game Engine and presented as a 360-degree video. The virtual environment simulates a cartoon street with various objects and landmarks (e.g., cars, buildings, stop signs) to provide visual references that enhance the participant's perception of motion (Figure 3.7). The VR environment movement is timed with the Go-Kart's motion, ensuring that participants don't experience any disjoint between visual and physical stimuli. We will expand more on this in Section 4.2.3. This synchronization is done through high-speed serial communication between Unity and the Arduino, and is essential for studying how participants perceive acceleration in a VR environment compared to their real-world experience.

The Oculus Rift's visual output is crucial for ensuring that participants remain engaged and can compare the visual motion with the actual physical acceleration of the Go-Kart. The headset delivers high-quality, immersive visuals that make it easier for participants to assess whether they perceive any discrepancies between the physical and virtual acceleration. The smooth rendering and high frame rate minimize the chances of motion sickness and ensure that participants can focus on the task without distraction.

However, due to limitations with the go-kart, there weight affects present. This led to to variability in acceleration, where some participants would experience faster or slower



Figure 3.7: VR Environment from Stereoscopic 3D Perspective

acceleration. To mitigate this, all participants were given a reference run in the VR environment and told that what they saw/felt is the reference acceleration. Through this, users are able to scale their perception of the virtual environment to one that matches the perceived physical acceleration. If the participant felt that the acceleration was faster than the visuals, then they were told to scale their perspective such that the buildings virtual environment are smaller relative to their size, thus they would move faster through the environment. The same is true if the participant felt the acceleration slower than the visuals. The users would see that the scale of everything is larger as they drive past it.

3.3 Virtual Reality Visuals

In this experiment, participants' perception of motion is heavily reliant on the visual cues provided by the Oculus Rift VR headset. As discussed in previous chapters, the synchronization between visual and physical motion is crucial for maintaining immersion in virtual reality. Due to the specific conditions of this study—where participants experience physical movement in a Go-Kart—the standard motion tracking systems used in VR are disabled. Instead, the experiment relies on a pre-rendered 360-degree video to create a cohesive virtual environment in which participants experience the sensation of moving through a virtual street.

Visual perception is central to maintaining immersion in VR environments. Although motion tracking is disabled, the pre-rendered 360-degree video continues to show the participant "driving" through a cartoon street, providing a consistent visual experience that matches the movement of the Go-Kart. As participants move forward in the Go-Kart, the video replicates the experience of moving through a virtual world, with objects like cars, buildings, and trees passing by as if they were driving through a real street (Figure 3.7).

This visual experience is crucial for allowing participants to focus on the differences between the visual and physical acceleration. The head movements are still tracked with

an internal gyroscope inside the Oculus, that, paired with the wide 110-degree field of view provided by the Oculus Rift ensures that participants have a natural visual experience, similar to looking around while driving. This helps participants stay engaged with the environment and enhances their ability to detect discrepancies between the physical motion of the Go-Kart and the virtual world displayed in the VR headset.

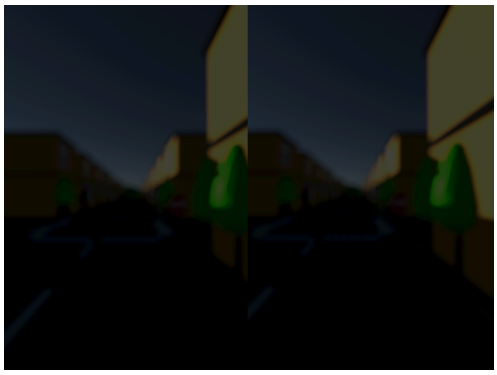


Figure 3.8: Split Screen VR Perspective

3.4 General Procedure

The general procedure for this experiment consists of recruiting participants, preparing them for the VR and Go-Kart experience, conducting the experiment using the adaptive staircase method to measure perception thresholds, and collecting data on participants' motion perception and subjective experiences. The following sections detail each step in the procedure, ensuring consistency and reliability across all trials.

3.4.1 Human Studies Ethics

Prior to any recruitment, the Go-Kart and procedure received extensive ethics protocol evaluation and safety clearance from the University of Waterloo. The entire ethics protocol (#45573) can be seen in Appendix B. The complete Safety Operating Procedure (SOP), and safety officer clearance was also done during this time. The SOP, which details testing procedure, on/off procedure, safety points of error, and more was written with assistance from the Ideas Clinic Go-Kart team, it is attached in Appendix A. Finally, the full safety clearance and signed document from the University of Waterloo Safety Office is included in Appendix C.

3.4.2 Recruitment and Preparation

Participants are recruited from the University of Waterloo, specifically targeting individuals with prior experience in VR or driving simulations. This is done through an ethics-approved information letter sent via email to potential participants, which includes the following:

- A detailed explanation of the experimental procedure.
- Inclusion/exclusion criteria (e.g., individuals with implants or vestibular impairments are excluded).
- Risks and benefits of participating in the study.

Interested participants who meet the criteria are scheduled for their experimental session. Prior to beginning, they are asked to wear comfortable clothing, as the Go-Kart experience involves sitting for a prolonged period. Upon arrival, participants complete a consent form and a pretest data collection form (The full questions can be found in Appendix D). The following data is gathered:

- **VR usage history**: Frequency and familiarity with VR systems.
- **Driving experience**: Level of familiarity with driving or driving simulators.
- **Medical information**: Any relevant medical conditions (e.g., vestibular impairments, implants) that might affect the participant's ability to perceive motion.

The participants are then prepared for the experiment, by sitting into the go-kart, and placing on the VR Headset (Figure 3.9).

3.4.3 Overview of the VR Environment

The virtual environment for this experiment is created using the Unity Game Engine and presented to participants via the Oculus Rift headset. The environment consists of a simplified, cartoon-style street with visual elements such as cars, buildings, stop signs, bushes, and trees, providing clear visual references for participants to gauge speed and motion. These elements are essential for establishing scale and simulating a realistic motion experience as the Go-Kart accelerates.



Figure 3.9: Participant in the Go Kart with VR Headset on

The experiment uses a pre-rendered 360-degree video that is synchronized with the physical motion of the Go-Kart. When the vehicle starts to move, the video starts, and ends when the Go-Kart comes to a stop. The video is structured in a way that directs participants' focus to the most critical phase of the experiment: the period of linear acceleration. The goal is to measure how participants perceive this steady acceleration while minimizing distractions from other phases of movement, such as the initial jerk during acceleration or the deceleration at the end of the run.

The video sequence is structured as follows:

1. Initial Acceleration (Dimmed): The first second of the video is dimmed to reduce distractions caused by the initial jerk as the Go-Kart accelerates from rest. This phase is not the focus of the research, and the dimming helps participants to disregard this transitional phase. Once the video brightens, they can focus fully on the primary motion (Figure 3.11).

2. Full Acceleration (Brightened): After the initial dimming, the video brightens and remains illuminated for the next six seconds, during which the Go-Kart accelerates

forward in a linear path. This is the central focus of the experiment. During this phase, participants experience the Go-Kart's linear acceleration with the visual representation of movement through the virtual street. The visual cues, such as moving buildings and trees, are designed to give participants a clear perception of forward acceleration (Figure 3.10).

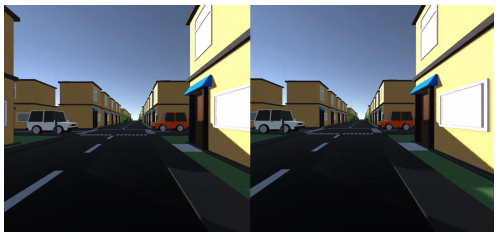


Figure 3.10: Full Acceleration VR View

3. Deceleration (Dimmed): The final two seconds of the video dim again as the Go-Kart decelerates to a stop. Like the initial acceleration, this phase is not relevant to the research's focus, which is why the dimming minimizes any distractions that might arise from deceleration (Figure 3.11).

4. Staircase Question: Following the stop of the vehicle the video is stopped and the participant is prompted with a yes or no adaptive staircase question. This portion of the experiment is where participants are asked to detect differences between the visual and physical acceleration (Figure 3.12).



Figure 3.11: Dimmed VR Environment in Stereoscopic 3D View

Dimming the video during the initial acceleration and deceleration phases helps minimize distractions such as the jerk caused by rapid changes in speed. Since these phases are not the focus of the research, they are deliberately de-emphasized. This approach ensures that the collected data reflects the participants' perception of motion under consistent

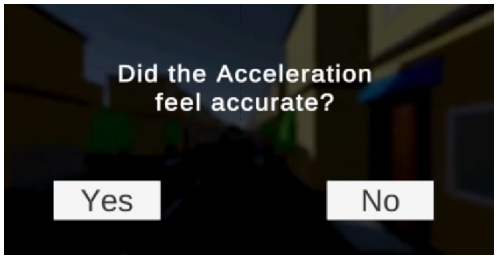


Figure 3.12: Staircase Question as asked on the VR Headset

and controlled conditions, allowing for a more accurate analysis of their ability to detect differences between physical and visual acceleration.

3.4.4 Staircase Method

The adaptive staircase method is the primary technique used in this study to measure participants' ability to perceive differences between physical and visual acceleration. This method allows researchers to efficiently determine the thresholds where participants detect changes in the alignment of the physical acceleration of the Go-Kart and the visual acceleration presented in the VR environment. By adjusting the Go-Kart's acceleration based on participants' responses, the staircase method hones in on the Just Noticeable Difference for acceleration perception, providing valuable insights into the perception of motion in virtual environments.

The use of the adaptive staircase method ensures efficient, precise measurement while minimizing the number of trials needed to reach accurate conclusions [23] [36] [84] [85]. The purpose of the staircase method in this experiment is twofold:

1. To determine the upper bound at which participants can no longer perceive a match between the physical acceleration of the Go-Kart and the visual acceleration in the VR environment.

2. To determine the lower bound at which participants begin to detect a mismatch between the physical deceleration and the visual cues presented.

Both the upper and lower bounds are measured using incremental adjustments to the Go-Kart's acceleration, providing a detailed understanding of participants' sensitivity to acceleration changes.

In this study, the Pulse Width Modulation (PWM) step size for adjusting the Go-Kart's acceleration is set at 0.05, with a PWM initial starting acceleration value of 0.5. These values are transmitted to the Go-Kart's motor as PWM signals, ranging from a minimum value of 0 to a maximum of 255. This range provides precise control over the motor's acceleration, enabling incremental adjustments necessary for the staircase method. However, the effectiveness of these adjustments can vary significantly across participants due to differences in weight, which inherently affect the Go-Kart's ability to accelerate. Participants with a higher body weight may cause the Go-Kart to accelerate more slowly compared to lighter participants, resulting in a potential disparity in how acceleration is perceived.

To address this, each participant is instructed to calibrate their perception to an initial reference acceleration run. This baseline run is designed to familiarize participants with the standard acceleration that will be used as a comparative benchmark throughout the study. By aligning their perception with this reference, participants can scale their responses relative to their unique experience of the Go-Kart's motion, mitigating the effects of weight differences on perceived acceleration. As the visuals for the experiment remain a constant, a participant with a lighter body weight would feel faster acceleration, leading to them to scale the visuals to to match that acceleration (by scaling the buildings to be smaller relative to their visual size, see Section 3.2.4).

Additionally, all acceleration data collected during the study is normalized during post-processing to account for the weight shifts mentioned in earlier sections. This involves using accelerometer readings to adjust the base acceleration, as well as the upper and lower JND bounds, ensuring that individual variations are accounted for. By normalizing the data in this way, the study ensures consistency across participants, allowing for meaningful comparisons of JND thresholds despite the inherent variability introduced by factors such as weight. This method not only ensures accurate measurements of perception thresholds but also enhances the reliability of the findings by minimizing the impact of external variables. This rigorous approach provides confidence that the observed JND values are representative of true perceptual thresholds, irrespective of individual differences.

The first step in the adaptive staircase method is to establish the upper bound of perception—this refers to the maximum level of acceleration at which participants can still perceive the motion as synchronized between the Go-Kart and the VR environment. The procedure is outlined below:

1. Baseline Setup: The Go-Kart starts at a baseline acceleration that is initially perceived by the participant as perfectly synchronized with the visual cues in the VR environment.

2. Incremental Increases: The Go-Kart's acceleration is gradually increased by a small PWM increment +0.05 after each trial. Following each increase, participants are asked whether they notice a difference between the Go-Kart's physical acceleration and the visual cues in the virtual environment.

3. Participant Response: If the participant reports no difference between the physical and visual acceleration, the experiment proceeds with another incremental increase. This process continues until the participant reports detecting a difference, indicating that the physical motion no longer feels synchronized with the virtual experience.

4. Staircase Reversal: Once the participant reports a difference, the direction of the staircase is reversed. The Go-Kart's acceleration is then decreased in small increments, and the participant is again asked whether they perceive the physical and virtual acceleration as synchronized. The goal is to reduce the acceleration until the participant reports that the two are once again aligned.

5. Repetition: This cycle of increasing and decreasing acceleration is repeated three times to ensure consistency in the data. For a total of three upper bounds where the acceleration is noticed by the participant, and 3 bounds where the acceleration is "aligned" with the visual reference.

The upper bound refers to the maximum level of physical acceleration at which participants still perceive synchronization between the physical and virtual motion. Beyond this point, participants begin to notice a difference, indicating the breakdown of the illusion of perfectly synchronized motion.

Once the upper bound has been established, the next step is to determine the lower bound of perception, which refers to the minimum level of acceleration at which participants begin to detect a mismatch between physical deceleration and the visual cues. The procedure for determining the lower bound is as follows:

1. Baseline Setup: The Go-Kart again starts at the baseline acceleration, which is perceived as synchronized with the visual motion.

2. Incremental Decreases: The Go-Kart's acceleration is then decreased in small steps by a PWM value of -0.05 after each trial. Participants are asked to report when they begin to perceive a mismatch between the physical deceleration of the Go-Kart and the visual deceleration shown in the VR environment.

3. Participant Response: As with the upper bound, if the participant perceives no difference between physical and visual deceleration, the experiment proceeds with further reductions in acceleration. Once the participant detects a difference, the direction of the staircase is reversed.

4. Staircase Reversal: After the participant detects a difference, the acceleration is gradually increased in small steps until the participant reports that the physical and virtual deceleration are once again perceived as synchronized.

5. Repetition: As with the upper bound, this process of decreasing and increasing acceleration is repeated three times to ensure reliable and consistent lower bound data.

The lower bound represents the minimum level of physical deceleration at which participants detect a mismatch between the real-world motion of the Go-Kart and the visual deceleration in the VR environment.

To ensure the robustness and reliability of the collected data, the entire adaptive staircase method (upper and lower bound determination) is conducted twice for each participant. This results in the following sequence:

- Three upper bound trials (with incremental increases and reversals).
- Three lower bound trials (with incremental decreases and reversals).
- A second round of three upper bound trials followed by three lower bound trials.

Upon conclusion of the testing, the participant would have recorded six (6) upper and six (6) lower bounds where the acceleration is noticed to be disjointed from the visual reference.

This repetition is crucial for reducing variability in participants' responses, ensuring that outliers or inconsistent reports do not skew the data. Running the staircase method twice also provides a more reliable estimate of each participant's true perception threshold, as it accounts for potential shifts in sensitivity due to learning effects or fatigue [23] [36] [84]. Repetition improves the accuracy of the final results by capturing a broader range of responses and providing greater confidence in the average thresholds.

The adaptive staircase method is particularly well-suited for this study due to its efficiency in identifying sensory thresholds. The method adapts dynamically to the participant's responses, allowing the system to focus on the exact point where the participant

begins to perceive changes in acceleration. Unlike fixed-step psychophysical methods, the staircase method requires fewer trials to achieve a precise estimate of the perception threshold [85].

In this study, the null hypothesis is that participants cannot distinguish a JND between physical and visual acceleration. The staircase method is used to test this hypothesis by gradually increasing or decreasing the physical acceleration and determining whether there is a point at which participants can detect a difference. The null hypothesis will be rejected if a statistically significant difference between an upper and lower physical and visual acceleration perception bound is detected. In other words, the null hypothesis is looking for JND = 0. This is because if the participants are randomly guessing on their staircase responses, then the average would equal zero. Furthermore, those who hit the maximum or minimum value of acceleration are considered outliers.

After completing the adaptive staircase method, the following data is collected:

- Upper Bound Acceleration: The maximum acceleration at which the participant still perceives synchronization between physical and visual motion.
- Lower Bound Acceleration: The minimum acceleration at which the participant begins to detect a mismatch between physical and virtual motion.
- Just Noticeable Difference: The difference between the upper and lower bounds, representing the smallest change in acceleration that the participant can reliably detect.

This data will be analyzed to determine the average upper and lower bounds of perception across all participants. The results will provide insight into human sensitivity to motion in VR environments and contribute to the broader understanding of motion perception thresholds.

3.4.5 Post-Test Data Collection

After each participant completes their testing, a post-test questionnaire is completed to collect to gather additional insights into their subjective experiences and their perceptions of the motion they experienced. This post-test data is essential for providing context to the objective measurements of acceleration perception and understanding how participants interacted with the visual and physical elements of the experiment. For the full post-test questionnaire, see Appendix E.

Motion Sickness Symptoms

Motion sickness, often referred to as simulator sickness in VR settings, is a prevalent issue that arises when there is a mismatch between visual and physical motion or when acceleration changes occur abruptly or are sustained for long periods. To better understand its impact within this investigation, participants are asked to report any symptoms of motion sickness they experienced during the experiment.

Participants are specifically asked to rate the intensity of symptoms such as:

- Sick to Stomach
- Queasy
- Nauseated
- Upset Stomach
- Stomach Ache
- Dizzy
- Spinning
- Faint-Like
- Lightheaded
- Blurry Vision
- Head Rush
- Disoriented
- Sweaty
- Cold Sweat
- Hot/Warm
- Annoyed/Irritated
- Tired/Fatigued

- Uneasy
- No Symptoms N/A
- Other

Visual Influence on Acceleration Perception

Participants are asked to evaluate how much the visual elements in the VR environment influenced their perception of the Go-Kart's acceleration. The goal of this evaluation is to understand the extent to which participants relied on the visual cues provided in the VR environment to assess changes in motion.

Participants are asked to rate their experience on how much did the visuals affect their acceleration perception? a scale of 1 to 10, where:

- 1 represents minimal influence of visual cues on their perception of acceleration.
- 10 represents a strong reliance on visual cues for detecting acceleration changes.

Perceived Fun and Realism

Participants are also asked to rate their overall enjoyment of the experiment, as well as the perceived realism of the virtual environment. These subjective measures are important for assessing the quality of the VR experience and its engagement factor, both of which can impact participants' focus and performance during the trials.

Participants are asked to rate their experience on a scale of 1 to 10 for both fun and realism:

- 1 represents a low level of enjoyment or realism.
- 10 represents a high level of enjoyment or realism.

Specific questions include:

- Please scale how immersive the experience is on a scale of 1 to 10
- Please scale how realistic the acceleration felt on a scale of 1 to 10
- Please scale how much fun you had on a scale of 1 to 10

Final Data Overview

At the end of the experiment, the following data points are collected for analysis:

1. Objective data: Upper and lower bound acceleration measurements from the arduino.
2. Accelerometer data: Recorded acceleration values for each trial, including baseline, upper bound, and lower bound measurements.
3. Subjective feedback: Participant responses related to motion sickness, visual influence, perceived fun, and realism.

This combined dataset provides a comprehensive view of each participant's experience. The data collected will be used to find the average Just Noticeable Difference values from the adaptive staircase method.

Chapter 4

Results

The primary objective of this study is to determine the Just Noticeable Difference (JND) in linear acceleration perception within a moving VR environment. The key metrics analyzed include the upper and lower bounds of JND for acceleration, calculated using participant responses, accelerometer readings, and motor control data. To ensure statistical reliability, a one-sample T-test was applied to assess the significance of the observed differences. The data underwent a series of filtering and normalization processes to account for noise, participant weight differences, and limitations in sensor accuracy. This chapter presents the results of the study, supported by statistical analyses and visual representations.

4.1 Data Summary

4.1.1 Participant Overview

A total of 20 participants experienced with VR or driving were involved in the study. Of these participants:

- 12 individuals (60%) had prior experience using VR devices, such as headsets or simulation platforms.
- 15 individuals (75%) had prior driving experience, ranging from regular automobile usage to professional driving simulations.

The inclusion of participants with predetermined criteria of VR and driving experience was intentional as we assumed that those with more experience will have smaller JND thresholds than those without experience. This provides us with a more concentrated and targeted dataset to investigate correlations between experience and detection thresholds for linear acceleration.

4.1.2 Collected Data

The data collected during the experiment can be categorized into three primary types:

1. **Raw PWM Data**
   The pulse-width modulation (PWM) signals from the motor controller were recorded to document changes in physical acceleration during the staircase method trials. These signals, collected in an open-loop system, allowed us to precisely identify when transitions between different acceleration levels occurred. In this configuration, the system did not adjust based on feedback but instead followed predefined acceleration steps, ensuring consistency in the experimental setup. The recorded PWM signals also served as a critical reference for aligning participant responses with the corresponding physical acceleration levels.

2. **Raw Accelerometer Data**
   The MPU6050 sensor recorded linear acceleration during each trial, providing the ground truth measurement of the actual acceleration experienced by the participants. This data served as the primary measure for quantifying the actual acceleration experienced by the participants due to our open loop approach. However, due to the sensor's limitations, this data required extensive processing and is not very reliable. Therefore, we are only using steady state acceleration values which we will go into detail later on.

3. **Participant Response Data**
   During each trial, participants were asked to indicate when they detected changes in acceleration through the user interface in the VR headset (see Figure 3.12). These responses were recorded alongside the corresponding physical acceleration levels to identify JND thresholds. The data was crucial for correlating subjective perceptions with objective measurements.

4.1.3 Raw Data Observations

The raw data collected presented both opportunities and challenges:

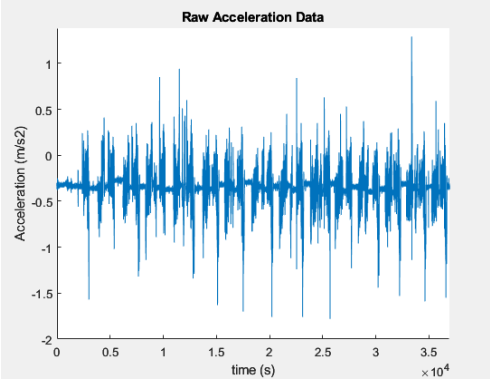


Figure 4.1: Accelerometer Ground Truth Data

- **PWM Data Observations**
  The PWM signals exhibited clear and consistent transitions corresponding to the staircase adjustments, making these transitions relatively straightforward to detect and align with participant responses. However, occasional delays were noted between the PWM signal changes and participant acknowledgment, likely due to individual reaction times. Additionally, the open-loop nature of the system introduces potential points of error, such as nonlinear effects in the motor's response to PWM signals, slippage between the Go-Kart's wheels and the ground, variations in friction, and other mechanical inconsistencies. These factors could lead to slight discrepancies between the expected and actual accelerations, emphasizing the importance of processing accelerometer data to account for these variations.

- **Accelerometer Data Observations** While the MPU6050 accelerometer provided a continuous stream of linear acceleration data, its performance declined over prolonged periods due to:

  - Sensor Drift: A gradual deviation in baseline readings over time.
  - Noise: High-frequency fluctuations in the data, particularly during rapid changes in acceleration.
  - Sensitivity Limitations: Reduced accuracy when measuring subtle variations in acceleration.

The sensor drift is a gradual decrease in the baseline readings over time, at a rate of around 0.001 every minute [86]. The noise was present every time there was a significant change in acceleration (such as acceleration from standstill), and sensitivity limitation was due to hardware limitations. For precise accuracy at low accelerations, we would have needed more expensive accelerometers [87]. These issues required extensive filtering and calibration to extract meaningful results. Despite this, the accelerometer data provided valuable insights into the actual ground truth acceleration experienced during the trials (Figure 4.1).

4.2 Data Processing

The data processing phase of this study was crucial to ensure the accuracy and reliability of the collected data, given the inherent challenges presented by the experimental setup and the limitations of the equipment used. Each type of data from PWM signals, accelerometer readings, and participant responses—required careful handling and analysis to produce meaningful results.

4.2.1 Accelerometer Data Processing

The accelerometer data, being the primary measure of physical acceleration, required significant preprocessing to address the noise and inaccuracies inherent in the MPU6050 sensor. The following steps were undertaken to refine the data:

1. Low Pass Filtering
   A low pass filter was applied to smooth high-frequency noise in the raw accelerometer data. This was particularly important for eliminating artifacts introduced by vibrations from the go-kart or the environment, as well as the initial jerk in acceleration when starting from standstill. Additionally, the filter effectively mitigated impulses generated when the go-kart returned to the starting position. Since this study focuses solely on steady-state acceleration values, the phase lag introduced by the low pass filter does not impact the results, ensuring that the processed data remains accurate and reliable for analysis.

   The low pass filter used can be seen in the equation below (Using Frequency Domain Analysis)

$$H(j\omega) = \frac{1}{1 + j\omega\tau}$$

where

$\omega = 2\pi f$ is the angular frequency

τ = Time constraint of the filter, defined by $\tau = \frac{1}{2\pi f_c}$, where

f_c = Cutoff frequency

2. Threshold Filters
   Threshold filters were implemented to identify key points in the data where changes in acceleration corresponded to the staircase adjustments made during the trials. This ensured that only the relevant segments of the data were analyzed, reducing the risk of including spurious readings. The ultimate purpose is to isolate the steady state values.

   The threshold filter equation used is shown below.

$$x_o(t) = \begin{cases} x(t) & \text{if} \quad |x(t)| \leq T \\ 0 & \text{otherwise} \end{cases}$$

   where

   $x_o(t)$ = The filtered output

   $x(t)$ = Input accelerometer data at time t

   T = Cutoff threshold value

3. Offset Adjustments
   Baseline drift, a common issue with the MPU6050 sensor over prolonged use, was corrected by recalibrating the sensor data at regular intervals. This adjustment ensured that the reported acceleration values remained consistent across trials and participants.

4. Normalization
   To account for individual differences in baseline acceleration due to weight variations, the data was normalized against the starting acceleration value for each participant. This allowed for a fair comparison of results across all participants. Participants were explicitly informed during the experiment that their first acceleration run would serve as their baseline reference. The participants are then told to scale their perception of the virtual environment to alight with there reference acceleration. This step helped

participants anchor their judgments to a consistent baseline, minimizing variability in their perception of scale and motion across different trials. The equation to then normalize all of the acceleration runs is described under the weight factor section.

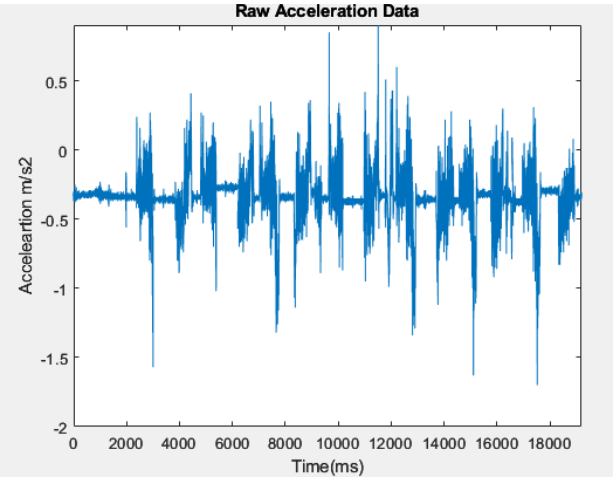


Figure 4.2: Raw Acceleration Data

4.2.2 PWM Data Processing

The PWM signals recorded during the experiment represented the physical adjustments to the go-kart's electric motor acceleration levels. To extract meaningful information, a simple detection algorithm was used to identify the exact moments when changes in acceleration occurred

- Impulse Removal
  Occasionally there would be impulses in the measured PWM signal that could affect the detection algorithm. This was removed with a smoothing filter that would remove impulses from the square signal.

$$x_o(t) = \begin{cases} x(t) & \text{if} \quad |x(t)| \leq T \\ 0 & \text{otherwise} \end{cases}$$

- Transition Points
  The algorithm detected transitions between PWM levels, marking the points where

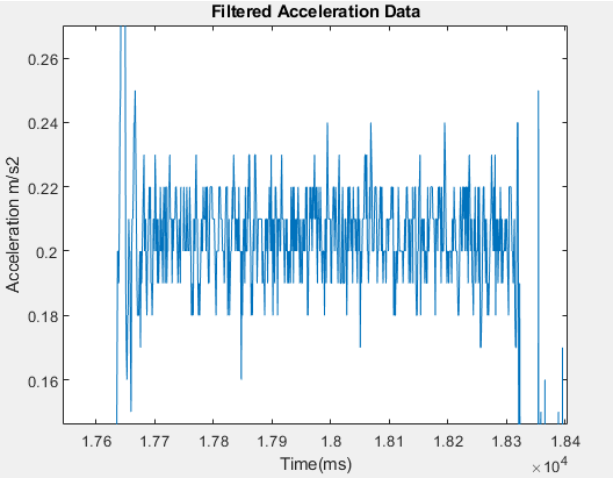


Figure 4.3: Filtered Acceleration Data (zoomed in on steady state)

the go-kart either increased or decreased its acceleration. This was done with MATLAB to detect when there was a change in the steady state PWM values.

4.2.3 Weight Factor

Participant weight had a significant impact on the go-kart's acceleration performance. This is a limitation for this experiment as the car's acceleration and speed would be affected by the participant's weight. This limitation is because of our usage of an open loop PWM. The data is then verified with the ground truth accelerometer. This difference in acceleration can be seen in Figure 4.13 and Figure 4.14. In general, the difference in base accelerations due to weight ranged from $0.011m/s^2$ to $0.05m/s^2$. To ensure consistency in the results, a weight-normalized factor was applied to the accelerometer data. The upper and lower acceleration values are used to calculate this factor with reference to the base acceleration because the participants were told to consider the virtual acceleration to be accurate. By applying this normalization, the study was able to adjust the raw acceleration data to a standard baseline, enabling comparisons across participants of varying weights.

In addition to normalizing the accelerometer data, the processed acceleration data was synchronized with the staircase switch points identified in the PWM signals. This synchronization ensured that the calculated JND thresholds accurately corresponded to the physical acceleration experienced by each participant during their trials. These adjustments were essential as we needed to assign ground truth accelerations to the open loop

PWM values, as they are affected by weight.

For the Upper Bound JND, we calculated the n_p as

$$n_p = 1 + (\frac{u}{b} - 1)(\frac{P_j - P_b}{P_u - P_b})$$

where

n_p = Normalized Upper JND

P_b = PWM Baseline

P_u = PWM Upper Bound JND

P_j = PWM Upper Bound JND Average

b = Baseline Accelerometer Acceleration (m/s^2)

u = Upper Bound Accelerometer Acceleration (m/s^2)

For the Lower Bound JND Calculations, we calculated n_d as

$$n_l = 1 - (1 - \frac{l}{b})(\frac{P_b - P_k}{P_n - P_l})$$

where

n_l = Normalized Lower JND

P_b = PWM Baseline

P_l = PWM Lower Bound JND

P_k = PWM Lower Bound JND Average

b = Baseline Accelerometer Acceleration (m/s^2)

l = Lower Bound Accelerometer Acceleration (m/s^2)

4.2.4 Challenges Encountered

Several challenges emerged during the data processing phase, primarily due to equipment limitations and the nature of the experimental setup. One significant issue was the limited sensitivity of the MPU6050 accelerometer in detecting subtle changes in low acceleration. While adequate for general motion sensing, the sensor struggled to register fine variations required for precise JND detection, especially at the lower bounds of acceleration. Addressing this limitation would have necessitated a much higher-end accelerometer, which was not feasible given budgetary constraints. Compounding this issue was the limited speed of the go-kart itself, with a maximum velocity of 1.5 m/s. This speed, comparable to an average walking pace, limited the range of accelerations that could be tested, potentially narrowing the scope of the findings.

Another challenge involved the jerk impulses generated when the go-kart accelerated from a stationary position. These impulses, while brief, created artifacts in the data that resulted in messy data, and required multiple algorithms before they could be filtered out. These jerks also posed potential distractions for participants, which may have affected their responses during the initial phases of a trial. Despite efforts to mitigate these effects through video dimming (see Section 3.4.3), the jerk impulses remained a source of variability in the results.

4.3 Just Noticeable Difference Results

The results of the experiment provide valuable insights into the Just Noticeable Difference thresholds for linear acceleration perception in a moving VR environment. These findings are presented in terms of upper and lower bounds, along with a statistical analysis to validate their reliability.

4.3.1 t-Test Analysis

The analysis of the JND thresholds for linear acceleration relied on a t-test to validate the results. This method was recommended by the University of Waterloo Statistics Department and previous research with low sample sizes [75] [1] [88] [89] [90] proved essential in determining whether the observed upper and lower bounds were statistically significant or occurred by random chance. The t-test was applied to both the upper and lower bounds of JND, ensuring the reliability of the findings. As mentioned in chapter 3, we expect the

calculated JND upper and lower bound to have a norm equal to the base acceleration if there is no difference and the null hypothesis is held to be true.

Normal Distribution Assumption

Before performing the t-test, we assumed that the JND data for both upper and lower bounds followed a normal distribution. This assumption is standard in many statistical analyses and ensures that the t-test results are valid. To confirm this assumption, the Anderson-Darling test was conducted. The Anderson-Darling test compares the empirical distribution of the data with the expected normal distribution, placing particular emphasis on deviations in the tails of the distribution. Its sensitivity to the tails is advantageous in studies like this, where extreme values can significantly influence the results.

To conduct the Anderson-Darling test, the empirical cumulative distribution function (ECDF) of the data was compared against the cumulative distribution function (CDF) of a normal distribution with the same mean and standard deviation as the dataset. The test produced an Anderson-Darling statistic (A^2), which quantifies the deviation between the two distributions [91] [92] [93] [94] [95].

$$A^2 = -n - \frac{1}{2}\sum_{i=1}^{n}[(2i-1)(\ln 1 - F(Y_{n+1-i})))]$$

where

n = Sample size

Y_i = Ordered data points (sorted in ascending order)

$F(Y_i)$ = Theoretical CDF of the normal distribution at Y_i

A^2 = Anderson-Darling Statistic (small A^2 indicates the data follows normal distribution, large A^2 represents a distribution that is non-linear

The calculated A values was extremely small for both the upper and lower bounds (< 0.01), and visually, the data closely followed the bell-shaped curve characteristic of a normal distribution.

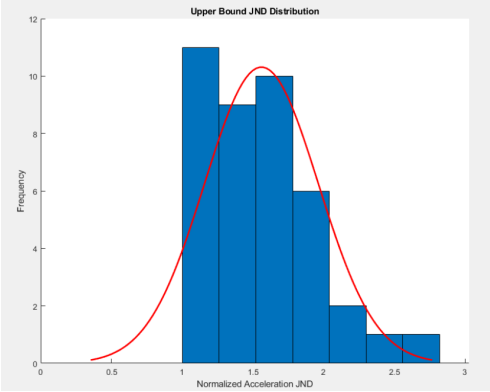


Figure 4.4: Upper Bound JND Distribution

t-Test Rationale

The t-test was chosen specifically because it performs reliably even with a limited number of participants, a common constraint in studies involving experimental platforms and VR systems [75] [1]. The relatively small sample size of 20 participants required a statistical method that could effectively detect meaningful differences without being overly sensitive to the dataset's size. The t-test excels in these conditions, making it an ideal choice for this research.

For this study, a one-sample t-test was employed for both the upper and lower bounds. This test compares the mean of a single group (the JND values) to a known value, which in this case is the base acceleration of the system. By using this approach, we were able to determine whether the observed mean JND values significantly differed from the base acceleration.

t-Statistic and p-Value

The t-test gives us two key numbers: the t-statistic and the p-value. The t-statistic, often denoted as t, is a ratio that measures the difference between the sample mean (the observed JND thresholds) and the known value (base acceleration), relative to the variability in the data. This statistic provides a quantitative measure of how far the observed data deviates from the baseline [96].

$$t = \frac{\overline{x} - \mu}{S/\sqrt{n}}$$

where

t = Calculated t-score

$\overline{x}$ = Sample Mean

μ = Assumed Mean

S = Sample Standard Deviation

n = number of samples

This value is then compared to the Student's t-distribution table [1]. To find the value from the table, we use degrees of freedom (df) and significance level (α). Degrees of freedom (df) is equal to $n - 1$, and we use $\alpha = 0.01$, which is standard for testing [75] [1].

If the absolute value of the t-statistic is greater than the value on the t-distribution table.

The p-value represents the probability that the observed differences occurred by random chance. In this study, a p-value threshold of 0.01 was selected, a standard value for establishing statistical significance in t-tests [1] [75] [36]. A p-value smaller than 0.01 indicates that there is less than a 1% chance that the observed results occurred randomly, providing strong evidence that the detected JND thresholds were true effects.

$$t = \inf\{\alpha : h > \tau_\alpha\}$$

Where

t = Calculated t-score

p = Calculated p-value

τ_α = Threshold associated with a type I error (or false positive of α

α = Region of values

In other words, the p-value is the smallest α (relative to the biggest threshold τ_α) for which we would reject the null hypothesis with our test statistic.

To support our JND findings, the t-statistic should be greater than the value found in the t-distribution table, and the p-value should be smaller than 0.01 to signify that the result was not a product of random chance.

t Table

cum. prob	$t_{.50}$	$t_{.75}$	$t_{.80}$	$t_{.85}$	$t_{.90}$	$t_{.95}$	$t_{.975}$	$t_{.99}$	$t_{.995}$	$t_{.999}$	$t_{.9995}$
one-tail	0.50	0.25	0.20	0.15	0.10	0.05	0.025	0.01	0.005	0.001	0.0005
two-tails	1.00	0.50	0.40	0.30	0.20	0.10	0.05	0.02	0.01	0.002	0.001
df											
1	0.000	1.000	1.376	1.963	3.078	6.314	12.71	31.82	63.66	318.31	636.62
2	0.000	0.816	1.061	1.386	1.886	2.920	4.303	6.965	9.925	22.327	31.599
3	0.000	0.765	0.978	1.250	1.638	2.353	3.182	4.541	5.841	10.215	12.924
4	0.000	0.741	0.941	1.190	1.533	2.132	2.776	3.747	4.604	7.173	8.610
5	0.000	0.727	0.920	1.156	1.476	2.015	2.571	3.365	4.032	5.893	6.869
6	0.000	0.718	0.906	1.134	1.440	1.943	2.447	3.143	3.707	5.208	5.959
7	0.000	0.711	0.896	1.119	1.415	1.895	2.365	2.998	3.499	4.785	5.408
8	0.000	0.706	0.889	1.108	1.397	1.860	2.306	2.896	3.355	4.501	5.041
9	0.000	0.703	0.883	1.100	1.383	1.833	2.262	2.821	3.250	4.297	4.781
10	0.000	0.700	0.879	1.093	1.372	1.812	2.228	2.764	3.169	4.144	4.587
11	0.000	0.697	0.876	1.088	1.363	1.796	2.201	2.718	3.106	4.025	4.437
12	0.000	0.695	0.873	1.083	1.356	1.782	2.179	2.681	3.055	3.930	4.318
13	0.000	0.694	0.870	1.079	1.350	1.771	2.160	2.650	3.012	3.852	4.221
14	0.000	0.692	0.868	1.076	1.345	1.761	2.145	2.624	2.977	3.787	4.140
15	0.000	0.691	0.866	1.074	1.341	1.753	2.131	2.602	2.947	3.733	4.073
16	0.000	0.690	0.865	1.071	1.337	1.746	2.120	2.583	2.921	3.686	4.015
17	0.000	0.689	0.863	1.069	1.333	1.740	2.110	2.567	2.898	3.646	3.965
18	0.000	0.688	0.862	1.067	1.330	1.734	2.101	2.552	2.878	3.610	3.922
19	0.000	0.688	0.861	1.066	1.328	1.729	2.093	2.539	2.861	3.579	3.883
20	0.000	0.687	0.860	1.064	1.325	1.725	2.086	2.528	2.845	3.552	3.850
21	0.000	0.686	0.859	1.063	1.323	1.721	2.080	2.518	2.831	3.527	3.819
22	0.000	0.686	0.858	1.061	1.321	1.717	2.074	2.508	2.819	3.505	3.792
23	0.000	0.685	0.858	1.060	1.319	1.714	2.069	2.500	2.807	3.485	3.768
24	0.000	0.685	0.857	1.059	1.318	1.711	2.064	2.492	2.797	3.467	3.745
25	0.000	0.684	0.856	1.058	1.316	1.708	2.060	2.485	2.787	3.450	3.725
26	0.000	0.684	0.856	1.058	1.315	1.706	2.056	2.479	2.779	3.435	3.707
27	0.000	0.684	0.855	1.057	1.314	1.703	2.052	2.473	2.771	3.421	3.690
28	0.000	0.683	0.855	1.056	1.313	1.701	2.048	2.467	2.763	3.408	3.674
29	0.000	0.683	0.854	1.055	1.311	1.699	2.045	2.462	2.756	3.396	3.659
30	0.000	0.683	0.854	1.055	1.310	1.697	2.042	2.457	2.750	3.385	3.646
40	0.000	0.681	0.851	1.050	1.303	1.684	2.021	2.423	2.704	3.307	3.551
60	0.000	0.679	0.848	1.045	1.296	1.671	2.000	2.390	2.660	3.232	3.460
80	0.000	0.678	0.846	1.043	1.292	1.664	1.990	2.374	2.639	3.195	3.416
100	0.000	0.677	0.845	1.042	1.290	1.660	1.984	2.364	2.626	3.174	3.390
1000	0.000	0.675	0.842	1.037	1.282	1.646	1.962	2.330	2.581	3.098	3.300
z	0.000	0.674	0.842	1.036	1.282	1.645	1.960	2.326	2.576	3.090	3.291
	0%	50%	60%	70%	80%	90%	95%	98%	99%	99.8%	99.9%
	Confidence Level										

Figure 4.5: T-Distribution Table [1]

4.3.2 Upper Bound Results

For the upper bound, participants reported detecting acceleration changes at an average of 1.6 times the base acceleration. This result indicates a clear threshold where participants perceive increased acceleration as distinct from the baseline. The mean was calculated with a relatively low standard deviation, reflecting consistency across the sample group. The statistical analysis using the one-sample t-test further supported these findings, yielding a t-statistic of

$$t = 24.5217$$

and a p-value of

$$p = 2.6e - 25$$

which is below the 0.01 significance threshold and larger than 1.328 from the t-distribution table. This finding establishes that our upper bound JND of 1.6 is statistically viable, and is not arbitrary but a reliable representation of the JND within this context.

4.3.3 Lower Bound Results

The lower bound results revealed that participants could detect deceleration at an average of 0.7 times the base acceleration. This threshold was similarly consistent across participants, with a slightly smaller standard deviation compared to the upper bound. The One-Sample t-test for the lower bound produced a t-statistic of

$$t = 27.1220$$

and a p-value of

$$p = 6.3e - 27$$

again below the significance threshold of 0.01 and larger than 1.328 from the t-distribution table. These findings confirm that participants reliably perceived reductions in acceleration at this level, validating the lower bound as a statistically significant measure of JND. The lower bound JND of 0.7 is statistically viable and not arbitrary in this context.

4.4 Additional Findings

Beyond the primary objectives of determining the upper and lower bounds for the Just Noticeable Difference in linear acceleration, several additional findings emerged that provide intriguing insights into participant behavior and response patterns. The findings will be highlighted in this section.

4.4.1 Post Questionnaire Questions

The post-questionnaire provided valuable insights into participant experiences and perceptions during the study. Each question was rated on a scale from 1 to 10, with 1 indicating a minimal factor and 10 indicating a significant factor. In total, there were a total of 11 questions. We will go over each question, and the justification for asking them in this section. The responses revealed a wealth of information about how participants interacted with the VR environment and perceived the acceleration cues. See Appendix E for all post questionnaire questions.

In the first question, we asked participants how immersive the experience was. This question was asked to see if the experience of combining VR and physical movement improved the immersiveness of the experience. As most of the participants have had VR experience before, a more immersive experience could indicate an impact of the linear motion.

We also asked about how realistic the acceleration felt. Ultimately, the goal is to find the JND of the acceleration perception threshold, there is merit to getting subjective opinions on the topic. Participants were asked to scale their answer from 1 - 10, with 1 being "not realistic" and 10 being "very realistic."

One of the carry over questions from our prior work with CET was to get the commercial viability of the research. More specifically, if the act of combining VR with physical motion fun. This question was left in the questionnaire to get the opinions of the participants, who, for many of them, is the first time they experienced VR combined with physical movement.

The next question focused on motion sickness and if the participants felt any symptoms of motion sickness during the experiment. Despite being VR/driving sim/driving users, there is still the potential of these symptoms showing up. These questions were asked to help future investigations know which potential symptoms might be more prevalent, as well as if symptoms impact the perception of JND or "perceived fun."

Following this, we asked how much did the visuals affect their acceleration perception. Similar to previous questions, this question is asked to hone in on how subjective do people feel their acceleration is impacted by their vision.

The final questions ask if the participant would be interested in participating again, as well as re-answering their initial screening questions to help with survey response data.

4.4.2 Post Questionnaire Findings

Participants generally found the experience to be highly immersive, with a particular emphasis on how much the visual elements influenced their perception of acceleration (Figure 4.6). This aligns with prior research highlighting the importance of visual cues in enhancing the realism of motion simulations. On average, participants rated the impact of visuals on their acceleration perception as 8 out of 10, indicating that the VR environment successfully conveyed a sense of motion and acceleration (Figure 4.8).

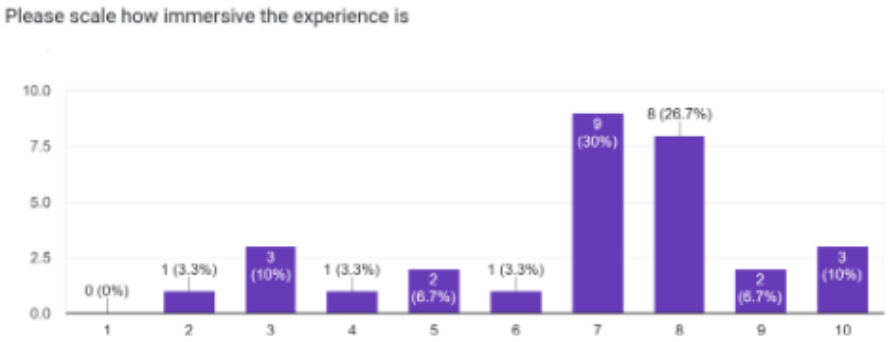


Figure 4.6: Participant Immersiveness Responses (Q1)

The perceived realism of the acceleration also garnered high ratings, with the majority of participants selecting scores between 7 and 8. This suggests that the integration of the go-kart platform with the VR system was effective in simulating realistic acceleration experiences. This feedback is particularly important for applications seeking to enhance user engagement and authenticity in VR motion simulations (Figure 4.7).

Another aspect assessed was the level of enjoyment during the experiment, a question originally designed with potential entertainment applications in mind. Combining VR with a physical go-kart platform proved to be a popular concept, as most participants rated their enjoyment highly, with scores clustering around 9 out of 10. This finding underscores the potential for using similar setups in commercial entertainment settings, such as VR arcades or amusement parks (Figure 4.8).

Motion sickness was also a focus of the post-questionnaire, as it is a known challenge in VR systems. While most participants did not report any symptoms, a minority experienced mild to moderate motion sickness, primarily in the form of dizziness and fatigue. This feedback highlights the need for further optimization of motion synchronization to minimize discomfort in future studies (Figure 4.9).

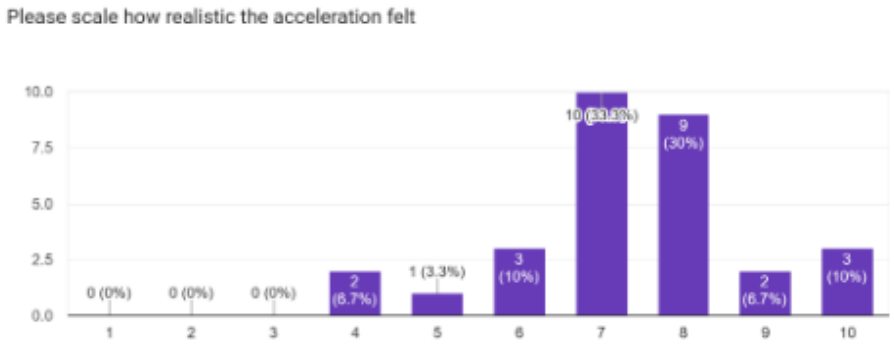


Figure 4.7: Participant Acceleration Realism Responses

Overall, the post-questionnaire findings affirm the effectiveness of the experimental setup while also identifying areas for refinement, particularly in addressing motion sickness and further enhancing the realism of acceleration perception. These insights will inform future improvements and applications of the system, ensuring both user satisfaction and practical utility in VR motion simulations.

4.4.3 Fatigue Effects on Perception

Fatigue may have influenced the perception of acceleration in this study, but the extent of its effect remains uncertain due to the lack of direct evidence. Observations from the data, particularly when comparing the first and second runs of the staircase testing procedure, hint at possible trends related to fatigue. For the upper bounds, a noticeable increase in the spread of responses during the second run was observed, as shown in Figure 4.10. This broader variability suggests participants faced greater difficulty in detecting increases in acceleration over time, potentially due to cognitive fatigue, reduced attention, or diminished sensory processing.

Conversely, for the lower bounds, the data displayed a tighter clustering of responses during the second run, indicating increased consistency in detecting deceleration thresholds. This trend might suggest that participants became more attuned to the sensory cues associated with slowing down, possibly due to the distinct physical sensation of deceleration compared to acceleration. However, without explicit fatigue metrics or participant-reported feedback on their cognitive or physical state, these trends remain speculative.

Figure 4.10 illustrates these shifts in response variability between runs, but it is important to acknowledge that the trends could also be influenced by factors other than fatigue,

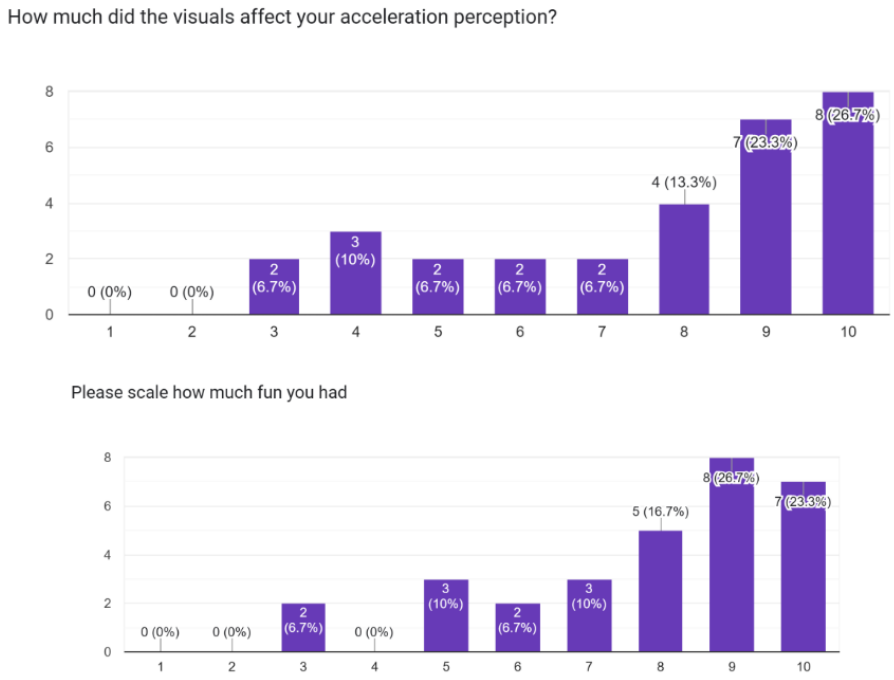


Figure 4.8: Participant Responses to Visuals and Fun

such as improved familiarity with the testing procedure. Future research could benefit from including fatigue measurement tools, such as physiological indicators, to confirm the relationship between participant fatigue and changes in perception thresholds.

4.4.4 Experienced VR and Driving Users

Another key observation was the influence of prior experience with VR and driving simulators on JND thresholds (Figure 4.12).

When we box plotted the JND distributions for participants identified as "power users" of VR and simulators, it visually showed a tighter clustering of mean thresholds compared to the full sample of 20 participants. While these observations provide valuable insights, it is worth noting that the subset of power users comprised only six individuals, resulting in a smaller sample size that may limit the generalization of these results. Nonetheless, these trends highlight the role of experiential factors in shaping motion perception (Figure 4.11).

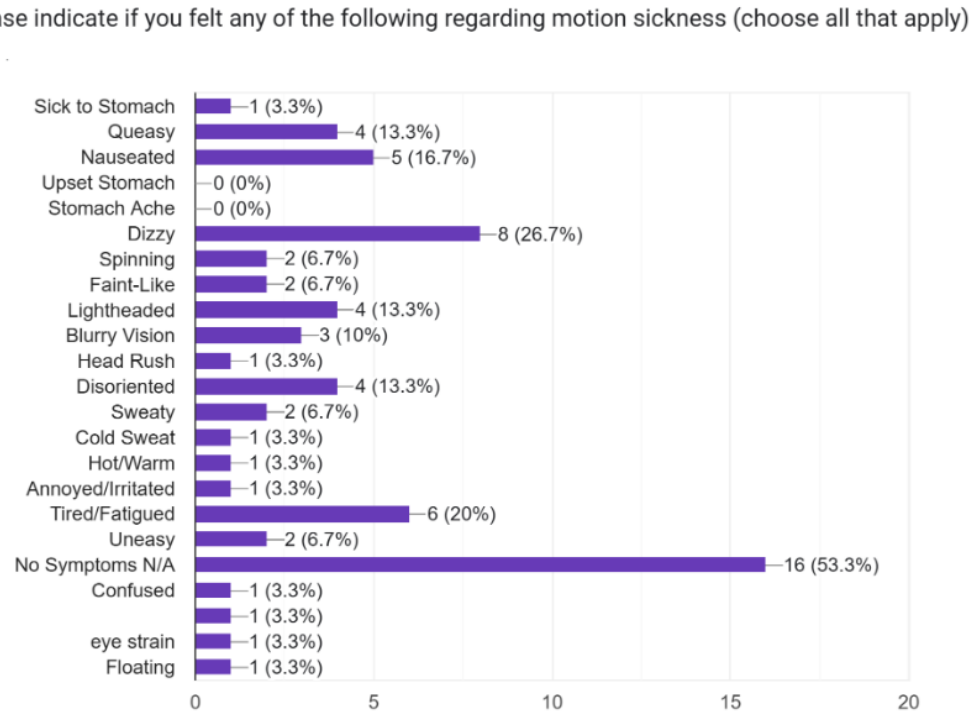


Figure 4.9: Motion Sickness Responses

To ensure the validity of these subgroup findings, additional One-Sample t-tests were conducted on the data from the power users. The results of these tests were consistent with those of the full sample, with $t = 22.64$, $t = 19.14$ and p-values of $p = 3.8e - 14$, $p = 6.1e - 13$ for the upper and lower bounds respectively.

We observed that participants with extensive VR experience tended to exhibit smaller thresholds for both upper and lower bounds, demonstrating quicker and more consistent detection of acceleration changes. Similarly, those with experience in driving simulators displayed a heightened sensitivity to acceleration and deceleration, likely due to their familiarity with dynamic motion environments. However, this is just an observation, and not a conclusion due to the low sample size.

4.4.5 Weber's Law

The psychological results of this study offer important insights into human perception of acceleration. For most of this investigation, we used the normalized JND accelerations.

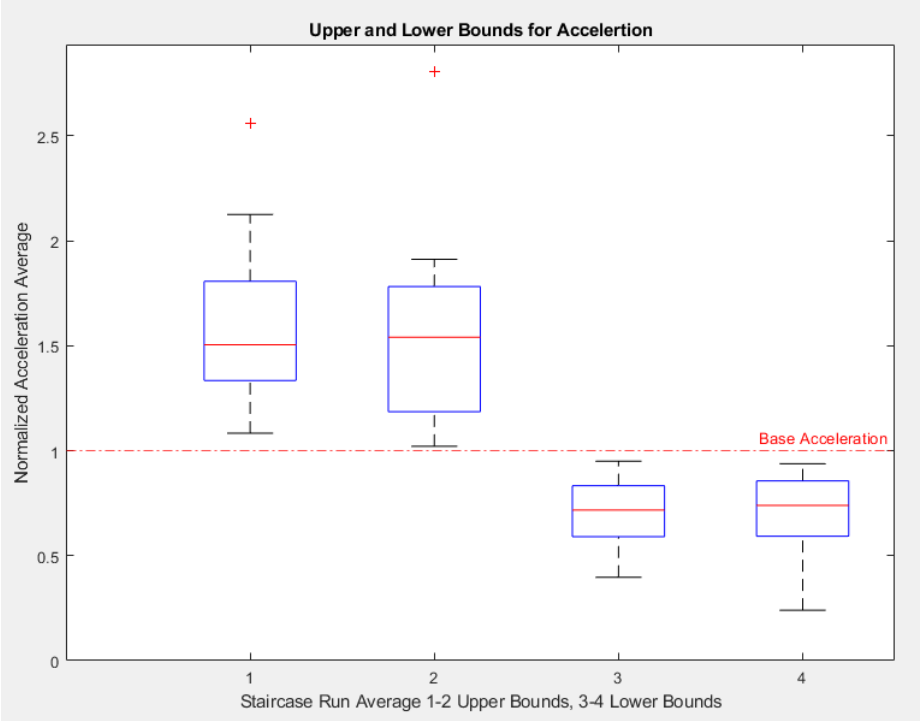


Figure 4.10: JND Upper and Lower Bounds Boxplot

Using the actual ground truth reference acceleration, as explained in section 4.2.3, we can investigate if Weber's law can be applied to the application of VR and linear physical acceleration.

Weber's law states that the ability to detect differences in stimuli should be proportional to the baseline stimulus magnitude, with greater sensitivity and variability at lower stimuli and reduced sensitivity at higher stimuli [64]. In other words, the JND variability should be smaller at lower accelerations and larger at faster accelerations. This is because at lower accelerations, the participant should have greater sensitivity, which leads to a smaller JND. Conversely, at higher accelerations, the participant should have reduced sensitivity, leading to a larger JND.

Our findings, however, don't align with this notion, as the variability in Just Noticeable Difference thresholds was greater at lower accelerations (e.g. 0.01 m/s^2) and less pronounced at higher accelerations (e.g. 0.05 m/s^2). This pattern suggests that participants found it more challenging to consistently detect small differences at lower accelerations, while their responses were more uniform as the magnitude of acceleration increased.

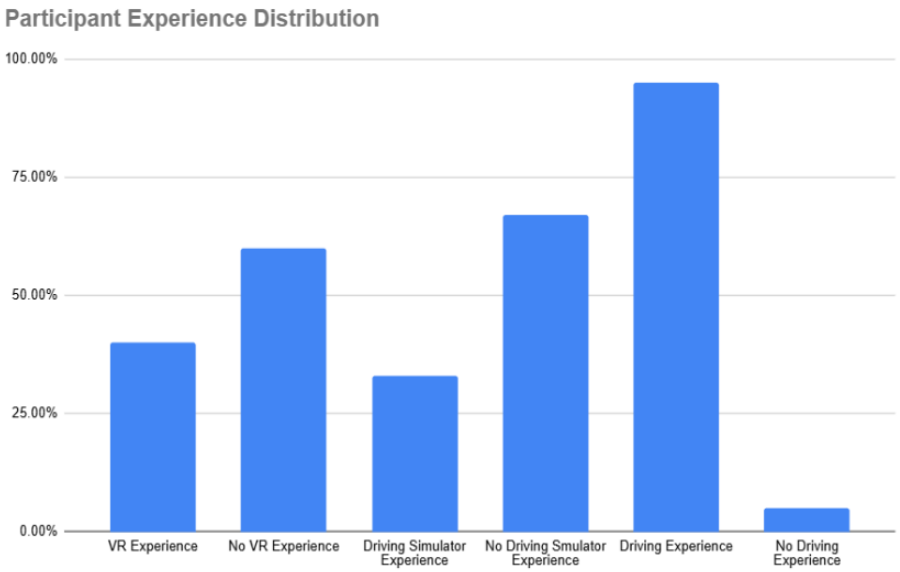


Figure 4.11: Participant Experience Distribution

As you can see from the figures below (Figure 4.13 & Figure 4.14), there is greater variability in JND bounds for slower accelerations than faster ones. We have grouped the acceleration ranges of the individual participants into three groups, $0.01 - 0.016m/s^2$, $0.02 - 0.03m/s^2$, $0.037 - 0.05m/s^2$. The ranges in JND responses are shown with boxplots, with the X-axis showing the ground truth base acceleration at which the JNDs are recorded.

Although these results don't seem to follow the general framework of Weber's Law, the small sample size of 20 participants limits the ability to draw definitive conclusions. In both figures, the JND ranges are more varied at lower accelerations, and more tightly clumped at higher accelerations. The variability observed at these accelerations may also be influenced by individual differences, such as participants' prior experience with VR or motion simulators, sensitivity to motion, or fatigue effects during testing. Additionally, the experimental setup, which involved low-speed testing and brief acceleration phases due to space constraints, may have amplified these variations. We only tested between a base range acceleration of $0.01 - 0.05m/s^2$. We assume that if the acceleration range was larger (i.e. between $0.01 - 10.0m/s^2$), there might be a better representation of Weber's Law. While the findings are intriguing, they highlight the need for further investigation to better understand the relationship between baseline acceleration and perceptual sensitivity.

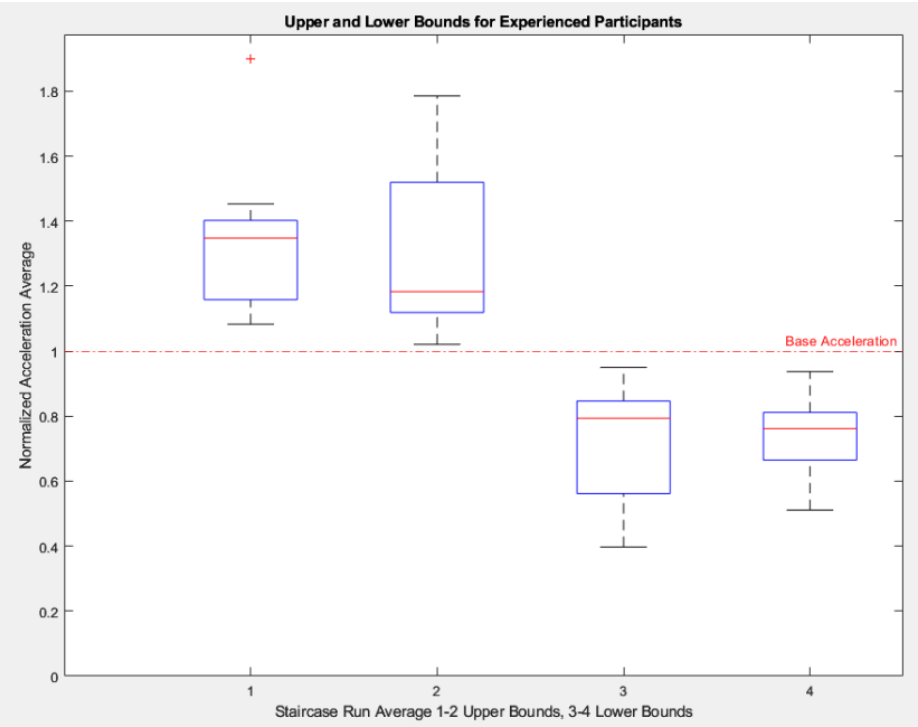


Figure 4.12: Experienced Participants Upper and Lower JND Boxplot

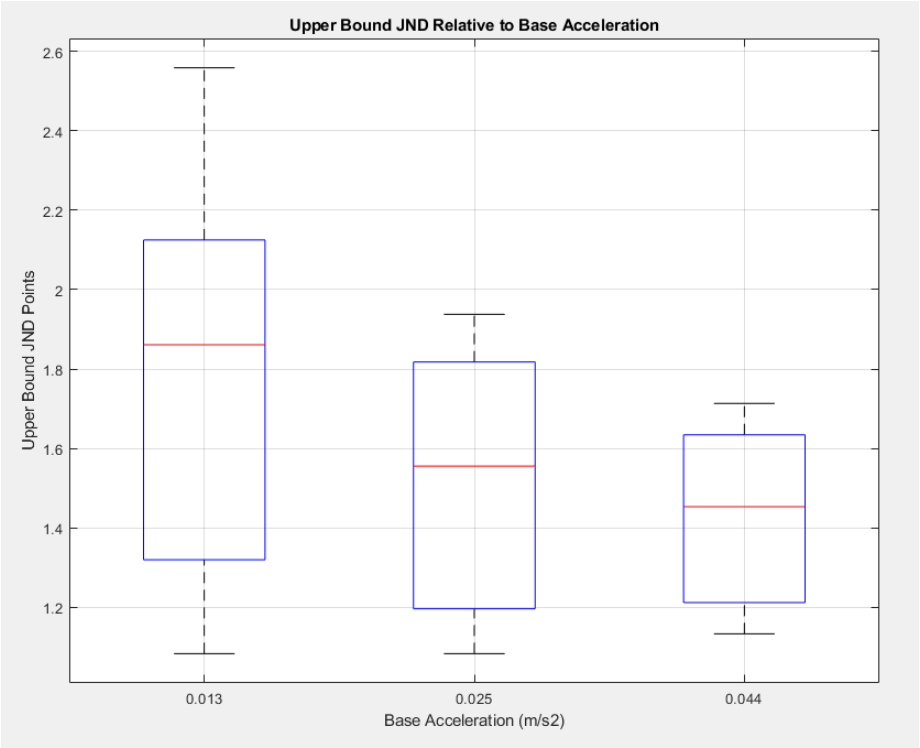


Figure 4.13: Upper JND Boxplot Relative to Base Acceleration

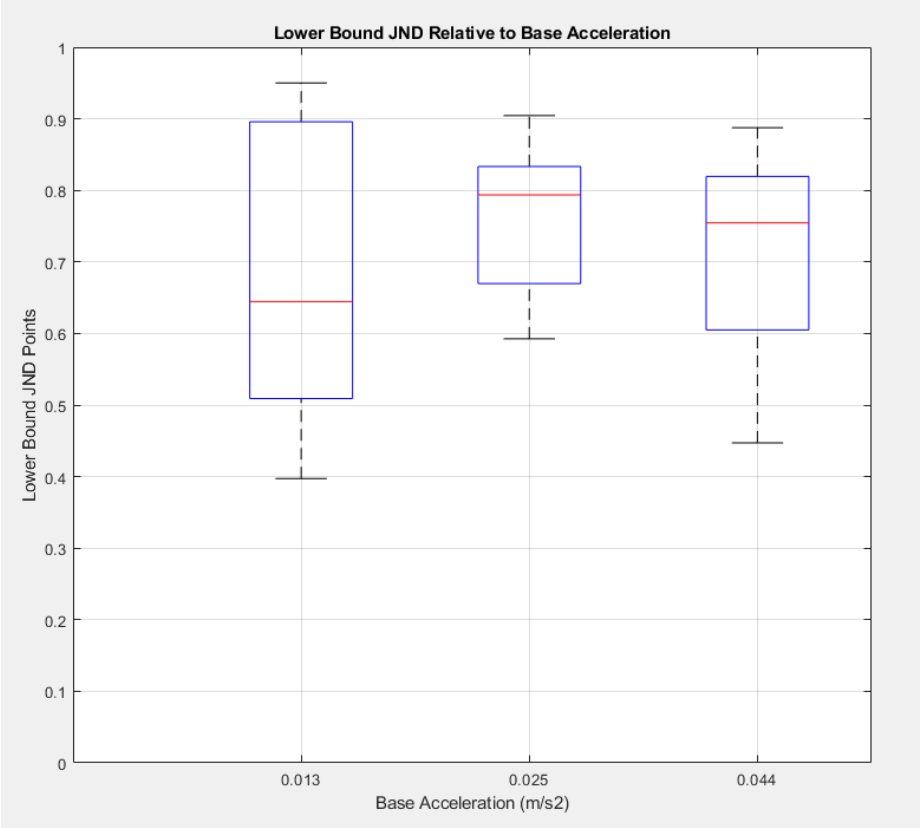


Figure 4.14: Lower JND Boxplot Relative to Base Acceleration

Chapter 5

Conclusion and Future Work

The primary purpose of this thesis was to investigate the limits of how people perceive linear acceleration within a virtual reality environment and to explore its implications for motion simulation and space optimization. By combining physical motion, visual cues, Just Noticeable Difference, and psychophysical principles, this research aimed to bridge the gap between virtual and physical movement, addressing challenges in VR design and providing insights into how humans perceive acceleration. The results contribute to both theoretical knowledge and practical applications in industries such as entertainment, simulation, and training.

The initial chapters of this thesis provided the foundational introduction and background upon which the research was built, outlining the motivation, theoretical framework, and methodology necessary for exploring the Just Noticeable Difference in linear acceleration perception.

Chapter 1 set the stage by articulating the overarching goal of the study: to understand how humans perceive changes in linear acceleration within a virtual reality environment and to explore the practical applications of this knowledge. It highlighted the significance of JND in bridging the gap between physical and virtual motion, underscoring its importance for improving VR immersion and optimizing space usage in motion systems. Additionally, the chapter contextualized the research within broader technological and industrial advancements, making a compelling case for why such investigations are vital for the future of VR applications in entertainment, training, and simulation.

Chapter 2 delved deeply into the background and existing body of knowledge relevant to the study. This chapter provided a comprehensive review of acceleration perception, exploring how the human vestibular and sensory systems interact with visual cues to detect

and interpret motion. It also introduced the principles of VR technology, emphasizing the challenges associated with replicating realistic motion sensations in virtual environments. Furthermore, the chapter discussed the psychophysical framework of Weber's Law, which predicts that human sensitivity to changes in a stimulus is proportional to the baseline intensity of that stimulus. This principle became instrumental in forming hypotheses about how participants would perceive acceleration changes in the experimental setup. The chapter concluded by reviewing prior research on JND, highlighting gaps in the literature, and establishing the novelty of this thesis in combining physical motion with acceleration perception testing.

Chapter 3 transitioned from background foundation to practical implementation, detailing the methodology used to address the research questions and investigation. It described the experimental design, emphasizing the importance of controlling variables such as visual and physical stimuli to ensure reliable results. The chapter elaborated on the equipment used, including the go-kart platform, VR headset, and accelerometer, providing technical specifications and explaining their roles in the study. A significant focus was placed on the staircase method, a widely used approach for measuring perceptual JND thresholds. This method allowed for precise determination of the upper and lower JND bounds by gradually adjusting the physical acceleration until participants reported a noticeable change. The systematic and iterative nature of the staircase method ensured that the collected data was robust and minimized variability due to individual differences or random errors. The methodology section also addressed participant selection, ensuring a diverse sample with varying levels of VR and driving experience to capture a broad spectrum of perceptual responses.

Chapter 4 presented the results of the study, from data analysis to highlighting the key findings. It was determined that the upper JND threshold was approximately 1.6 times the base acceleration, while the lower threshold was 0.7 times the base acceleration. These values illustrate the asymmetry in human sensitivity to increases and decreases in acceleration, a phenomenon consistent with principles such as Weber's Law. Statistical analysis using a one-sample T-test confirmed that these thresholds were statistically significant, supporting the hypothesis that humans can discern changes in acceleration above or below specific perceptual limits. Additional findings revealed the impact of participant fatigue, prior experience with VR and driving, and the potential commercial space conservation applications.

The results of this thesis have significant implications. First, they provide a framework for designing motion simulations that align with human perceptual capabilities. By understanding the JND thresholds, designers can optimize motion systems to conserve space without compromising the immersive experience. For example, using the lower JND bound

allows for reduced physical track lengths while maintaining the illusion of continuous motion, a finding particularly valuable for commercial applications such as VR arcades and driving simulators.

Despite its contributions, this thesis is not without limitations. The study relied on a sample size of 20 participants, which, while sufficient for detecting trends and achieving statistical significance, limits the generalizability of the findings. Future research with larger and more diverse participant groups could further validate the results. Additionally, the physical constraints of the go-kart platform, such as its maximum speed, weight shift distributions, and the limited sensitivity of the accelerometer at low accelerations, posed challenges in accurately capturing subtle changes in motion. These technical limitations suggest that more advanced equipment and higher-speed platforms could yield more precise measurements. Lastly, the focus on linear acceleration excludes other aspects of motion perception, such as angular acceleration and deceleration, which could be explored in future studies.

One key area for future research is the incorporation of more advanced equipment, particularly tilt platforms. Many high-fidelity simulators, such as those used by NASA, employ tilt mechanisms to replicate the physical sensations associated with acceleration, such as the jerk experienced during rapid changes in motion. Integrating a tilt platform into the go-kart setup could provide a more realistic simulation, likely influencing the upper JND bound by amplifying participants' sensitivity to acceleration changes.

Another limitation of this study was the speed and acceleration constraints imposed by the go-kart platform. The maximum speed of 1.5 m/s, while sufficient for this investigation, is only marginally faster than an average walking pace. These limitations were compounded by the variability introduced by weight differences among participants, which affected the acceleration profiles. Future research should aim to conduct experiments at higher speeds using a platform that is less impacted by weight shifts. A more powerful, calibrated go-kart or an entirely different vehicle could provide data that is more representative of real-world applications. Adding weights to the go-kart so that each participant runs at the same weight is also another solution that could work. Additionally, the relatively short test durations, necessitated by the limited testing space, restricted the length of acceleration phases to 7–8 seconds. Expanding the testing area and duration would allow for a more comprehensive examination of sustained acceleration and its effects on perception.

The testing protocol used in this study also presents opportunities for refinement. Each staircase run began with a 1:1 reference acceleration, which served as the baseline for participants to compare changes. While this approach was effective, exploring alternative starting accelerations, either slower or faster, could yield insights into how initial conditions

influence perception thresholds. Testing across a range of starting accelerations could reveal whether the JND ratios observed in this study hold consistent or vary under different initial conditions.

Future research should also consider broader statistical analyses, particularly focusing on participant feedback regarding motion sickness and satisfaction with the VR experience. Correlating these subjective measures with objective JND thresholds could uncover patterns that inform the design of more user-friendly and immersive VR systems. Expanding the sample size to include a larger participant pool would further validate the findings and provide insights into individual differences in motion sensitivity. This could be particularly relevant in identifying how prior experience with VR or motion simulators impacts perception.

Expanding on the application of Weber's Law in future studies, a key direction would be to involve a larger and more diverse group of participants to validate and refine the findings. The current study, while insightful, was limited by its sample size, which may not fully capture the variability in sensitivity to acceleration across different demographics, such as age, gender, or prior exposure to VR and motion simulation. By conducting experiments with a broader participant base, researchers could establish more robust estimates for the Weber fraction (k) in the context of acceleration perception. This expanded dataset would also allow for subgroup analyses to explore how individual differences influence adherence to Weber's Law, providing a deeper understanding of the factors that modulate motion sensitivity. Additionally, larger sample sizes would enhance the statistical power of the study, reducing the likelihood of Type II errors and allowing for more nuanced interpretations of the data. Such efforts could ultimately yield findings that are more generalizable, further solidifying the relevance of Weber's Law to VR motion systems and related applications.

Finally, a promising expansion from this investigation involves extending the current methodology to explore JND thresholds for deceleration and angular acceleration. While this study focused exclusively on linear acceleration, real-world applications often involve complex motion patterns, including turning and braking. For example, testing the JND for small angular deviations (e.g. 1 or 5 degrees) could provide valuable data for designing VR environments that simulate vehicular motion, such as navigating curves or sharp turns, and can further reduce commercial space applications. Similarly, investigating JND thresholds for deceleration could enhance the realism of braking simulations, offering a more complete understanding of motion perception.

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APPENDICES

Appendix A

Go Kart Technical Specifications

A.1 Go-Kart Technical Documents

Autonomous Go-Kart

Software Technical Binder

Winter 2024



Property of the Ideas Clinic

Created by Leo

Preface

This document was made in early 2024. It should be used to understand the parts used in the gokart. Refer to the README to find where to find the information about how these parts are implemented in the gokart.

The goal for the go kart in 2024 is to make it fully autonomous and give it self-driving capabilities. Multiple sensors and algorithms are used to achieve this. Further updates and improvements to the low-level components were applied. No control software was written prior to Winter 2024, so this will be the first major iteration of the autonomy stack. Before proceeding, it is assumed the reader has a basic understanding of ROS terminology.

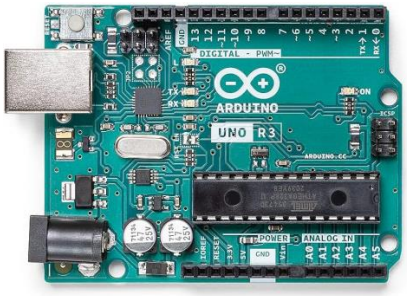
Main controller boards:

- Nvidia Jetson Nano
- Arduino Uno (x2)

The Nvidia Jetson Nano is the main controller board on the go-kart, handling all calculations, computations and decision making. All self-driving algorithms will be run on the jetson. The control software runs on ROS melodic with a few on-board packages for additional functionality.



The Arduino uno controllers act as the low-level firmware boards. They take input from physical peripherals like the pedals to output power signals to devices like the motor controllers. One is located at the front of the car next to the steering column, and the second is located at the back near the batteries.



The front Arduino uno controls power steering, connecting to the steering motor and digital encoder for feedback. The back Arduino controls the chassis motor (powering back wheels), taking inputs from the pedals and brakes, as well as the brake servo.

Both Arduinos communicate with the Nvidia jetson nano through dual dedicated serial USB connectors. Communication is bi-directional, data can be sent and received from the Arduinos, and viewed on the Nvidia Jetson Nano.

Main sensors:

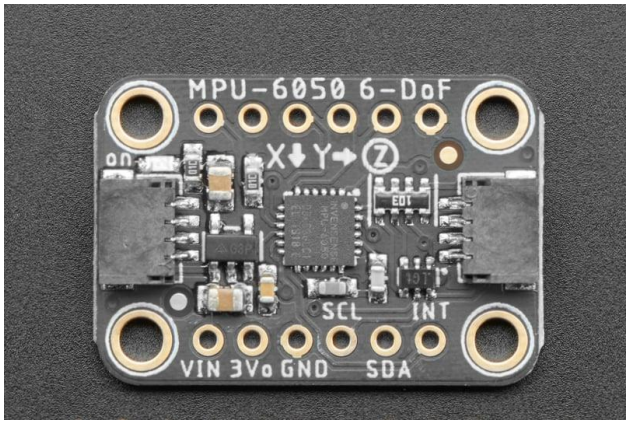
- A1M8 Lidar
- Orbec Vision Camera (TBD)
- MPU6050 6-DOF accelerometer and gyro
- Linear hall-effect sensor
- Digital Encoder

The A1M8 lidar by SLAMtec provides the mapping data for the car. It provides a continuous live feed of data in a 2D plane. Subsequently, anything below the sensor will not be scanned. It is currently mounted above the orbec camera to scan the front of the car for a drivable path. To parse data, the RPLidar Ros package is used (more below). The more powerful A2 lidar is available, but due to power consumption concerns, is omitted for this project.



The orbec vision camera is currently planned for obstacle detection. As of March 2024, it is currently put off prioritizing development of other algorithms. A similar vision camera is used in the conveyor project and the TIC challenge.

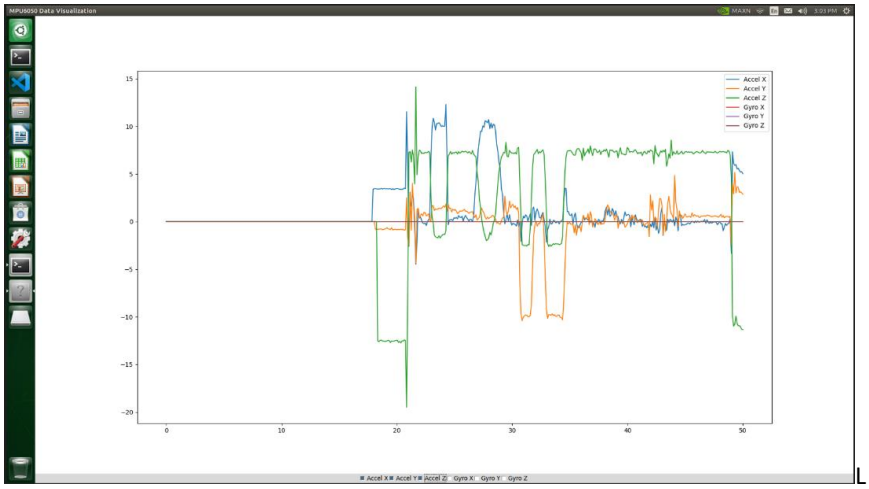
The MPU6050 6-DOF (degrees of freedom) accelerometer and gyro provides angle feedback for the car. It is currently used in localization (position tracking) in conjunction with the hall-effect sensor. It is currently directly connected to the nvidia jetson and communicates using the I2C bus protocol. The default address is linked to 0x68, and this plug-and-play sensor should be easy to configure and use. To learn more about the MPU6050 by Adafruit, visit:



Additional scripts have been created to test the data from the MPU6050 without deploying ROScore. These are located on the desktop folder of the Nvidia Jetson nano:

- Mpu6050-simpletest2.py
- Mpu6050-simpletest3.py
- Mpu6050-tkinter.py

Mpu6050-tkinter.py provides a graphical interface to select which data lines to view.



The linear hall-effect sensor is used as a rotation sensor for the driving axle of the car. It utilizes one digital port to return data. A magnet is attached to the physical shaft, and the hall effect sensor detects how many times / revolutions the magnet enters and leaves the magnetic field. For additional reference, this sensor is also used in the ball bearing machine. Previously it was connected to the Arduino, but has since been moved to be directly connected to the Nvidia Jetson.



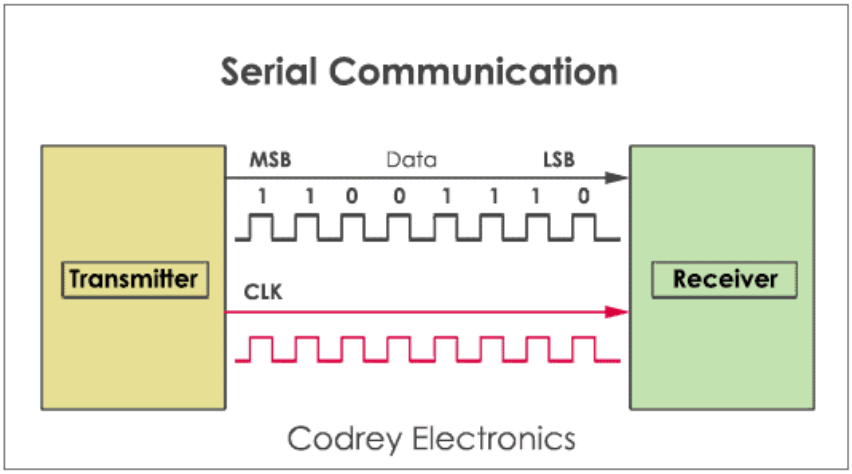
Digital Encoder (I don't know much about this, it was put onto the steering column so I gotta find out what this is about). The purpose of the digital encoder is to track position of the steering axle. It will be used to control power steering and lock the steering column at certain positions.

Ros Serial

Ros Serial is a package that allows for serial communication between the jetson nano and the arduino controllers on the car. This is necessary as we need to send velocity commands to the arduino, as well as steering data. The arduinos will also subsequently return encoder positions, throttle/brake status, etc. The previous iteration of this communication link is based upon using the header pins. The current implementation uses standard USB cables.

rosserial_arduino - ROS Wiki

Serial communication protocol is the most widely used approach to transfer information between data processing equipment and peripherals. In serial communication, data is in form of binary pulses, and the current transmission mode is full duplex, where both the sender and receiver can transmit and receive at the same time.



Ros serial will also be used to implement data logging on the car. Like any ROS node, we can log messages at the appropriate verbosity level, and ros serial will forward the string to the standard ROS network and outputs to rosout and its log file.

Special things to note is that the ros serial package also needs to be installed on the arduino IDE, with version 0.7. Version 2.9 has build bugs involving cstring reference errors, so to avoid this problem, simply downgrade to the 0.7 release. Potentially in the future, this error will be fixed.

ROS Simulators – Gazebo

Before testing on physical hardware, it is sometimes helpful to run the code through a simulator environment. Some popular options include Rviz and Gazebo, both of which should be installed on the Jetson Nano. Similar approaches have been used for the Toyota Innovation Challenge (TIC).

The kart currently runs ROS-melodic (ROS1), using the URDF file provided, typically exported from solidworks. The current tool used for exporting models is (insert name), found at (insert github link). Follow the install instructions from the readme on github. This tool has been tested to work on solidworks 2023.

A.2 Go-Kart Standard Operating Procedure

Safe Operating Procedure

Electric Go-Kart			
Dept:	Engineering Ideas Clinic	Date:	Jun 7, 2024
Procedure:	General Operation & Safety	Revision #:	2
Principle Investigator:	Chris Rennick	PI Phone:	x38178
PI Signature:	X_____		

***Complete and submit an incident report for all incident and near-misses**

1.0 Procedure Summary

This SOP covers the basic procedures for the IDEAs Clinic Electric Go-Kart, including general safety precautions, hazards, controls, and operation.

If performing maintenance/working on the powertrain and mechanical structure (including jacking the car up, separating the modules, or charging batteries), refer to the Powertrain/Mechanical Maintenance SOP.

If performing autonomous driving operations, some operating procedures may differ, as detailed in the Autonomous Operation SOP.

2.0 Controls

Administrative Controls:

- All users must be authorized and supervised by the lab staff and/or IDEAs clinic staff [etc.]
- Staff have possession of kill-switch key

Engineering Controls:

- 3 red power battery isolators (or kill switches) located on the rear of the electrical box. They correspond to the 12V, 24V and 36V circuit respectively.
- Hand brake (physical bypass) located at the left of the drivers seat.

3.0 Risks

This safe operating procedure was developed in response to the risk assessment completed under the University of Waterloo's Risk Assessment Program.

The process specific risk assessment can be found in the *Safety* channel on the Engineering Ideas Clinic MS Teams site.

Hazards

Several hazards are present when operating the go-kart, falling generally into 'electrical' and 'physical' categories.

Electrical Hazards:

- IMPORTANT: When Arduino to a laptop, ensure all 3 kill switches are in the OFF or RED position.
- The go-kart is powered by three 12V AGM lead-acid batteries (36V system)
    - Human skin resistance can be as low as 1kΩ. Ohms law: ~36mA flowing through your body — enough to cause loss of muscle control
    - Constant awareness of the go-kart's power status is essential
    - With the electrical box closed, risk is significantly lower.
- To cut power from going into the circuit, ALL 3 kill switches must be switched to the OFF position. Always ensure the 3 kill switches are in the OFF position when doing **any** work in the rear
- The 3 kill switches and which circuit they correspond to is pictured below.

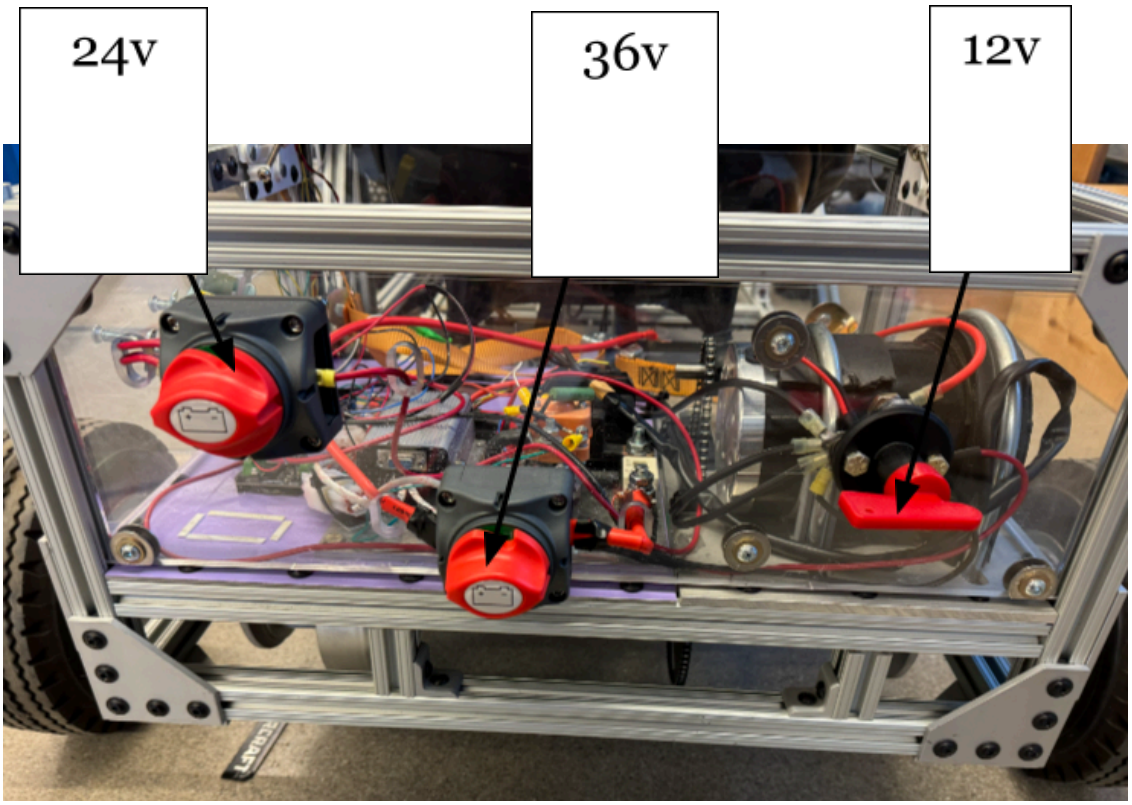


Figure 1: All switches in ON position

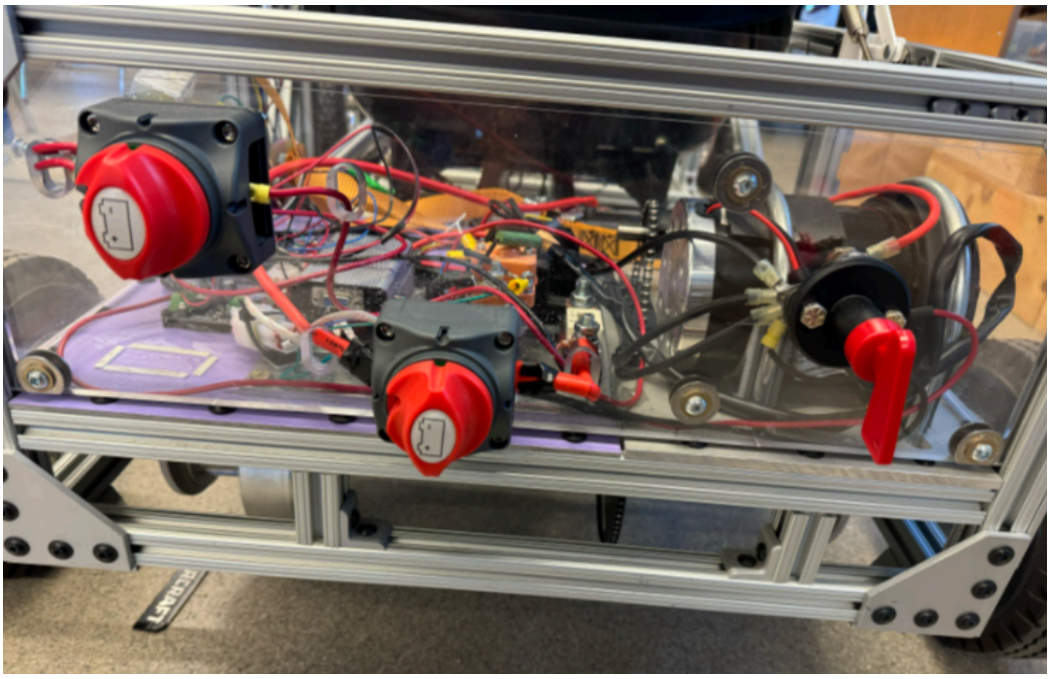


Figure 2: All switches in OFF position

- The start/stop button on the steering wheel is NOT the same as the kill switch — the system will still be powered even if the vehicle is 'off'
- Do NOT make assumptions about the system's power status — if you are unsure, consult with the lab or IDEAs clinic staff

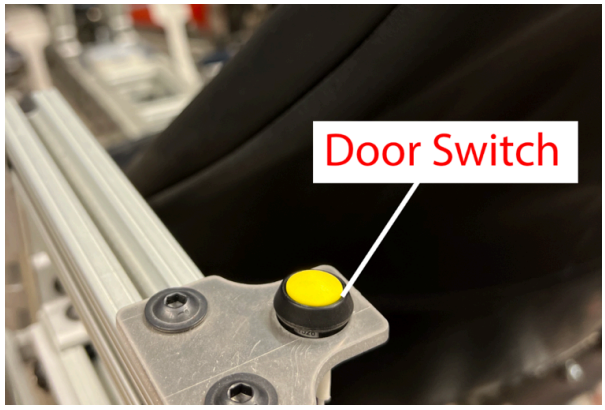
- Do NOT open the electrical box without prior permission and/or supervision

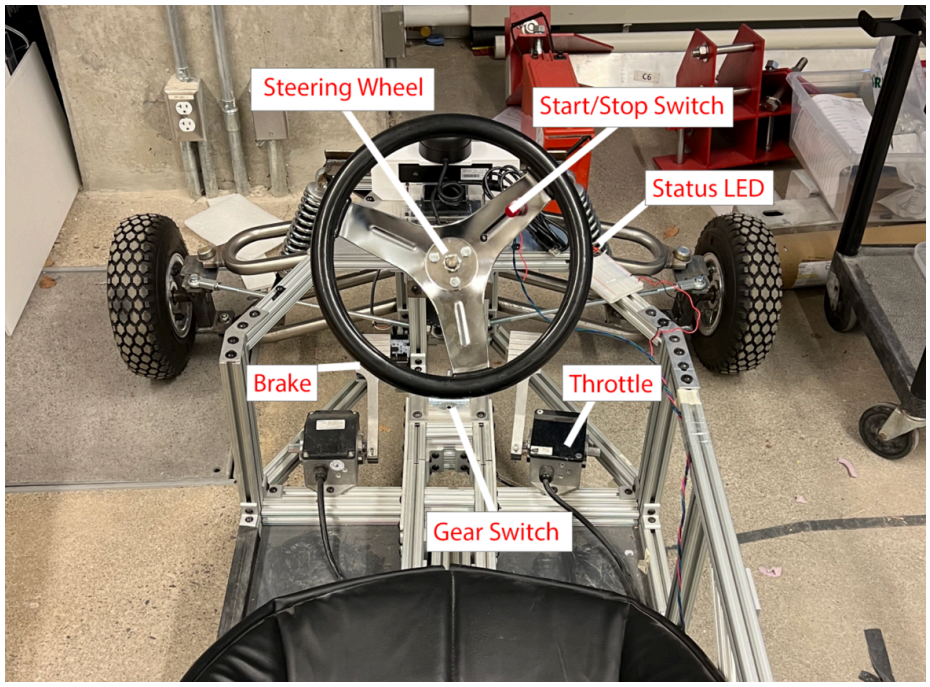
Physical Hazards:

- Pinch points are present throughout the vehicle:
  - Hinged lid for the electrical box
  - Actuating door
  - Exposed steering mechanisms
  - Drivetrain, especially the driving chain
    - Eliminate any loose wires/objects that can fall into the driving chain's path
  - Front suspension
- Sharp edges exist in many parts of the vehicle. Care should be taken when reaching into spaces with low visibility.

- Impacts with the go-kart during operation could cause bodily injury
    - Maintain reasonable distance from the vehicle's path when in motion
- Due to the drive system being a chain-driven solid driveshaft, the driving characteristics are different from most modern vehicles

4.0 Layout


Door Switch


Steering Wheel
Start/Stop Switch
Status LED
Brake
Throttle
Gear Switch

5.0 Training

Prior to completing this task the following training must be completed and documented.

Training Type	Training Details
Online Training	SO2033 (Electrical Awareness)
Practical Training	Class instruction by IDEAs clinic staff

Practical training should be up to 30 minutes of driving the car. This should include acceleration, deceleration, and turning. The training should teach two-pedal driving, the shutdown procedure, as well as practice use of the emergency handbrake. The driver should be given sufficient time to be comfortable with the operation of the steering wheel, pedals, and handbrake.

New Change: Prior to operating the go-kart, drivers must complete a minimum of **30 minutes** of practical training, as outlined below:

1. **Orientation**: Introduction to vehicle controls and safety procedures.
2. **Acceleration and Stopping**: The driver must complete **four rounds of accelerating and coming to a complete stop**.
3. **Emergency Stop**: The driver must demonstrate the ability to stop the vehicle immediately upon instruction.
4. **Obstacle Avoidance**: A course will be set up using pylons, and the driver must navigate the course safely without hitting the obstacles.

Only once all the above tasks are completed to satisfaction will the driver be authorized to operate the vehicle.

6.0 Tools and Equipment Required

- Interfacing with the Microcontrollers: Laptop
- Troubleshooting hardware issues: Multimeter

7.0 Personal Protective Equipment

The following guidelines should be followed at all times:

- Close-toed shoes

- Keep loose clothing/long hair/jewelry away from risk points, including the automatic steering rack, wheels, actuating door, and rear drivetrain
- Build-in seatbelt for operation
- A helmet is not required, as the user will be wearing an VR headset. With the operating speeds, a helmet is not needed.

If operating the vehicle, the following is required:

- Tied hair

8.0 Emergency Shut-Down Procedure

- Open contactors by pressing the button the steering wheel and visually noting that the steering wheel LED turns off
- Turn off all 3 battery isolation switches

In the event of a fire, the driver should immediately leave the vehicle and any bystanders should leave sufficient space. If possible on exit, the driver should press the steering wheel switch (to cut power to the drivetrain).

The fire extinguisher can be found in the back corner of the backroom of the first floor IDEAS Clinic, adjacent to the lockers. Vehicle testing should be done near this location. See photo below.

New Change: The emergency response plan has been expanded as follows:

- **Fire (Vehicle Not Operating)**: All personnel should immediately evacuate the area if a fire occurs while the vehicle is not operating. If safe, use the fire extinguisher located in the backroom.
- **Fire (Vehicle Operating)**: The driver must press the emergency stop button, exit the vehicle, and evacuate the area. Bystanders should also evacuate immediately.
- **Battery Fire**: Use the designated **Class C fire extinguisher** for electrical fires.
- **Crash Response**: In the event of a crash, the vehicle should be immediately shut down by pressing the emergency button and turning off all kill switches. The driver should be checked for injuries, and the vehicle should be inspected for damage.

In the event of a crash, the contact button should be pressed before exiting the vehicle, and if the kill-switches are accessible, should be turned OFF.

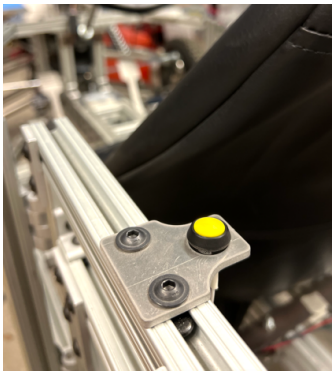
9.0 Pre-Start Checklist

1. Ensure familiarity with basic controls layout (Section 4.0)
2. Ensure all modular wiring connectors are securely connected
3. Ensure gear switch (between two pedals) is in the middle (NEUTRAL) position
4. Ensure all battery connections are connected (if not, refer to Powertrain/Mechanical Maintenance SOP)

10.0 Start-Up Procedure

Visually check that all 3 kill switches are on, and press the steering wheel button to close contactors.

The door (to the left of the vehicle) is actuated through the press of the yellow button shown below:



The start/stop button on the steering wheel will toggle the vehicle ‘on’ and ‘off’. An LED attached to the frame (to the right of the steering wheel) indicates the status of the system:

- LED is on ‘ON’, car is ready to drive/systems are all active
- LED is off ‘OFF’, car cannot drive but the system may still be powered
- LED is blinking ‘LOW BATTERY’, car does not have enough charge to run

11.0 Operating Procedure

List steps here. These steps should be in sufficient detail and clearly expressed to enable a trained person to perform the procedure without supervision. Including diagram or picture may be helpful. Reference any safety precautions that the worker should be particularly aware of or what they should avoid.

The gear switch controls the gear (direction) of the car

- RIGHT position for FORWARD
- LEFT position for BACKWARD
- MIDDLE position for NEUTRAL (car cannot run)

The driving system uses two pedals, on the left and right of the vehicle. It requires two feet for operation. The RIGHT pedal is throttle and the LEFT is for braking. These are drive-by-wire systems, so the pedals do not need much actuation force. For emergency situations, use the handbrake.

Again, because of how the drivetrain is set up, the vehicle will handle differently than most modern vehicles. Start slow to familiarize yourself with the driving characteristics.

Best practice is to drive with at least one other person supervising.

A minimum of 3 meters of stopping distance should be allocated for driving the car. This is determined from the maximum speed of the kart to give appropriate response time if something goes wrong. As the track is 18m in distance, with an additional 6m before any wall, this gives sufficient time for the kills switch to be activated before anything happens.

12.0 Test Description

Determining the JND statistically between linear & angular acceleration.

Determining the statistical average of physical acceleration of the mobile platform of which the general public rated how much “fun” the experiences are.

Continuous tests are when the users are in the experience for an extended period of time, where tests are run back-to-back.

Prior to all tests, a calibration test will be done so that participants are familiarized with the equipment. No VR will be used in the calibration. The path is a simple oval, and it will include

Short linear section

Short turn/angular section

Both of the tests will utilize an adaptive staircase, where users will say if the test felt real/authentic or not. In this case, real and authentic mean that the movement and acceleration perception matches what they would expect based on what is visually shown.

Linear Tests:

Designed to test linear acceleration perception

The hypothesis is that the initial “burst” is what how people perceive linear acceleration

1. Static visual perception

The visual component shows the acceleration at the same change rate of 1m/s^2

Physical acceleration gradually increased by 0.2m/s^2. After, the participant is asked if they felt a difference between the two runs.

If no, then physical acceleration is increased by another 0.2. And the sequence is run again (1:1 run, then difference run).

Once a difference is noticed, then we start to decrease by 0.2m/s^2 until the lower bound is found.

Repeat the entire process, bouncing back and forth until 12 “differences” are noticed by the participant.

The maximum speed is 1.5 m/s, and the minimum speed is 0.2 m/s. The max speed for the car is set at 3m/s, but this maximum speed will be capped with software control.

13.0 Driving Routine

Before starting any driving routines, the participants will first be familiarized with the setup, briefed on the routines and what to expect, and informed of their safety and their ability to opt out of testing at any moment. There will also be a control run without the

VR headset of linear and turning movement so that the participants have a reference and are acquainted with the vehicle's movement. The control run is set to an acceleration of 0. 5m/s in a linear 2 acceleration/motion. In this research project, the participants will engage in Adaptive Staircase routines. These break into linear acceleration at a set physical acceleration and a changing visual acceleration. The visual acceleration will continually increase until a Just Noticeable Difference (JND) is identified by the participant. Afterwards, the visual acceleration will gradually decrease until the participant notices the JND again. This repeats for a total of 12 JND identifications. Afterward, the participants will be asked to complete a questionnaire about their experiences. The methods behind these routines are found in the background research and include several similar methods. The participants will be engaging in linear movement and virtual environments as described in the above section. This testing method is built from the “staircase methods” discussed in the background section. Participants will start with a 0. 5m/s physical and visual acceleration, followed by another run 2 where the physical acceleration is increased by 0. 1m/s . After each routine, they will be 2 prompted with yes or no questions relating to the previous two routines (Did you notice any difference between the physical acceleration and what was visually presented?) If the participant answers “No,” then the system will continue to run tests until the participant answers that they notice a JND. At that point, it will gradually decrease the physical acceleration by 0. 1m/s until a similar difference is noticed. This entire process is then repeated until 12 “yes” 2 answers are provided by the participant. Note that the visual acceleration is kept at 0. 5m/s 2 while the physical acceleration is the only component that changes

14.0 Safe Observable Distance

The safe observable distance for the vehicle is one (1) meter away in a radius from the car. Due to the speed that the car is operating at (around 1 - 2 m/s), this has been determined as the safe observable distance for data collection.

New Change: A **safety zone** will be marked around the track, based on the vehicle's 3-meter stopping distance. **Only authorized personnel** are allowed within this zone during testing. Visitors must remain outside the designated safety zone, a minimum of **3 meters** from the track edge.

15.0 Shut-Down Procedure

1. Come to a complete stop
2. Change gear to NEUTRAL
3. Power vehicle ‘OFF’ using start-stop switch

16.0 Lockout Procedure

- Disconnect all 3 kill-switches in reverse order, starting with the 36V switch, then the 24V switch, and then the 12V switch.
- Validation for lockout is as follows:
    - Once all switches are turned off, sit in the vehicle and attempt to turn the wheels with the steering wheel. If there is no movement, the the vehicle is indeed in lockout.
- Battery terminals can be disconnected for electrical box work
    - Reference Powertrain/Mechanical Maintenance SOP prior to performing this action

17.0 Procedure Review

This procedure shall be reviewed annually by the author to ensure it reflects the most current conditions.

A minimum of two researchers must be present during all trials to ensure safety and effective supervision.

18.0 Sign-Off

By signing the sheet below, you acknowledge that you have:

1. Completed the necessary training as per the Training section described above including review of the process specific risk assessment
2. You have completed practical training and had the opportunity to ask questions

Name (Print)	Signature	Date

19.0 Record of Revisions

Date 1/10/2023	Name Chris Tseng (chris.tseng@uwaterloo.ca)	▪ V1 created	V**1**
Date 4/18/2023	Name Daniel Montazeri (d2montaz@uwaterloo.ca)	▪ Removed sections referring to kill switch as kill switch is now used as LV system switch ▪ Modified start-up and shut-down procedures ▪ Added further explanations to electrical hazards	V**1.1**
6/7/2024	Name Abhi Persad (apersad@uwaterloo.ca)	▪ Modified sections to include the 3 total kill switches and parallel 12V, 24V and 36V circuits.	V**1.2**

Appendix B

Ethics Documents

PROTOCOLS

#45573 - Linear Acceleration Perception on a Moving VR Environment

Protocol Information

Review Type	Status	Approval Date	Renewal Date
Expedited	**Approved**	**Sep 27, 2024**	**Aug 25, 2025**

Expiration Date	Initial Approval Date	Initial Review Type
Sep 17, 2025	**Sep 16, 2024**	**Expedited**

Feedback

Approval Comment

This amendment has received ethics clearance. Please direct any questions or concerns to Heather Dekker (hdekker@uwaterloo.ca).

Protocol Amendment Form

Amendment

Describe the proposed changes and why these changes are being made. Review the full application and ensure that you:
1) Revise/edit all sections that relate to the amendment;
2) Upload all revised or new study materials to the appropriate section. Use track changes or highlight within the document to show where changes have been made.

Adding a research assistant

General Information

Only the Principal Investigator/Faculty Supervisor can submit the application. This acts as a signature indicating approval of the application.

Principal Investigator / Faculty Supervisor

David Wang

Department

Electrical and Computer Engineering

Study title

Linear Acceleration Perception on a Moving VR Environment

General Questionnaire

Indicate the type of application you would like to complete

Standard application *

*** The Standard application is for faculty level research and thesis level research.**

**** The course project application is for single-term (non-thesis) course based research and can be completed by students or the course instructor**

Please confirm:

I understand that the type of applications listed above determine the form I am about to complete. If I have chosen the incorrect form I acknowledge that I may need to complete a new application.

People

University of Waterloo research team

Ensure all information in this table is completed.

Person

David Wang

Waterloo Department

Electrical and Computer Engineering

Email Address

dwang@uwaterloo.ca

Phone

Researcher Role

Principal Investigator

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

REQUIRED: Upload a copy of the TCPS 2 certificate or a screen shot showing module completion. Applications where the certificate/screen shot is not uploaded will be sent back to the researcher and not reviewed.

Certificate.pdf

As per the Waterloo policy on mandatory research ethics training, if you completed the TCPS2 tutorial more than 5 years ago, you may be asked to update your training within the next 6 months. You will be notified by email if this is the case.

Ensure all information in this table is completed.

Person

Justin Zhou

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Email Address

justin.zhou@uwaterloo.ca

Phone

Researcher Role

Student investigator

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

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tcps2_core_certificate.pdf

As per the Waterloo policy on mandatory research ethics training, if you completed the TCPS2 tutorial more than 5 years ago, you may be asked to update your training within the next 6 months. You will be notified by email if this is the case.

Ensure all information in this table is completed.

Person

Jordan Wang

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Electrical and Computer Engineering

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jt4wang@uwaterloo.ca

Phone

Researcher Role

Student investigator

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

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tcps2-eptc2-certificate.pdf

As per the Waterloo policy on mandatory research ethics training, if you completed the TCPS2 tutorial more than 5 years ago, you may be asked to update your training within the next 6 months. You will be notified by email if this is the case.

Ensure **all** information in this table is completed.

Person

Keegan Fernandes

Waterloo Department

Electrical and Computer Engineering

Email Address

ka3ferna@uwaterloo.ca

Phone

Researcher Role

Student investigator

Permissions

Full Access

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

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tcps2_core_certificate.pdf

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Ensure all information in this table is completed.

Person

Tony Wu

Waterloo Department

Electrical and Computer Engineering

Email Address

t99wu@uwaterloo.ca

Phone

Researcher Role

Research assistant

Permissions

Read-Only

Mandatory Training

All University of Waterloo undergraduate and graduate students, faculty, and staff must complete the TCPS 2 CORE tutorial prior to submitting an application for review. See instructions or email researchethics@uwaterloo.ca if you have questions.

REQUIRED: Upload a copy of the TCPS 2 certificate or a screen shot showing module completion. Applications where the certificate/screen shot is not uploaded will be sent back to the researcher and not reviewed.

tcps2_core_certificate (1).pdf

As per the Waterloo policy on mandatory research ethics training, if you completed the TCPS2 tutorial more than 5 years ago, you may be asked to update your training within the next 6 months. You will be notified by email if this is the case.

Do you have any investigators external to the University of Waterloo?

No

General details

Is this new study related to any previous application?

No

What is the estimated start and end date for the study?

Start Date (Date you anticipate beginning the recruitment of participants)

May 12, 2024

End Date (Date you expect the study will end, for example, the date when there will be no further contact with participants or when the data analysis will be completed for US funded research)

June 27, 2024

Does this research require approval from a UWaterloo departmental committee?

Not a department requirement

What is the level of the research to be conducted? Choose one.

Master's thesis

Will this study involve Wilfrid Laurier University, Western University, Conestoga College or Local hospitals covered by the Tri-Hospital Research Ethics Board (Cambridge Memorial Hospital, Grand River Hospital and St. Mary's General Hospital)?

No

Has a version of this study been disapproved or rejected by any Research Ethics Board/Committee?

No

Study description

State your research question(s)

Can human users distinguish between changes in physical linear acceleration when placed in a moving virtual reality environment? If so, can this Just Noticeable Difference (JND) be quantified?

Provide a clear, detailed description of the purpose, hypothesis, aim, and objectives of this study

Hypothesis: When placed into a moving VR environment, the null hypothesis is that users cannot distinguish between physical acceleration changes in virtual visual cues and physical acceleration/movement when they are presented at a 1m/s^2 to 1m/s^2 1:1 scale. That is, the VR environment is visually moving at the same rate as the mobile platform is physically. However, through gradually increasing/decreasing the physical acceleration, there will eventually be a point at which they will be able to detect the changes, provided the change in physical acceleration values exceeds some JND. Specific Aims: Determine the statistical medium of physical acceleration of the mobile platform by which participants can tell that there is a difference between the JND in physical vehicle acceleration and the virtual environment. Determine the statistical medium of physical acceleration of the mobile platform by which participants find “most enjoyable” between changes in physical vehicle movement and the virtual environment.

Provide background information, a rationale, and justification for conducting this study. Describe why the research is being done and what research has already been done in this area. Be sure to explain why this research is important.

In virtual reality (VR) environments, several factors provide senses to the users. The main component is visual cues[1]. These visual components can make the users feel like they are in a completely different space from their physical surroundings[1][2]. Recent developments have been made to make these virtual realities as immersive as possible for the users. These methods allow the users to provide more physical movement through the usage of treadmills and Omnidirectional shoes[3][4]. However, these solutions and measurements of immersion have only been used on a stationary base[3][4]. These immersion methods work because they pair the physical movement with visual cues that the virtual environment is changing. However, there is a limit to how fast the virtual environment can change, as the rate of change in the environment needs to match the physical movement[3][4]; otherwise, the immersion is broken i.e. the participants are no longer immersed in the environment as a result of mismatched visual and physical changes. It is this link between physical movement/acceleration and the virtual environment that this research project intends to measure. The novel contribution is to measure and characterize the differences between physical 2D movements on a moving vehicle and the rate at which the virtual environment can change. Building upon previous research on VR and driving psychology, we can utilize VR, visual virtual environment scaling, and an omnidirectional moving vehicle to determine the JND of linear and 2D acceleration/movement in virtual environments. In this research project, we intend to measure and determine the limits of what is visually presented to people in virtual environments and what they are physically/actively doing. The uses of this research have several applications for commercial use. It can be used as data to evaluate the limits of VR implementations and how big of a factor acceleration and motion affect the majority of people. One main outcome is to attempt to conserve space in commercial use by “tricking” users that they are moving/turning when they physically aren't. [1] - N. Ogawa, T. Narumi, and M. Hirose, “Object size perception in immersive virtual reality: Avatar realism affects the way we perceive,” 2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), 2018. [2] - J. Ping, Y. Liu, and D. Weng, “Comparison in depth perception between virtual reality and Augmented Reality Systems,” 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (VR), 2019. [3] - H. Iwata

and T. Fujii, “Virtual perambulator: A novel interface device for locomotion in virtual environment,” Proceedings of the IEEE 1996 Virtual Reality Annual International Symposium, 1996. [4] - D. Li, D. Weng, H. Zhou, and J. Xie, “Motion Interactive System with Omni-directional display,” 2013 International Conference on Virtual Reality and Visualization, 2013.

In a maximum of 250 words, provide a non-scientific lay language description that summarizes the project outlining the purpose, anticipated benefits, and basic procedures. Write this summary as if it would be read by members of the general public who are not familiar with academic terms or acronyms. Use language suitable for a media release.

Virtual Reality (VR) isn't just about games and simulations anymore; it's becoming a part of our daily lives. What is the secret sauce that makes VR so captivating? This research project aims to demystify this for the everyday person. When you put on a VR headset, you're transported to a digital world, and your senses are captivated by what you see. But what if we could make this experience even more real? When we walk, we use our eyes to tell how fast we are moving, and whether we are moving in a straight line. The same logic also applies to when we are driving. While we are able to tell some changes in acceleration, it is mainly our eyes that allow us to determine how fast we are moving. Enter our research initiative. We're trying to decipher the connection between our tangible actions and what unfolds in VR. Imagine this scenario: you're donning a VR headset while aboard a moving vehicle. How does your physical movement tie into the vehicle's speed? ' Our research leverages a concept called the "Just Noticeable Difference" (JND) to revolutionize the way we design VR environments. In simple terms, it means we can create different design choices for VR settings, including ways to shrink the required physical space by harnessing the power of JND. Picture this: You're wearing a VR headset while in a moving vehicle. How does the speed of the vehicle affect what you experience in VR? That's the mystery we're solving. What if we showed visual speed and acceleration different from what was physically happening? At what point would you be able to tell a difference?

What is the study design?

Quantitative Observation, Systemic Observation

Is this a pilot study?

No

Sample Size

What is the expected sample size? Outline the number of participants anticipated to take part in the study.

30 participants who are experienced in VR and have driving experience (or driving simulation experience) are expected to take place in this study

Was a formal sample size calculation completed?

No

Provide a rationale for the number of participants specified

To our best efforts, the vast majority of VR research doesn't follow standard sample size calculations. This is due to the large variety of VR users and the large use case scenarios. For this study, we will be testing with 30 participants who are familiar with and have used VR and Driving simulators best to quantify the Just Noticeable Difference for linear acceleration perception. The rationale is that if experienced users in the field can be "tricked" or "fooled," then the majority of people wouldn't notice the same detail that experienced users do. Otherwise, the sample size for the experiment would grow to a scale that isn't feasible to test.

Study sites

Where is this study taking place?

On a University of Waterloo campus

Are there any permissions required to conduct this study on campus?

No

Funding

Is the study funded/will it be funded?

Yes

Funding
List all funding sources that are new or ongoing

Funding status

Ongoing funding

Funding source is

Tri-agency / Canadian Government sponsor

Canadian Government agency

NSERC - Natural Sciences and Engineering Research Council of Canada

Program name if applicable

NSERC Discovery

Work-order or award number, if known

What is the expected period of funding

Funding from

August 31, 2022

Funding to

August 29, 2024

Conflict of interest

Are there any potential, perceived, or actual financial or non-financial conflicts of interest of the research team in undertaking the proposed research?

No

Benefits

Are there direct benefits of the proposed research to the study participants?

No

What are the scientific and/or scholarly benefits of the proposed research?

Understanding of what effect visual cues play on the perception of linear acceleration.

Participants

Participant general categories

University of Waterloo undergraduate and/or graduate students
Adults (age 18-64 years)

Are you conducting research in classes with students as your participants to evaluate a teaching method or object?

No

Describe the sample in detail and list any specific inclusion/exclusion criteria for the study

Participants must be between the ages of 18 - 40, with no major health conditions or hearing/visual impairments. The purpose of these exclusion criteria is because the study is to verify if the proposed test methods can be used for general study/testing. Health conditions and hearing/visual impairments would hinder the participants ability to perceive the acceleration and visual aids presented in the study, thus not providing us with valid/expected information and data. Participants must have experience with Virtual Reality (VR) and driving simulators.

If you are excluding people on certain characteristics provide a justification for the exclusion.

Exclusion on people with disabilities due to the nature of the investigation. VR relies on complete stereoscopic 3D to create proper immersion effects. Furthermore, the moving platform is only rated for healthy participants with no health conditions/disabilities. Health exclusions include: - musculoskeletal - vestibular - hearing/visual - neurological - medical implants

Will a screening process be used to determine eligibility in the study based on the inclusion and/or exclusion criteria identified above?

Yes

Is a screening questionnaire to be used?

Yes

Explain how eligibility will be determined using the form (e.g., would checking off any of the criteria on the form preclude participation in the study) and who will be responsible for reviewing the completed questionnaire.

Eligibility is determined by a few different factors: 1. Has the participant used VR before (and if they are experienced with it) 2. Has the participant used a driving simulator (and if they are experienced with it) 3. Does the participant have any health conditions, impairments, or medication? 4. Participant is born after 01/01/1995 and born before 01/01/2005 (as indicated by age and not Date of Birth)

Upload a copy of screening questionnaire
Please "Add line" for each file you have

Screening questionnaire file

Questionnaire Q2.png

Screening questionnaire file

Questionnaire Q3.png

Screening questionnaire file

Questionnaire Q4.png

Screening questionnaire file

Questionnaire Q5.png

Screening questionnaire file

Questionnaire Medical Questions.png

Screening questionnaire file

Questionnaire Pass Screen.png

When is the screening to be conducted in relation to other study procedures (i.e., consent)?

Screening will be done before any study procedures begin, potential participants will have an opportunity to review the information letter prior to participating in the screening. Once participants have been selected, then they will be sent consent forms and details about the research.

What are individuals told if they do not meet the eligibility criteria?

They will be provided with the following message: Thank you for your interest in participating in this research investigation! Unfortunately, due to the scope of the research project, you do not meet the eligibility criteria. Your information will not be saved.

What will be done with the information or data collected if an individual is deemed ineligible to participate in the study?

The information will not be saved and will be destroyed.

Recruitment

Identify from where/what sources potential participants will be recruited.

University of Waterloo campus (e.g., SLC, Engineering Foyer, laboratories)

Where on campus do you intend to recruit?

Faculty of Engineering

What recruitment materials will be used? See sample recruitment materials.

Verbal script

Upload your recruitment materials

Upload your recruitment materials

Linear Acceleration Perception on a Moving VR Environment Verbal Recruitment Script (1).pdf

Study group

Will potential participants be recruited through pre-existing relationships with members of the research team (e.g., employees, students, or patients of research team, acquaintances, own children or family members, colleagues, etc.)?

Yes

Outline the relationship between the researchers and potential participants (e.g., professor-student, colleagues)

Friends & acquaintances

Could this relationship compromise the potential participant's freedom to decline participation?

No

Explain

Participants are not forced to participate in the research. Furthermore, they must pass the eligibility test to be considered.

Methods and procedures

Which of the following will be conducted for this study?

Surveys/questionnaires
Observation as described in TCPS 2 Chapter 10
Other

Describe the other procedure

Virtual Reality & Driving Simulation

How will the survey(s) or questionnaire(s) be administered?

In-person - Paper and pen/pencil
In-person - Computer-administered or web/online

Will quotations be used in the write-up of the study

No

What type of observations are planned?

Participant observation (where the researcher engages in, and observes, the action; participant knows they are being observed)

Will the people being observed have an expectation of privacy?

No

Explain why there will not be an expectation of privacy

Participants will be informed of the test and the observation of their behaviour while in the moving VR platform.

For each of the procedures indicated above, provided a detailed, sequential description of how they will be used in the study. Provide one or more paragraphs describing how you are recruiting participants, obtaining consent, what participants are asked to do, and how the research team will be using the collected data.

Objectives: Determining the JND statistically between linear & angular acceleration. Determining the statistical average of physical acceleration of the mobile platform of which the general public rated how much “fun” the experiences are. Continuous tests are when the users are in the experience for an extended period of time, where tests are run back-to-back. Prior to all tests, a calibration test will be done so that participants are familiarized with the equipment. No VR will be used in the calibration. The path is a simple oval, and it will include Short linear section Short turn/angular section Both of the tests will utilize an adaptive staircase, where users will say if the test felt real/authentic or not. In this case, real and authentic mean that the movement and acceleration perception matches what they would expect based on what is visually shown. Linear Tests: Designed to test linear acceleration perception The hypothesis is that the initial “burst” is what how people perceive linear acceleration 1. Static visual perception The visual component shows the acceleration at the same change rate of 1m/s^2 Physical acceleration gradually increased by 0.2m/s^2. After, the participant is asked if they felt a difference between the two runs. If no, then physical acceleration is increased by another 0.2. And the sequence is run again (1:1 run, then difference run). Once a difference is noticed, then we start to decrease by 0.2m/s^2 until the lower bound is found. Repeat the entire process, bouncing back and forth until 12 “differences” are noticed by the participant. Following the test, the participants are then asked to answer a simple questionnaire. Questionnaire: Questions will be marked with a scale from 1-10: Scale how immersive the experience is Scale how realistic the acceleration felt Scale how fun Motion sickness. Rate if you experienced any of the following descriptions: Sick to stomach Nauseated QUeasy Upset Stomach Stomach ache Dizzy Spinning Faint-like Lightheaded Blurred Vision Head rush Disoriented Sweaty Cold sweat hot/warm annoyed /irritated tired/fatigued uneasy How much did the visuals affect your acceleration perception? Would they want to participate again?

Please upload any study materials related to the procedure(s)

Study material

Methods & Routines (2).pdf

Study material

Study equipment setup.png

Does the study involve the administration or use of an approved drug or natural health product?

No

Will you be collecting any biological specimens?

No

Will you be creating or contributing to a bio-bank, bio-repository, registry, as part of the study?

No

Will you be doing any genetic testing or analysis?

No

Incidental and secondary findings

See Guideline for reporting incidental and secondary findings to study participants

Are any of the methods or procedures used likely (i.e., a real possibility and probability) to reveal an incidental finding (i.e., discoveries made in the course of research but that are outside the scope of the research and/or results that are outside the original purpose for which a test or procedure was conducted)?

No

Are any of the methods or procedures used likely to reveal a secondary finding (i.e., findings that are not the primary target of the test or procedure; rather, it is an additional result that is actively sought)?

No

Equipment use

Will there be any equipment used as part of this study?

Yes

Please list all equipment being used in this study

Full name of device or equipment

Electric Go Kart

What type of device or equipment is this

equipment or device that has been created or built and/or modified by the researchers to be used with participants

Has this equipment or device been used in a previous study?

No

Upload a copy of the assessment form, if already approved by the Safety Office

Wang - Acceleration comparison GoKart and VR - Sept 13 2024.pdf

Upload your team's SOP, for the equipment or device.

EQUIPMENT OR DEVICE SAFETY RISK ASSESSMENT REVIEW FORM.pdf

Full name of device or equipment

HP Reverb G2 VR Headset

What type of device or equipment is this

equipment or device that is approved for sale or use in Canada to be used with participants

Is this a medical device?

No

Select how you will be providing more information on the device/equipment

I am providing other supplementary information (e.g., user manual)

Attach the other supplementary information (e.g., user manual)

Acceleration Research HPG2 User Manual.pdf

Full name of device or equipment

Electric Go Kart SOP

What type of device or equipment is this

equipment or device that has been created or built and/or modified by the researchers to be used with participants

Has this equipment or device been used in a previous study?

No

Upload a copy of the assessment form, if already approved by the Safety Office

ElectricVehicle_GeneralSOP_Updated.pdf

Upload your team's SOP, for the equipment or device.

ElectricVehicle_GeneralSOP_Updated.pdf

Deception

Does the study involve deception or partial disclosure?

No

Risks and safeguards

Considering each method or procedure to be used in this study, indicate if participants might experience any of the following risks or harms

Physical risks or harms (e.g., bodily contact, fall, muscle strain, administration of a substance)

Risk details

For each risk identified above, please add additional details describing that risk

Describe the risks or harm

low-risk short term. There is a little chance of the moving platform hitting a stationary object such as a wall or a pole. The testing will occur at Catalyst Entertainment, which as several safety protocols implemented

Are any of the risks or harms identified above greater than those the participants might encounter in their everyday life?

No

A determination will be made, upon receipt of the application, if the research can be reviewed by delegated review or must be reviewed by one of the two Research Ethics Boards.

Describe the safeguards (or procedures) to be put in place to mitigate each of the risks or harms identified above.

There is a dead-man trigger to be operated by the test operator. This trigger will shut off any movement and remove power to the mobile platform in the event that the test operator senses that the platform will hit a wall or a pole. Furthermore, the platform is moving in pre-planned and coded routines, which further reduces the chances of it hitting a stationary object.

For the risks or harms identified above, is there any monitoring that will need to be undertaken during the study?

No

For the risks or harms identified above, is there any monitoring that will need to be undertaken following the study conclusion?

No

Describe the risks or harm

Simulation / Motion sickness (Short-Term), this is low-risk and low-severity as is a well-known potential common side effect of VR and simulator use.

Are any of the risks or harms identified above greater than those the participants might encounter in their everyday life?

No

A determination will be made, upon receipt of the application, if the research can be reviewed by delegated review or must be reviewed by one of the two Research Ethics Boards.

Describe the safeguards (or procedures) to be put in place to mitigate each of the risks or harms identified above.

Participants are first filtered if they are easily susceptible to nausea (indicated from the recruitment survey). Furthermore, if the participant starts to feel nauseous, then they can request a short break or leave the study entirely.

For the risks or harms identified above, is there any monitoring that will need to be undertaken during the study?

No

For the risks or harms identified above, is there any monitoring that will need to be undertaken following the study conclusion?

No

Outline the criteria for stopping the study early due to safety concerns/other issues.

If the mobile platform is faulty and/or breaks down, the study will end before the planned end date.

Privacy

Will demographic and/or background information be asked of participants? If so, ensure that the demographic questions have been uploaded in the methods section.

Yes

What demographic/background information will be collected?

Age

Other

Describe what “other” demographic/background information will be collected.

VR , driving simulation experience, and any health conditions.

Will demographic/background information be collected separately from names and other identifying information?

Yes

Participant identification - If applicable, include how participants will be referenced in study results.

Participants will be identified on the data collection forms as data from study numbers.

If applicable how will the key/list that links participants’ codes with their actual name and/or consent forms be stored and protected? Also, outline how long the key/list will be stored.

It will be stored offline on a test PC during the duration of the testing. Afterwards, it will be destroyed.

Are there any limitations to the promise of confidentiality?

No

Will any study data be leaving the University of Waterloo, the province, or country (e.g., member of research team is located in another institution, province, or country, etc.)?

No

Will any collected data or information be entered into a database for future use?

No

Are there other members of the research team who are not named on this application (e.g., co-op students, research assistants, or other temporary personnel) who may carry out specific tasks involved in your study?

No

Will individual participant identities be confidential in the publication or release of the study findings?

Yes

Data storage

What type(s) of data will be collected for this study?

Electronic files
Other

Other type of data collected

Accelerometer data, timestamps, and mobile platform position.

For each type of information collected, identify where the data will be stored

All information will be stored offline, encrypted on the research test PC

For each type of data collected, identify the minimum retention period

The data will be kept for a minimum period of one year after the last use following the end of the research investigation, which is projected to end on August 31, 2024.

Data Management

Are there plans to link the data collected with other data sets, databases, or registries?

No

The Tri-Agency Open Access Policy on Publications and some journals are requesting that research data be provided to an open access repository to promote the availability of findings, to enhance transparency and share with the widest possible audience.

Do researchers plan to make the data-set available in an online repository/archive?

No

Do you have a data management plan?

Yes

Consent and Withdrawal

What member(s) of the research team will be responsible for obtaining informed consent?

Justin Zhou

Is there a relationship between the potential participant(s) and the person obtaining consent?

Yes

Explain the nature of the relationship (e.g., professor/course instructor, teacher, supervisor, employer, health care professional/physician, etc.)

Friends / Acquaintances

Describe how undue influence and/or authority to participate will be mitigated.

Participants will be informed before anything that they are not forced to do anything, and that they have the right to exit the research at any moment.

How will consent be obtained

Written signature on a consent form

Upload Information and Consent Materials - See resources and samples for creating information consent letters. Refer to the guide for creating an information consent letter on this webpage.

Upload Information and Consent Materials

WRITTEN CONSENT FORM.pdf

Study group

Upload Information and Consent Materials

Information-Consent Letter - Google Docs.pdf

Study group

Do you anticipate that you will need to make special accommodations for your participant group?

No

Do you anticipate needing to put in place any special procedures when obtaining informed consent?

No

Will consent need to be re-documented throughout the life of this study?

No

Describe the participants rights and processes for withdrawing consent.

Should a participant want to exercise the right to leave the research, then they simply need to verbally notify the test operator, and the will be able to withdraw from the investigation. Their information and results will then be destroyed,

Outline what will be done with the participant's information (data, samples, etc.) if they withdraw from the study.

Their information and results will be destroyed and not used in the study.

Will any individuals taking part in this study be unable to provide their own informed consent?

No

Remuneration

Will there be remuneration provided to show appreciation for a participant's time, effort, skills, etc. to take part in the study?

Yes

Type of remuneration

Cash

Dollar amount:

25

If a participant withdraws from the study will remuneration be pro-rated?

No, participants will receive maximum remuneration

Will participants incur any expenses by participating in the study?

No

Feedback and Appreciation

How will you show appreciation to participants for taking part in the study?

There will be a written appreciation letter sent to the participants. The letter will describe the purpose of the study, restate the confidentiality and security of the data, an indication of when a study report will be available and how to obtain a copy, contact information for the researchers, and the ethics review and clearance statement.

When will feedback/appreciation be provided to participants (e.g., immediately after the session, at the end of a survey, mail results at time X.)?

The appreciation letter will be sent to the participants following the session.

Upload Feedback/Appreciation materials

Upload Feedback/Appreciation materials

Appreciation Letter.pdf

Study group

How can participants learn about the study results/obtain a summary of the findings if interested?

An email will be sent out to them if they are interested. They will be verbally asked if they would like to learn about the results.

Other Details

Provide any other information relevant to this study you wish to explain to the Research Ethics Board reviewers or to the staff in the Office of Research Ethics.

N/A

Other Attachments

Upload any additional study documents

Attachments

Attestation

As the Principal Investigator/Faculty Supervisor/Local Investigator, I attest to the following:

- I will ensure all co-investigators, collaborators, and student investigators listed on this application have reviewed the application contents and will conduct the study according to the application/protocol.
- I am aware that any changes made to the research must be reviewed and provided clearance before the changes are implemented. Change requests (i.e., an amendment) are to be submitted through the system. I am also aware ethics clearance for this study is valid for only 12 months unless I renew the study prior to the ethics clearance expiry date. If an annual renewal report is NOT submitted through the system prior to the expiry date, the study will be suspended, all work on the study must stop, and Research Finance will be notified which will result in a hold being put on the funds associated with this study.
- I agree to comply with the Tri-Council Policy Statement (TCPS2) for conducting research with human participants and with University of Waterloo policies and guidelines when conducting this study (e.g., statement on human participant research, IST policies, etc.).
- I confirm I have read the University of Waterloo Research Integrity guidelines and I agree to comply with the policies and guidelines of my profession or discipline regarding the ethical conduct of research involving humans.

By submitting this application I agree to the above attestations and will ensure the research is conducted accordingly

Only the Principal Investigator/Faculty Supervisor can submit the application. This acts as a signature indicating approval of the application.

This is the end of the application form. Click submit in the right menu if you are ready to send it to the Research Ethics Office.

Appendix C

Go Kart Safety

C.1 Risk Assessment Form

EQUIPMENT RISK ASSESSMENT

RESET FORM

This form can be expanded electronically or extra information (e.g. photos) attached.

#: 1

Department: Electrical & Computer Engineering

Assessment/Equipment Name:	Assessment Date:	Review Date: N/A (3 years maximum)
Electric Go Kart	May 01, 2024	

Description of equipment:

Location: Building E7 Room #: 1437 Person in charge of the equipment: Chris Rennick

Manufacturer/Make/Model: N/A

Serial no and/or UW Asset No: N/A Purchase date: N/A

Installing company (if applicable) : N/A

Service/calibration contractor (if applicable): N/A

Any relevant regulation, code, standard, guideline or manufacturer handbook (list):

Licensing

Are there any licensing requirements associated with ownership or operation of the equipment? ☐ Yes ☒ No

E.g.: Ionizing radiation, Biosafety, Laser, X-ray, Cannabis

- Are licenses obtained and displayed? ☐ Yes ☐ No Permit #:

Risk assessment and Control — Identify hazards (use the checklist pg. 2) to list hazards and then rate the risk using the Risk Rating Matrix. Detail control measures required to address the risks

Controls to be considered in the following order:

1. Elimination (is it necessary?)
2. Substitution
3. Isolation (restrict access)
4. Engineering (guarding, redesign)
5. Administration (training, SOP,)
6. Personal Protective Equipment (PPE) (e.g. gloves, leather apron, coveralls, respirator)

Identified Hazards Exposure	Risk assessment		Risk Rating	Required Controls	Controls Implemented	
	Consequences	Likelihood				
Cables on the floor, tripping	Minor	Likely	Medium	SOP, Training	Yes ☒	No ☐
Hinges on the kart, pinching	Minor	Unlikely	Low	SOP, Training	Yes ☒	No ☐
Enclosed battery, low voltage&amp	Minor	Very Unlikely	Very Low	SOP, Training	Yes ☒	No ☐
VR, Nausea	Negligible	Likely	Low	SOP, Training	Yes ☒	No ☐
					Yes ☐	No ☐
					Yes ☐	No ☐
					Yes ☐	No ☐
					Yes ☐	No ☐
					Yes ☐	No ☐

Implementation Plan (for controls not already in place)

Control Selected	Person(s) responsible	Proposed completion	Actual completion
Standard Operating Procedure	Justin Zhou	May 01, 2024	May 08, 2024
Training	Justin Zhou	May 10, 2024	

Person Completing Assessment

Name: Justin Zhou Signature: Date: May 05, 2024

Assessment Approval: (eg Principal researcher, Technical Director, Manager)

I am satisfied that the risks are adequately controlled.

Name: Signature: Date:

Position Title:

	Hazards: Potential to cause harm to people, property or the environment. Check the applicable hazards				
	Mechanical hazards		**Radiation**		**Movement and controls**
☐	Accumulation of energy e.g. springs, liquids or gases under pressure, vacuum	☐	Low-frequency, radio frequency radiation; microwaves	☐	Failure/lack of display or alarm system
☐	Crushing hazard	☐	Infrared, visible and UV radiation	☐	Restoration of energy supply after Interruption
☐	Cutting, shearing, friction or abrasion hazard	☐	X-rays and gamma rays	☐	Errors or vulnerability in software or programming
☐	Entanglement, drawing in or trapping hazards	☐	Lasers	☐	Errors made by operator (human/machine mismatch)
☐	Impact hazard	☐	Alpha and beta rays, electron beams neutrons	☐	Movement when starting engine
☐	Puncture/injection hazard		**Ergonomics/Human Factors**	☐	Movement without all parts in a safe position
☐	High pressure	☐	Unhealthy postures or excessive effort	☐	Insufficient ability to slow down, stop and immobilize
	Electrical hazards	☐	Inadequate consideration of hand-arm or foot-leg anatomy	☐	From load falls, collisions, machine tipping (lack of stability)
☐	Contact with live parts (direct contact)	☐	Inadequate lighting	☐	Uncontrolled loading-overloading-overturning moments exceeded
☑	Contact with parts which have become live under faulty conditions (indirect contact)	☐	Inadequate design or identification of manual controls or visual display	☐	Unexpected/unintended movement of loads
☐	Approach to live parts under high voltage (arc flash)		**Thermal hazards**	☐	Hazards from coupling and towing
☐	Electrostatic phenomena	☐	Burns, scalds by contact with objects or materials (hot or cold)		**Vibration**
	Materials and substances		**Noise**	☐	Hand-arm vibration
☐	Contact/inhalation of harmful fluids, gases, mists, fumes, dusts	☐	Hearing loss or other physiological disorders	☐	Whole body vibration
☐	Fire and explosion	☐	Interference with speech, acoustic signals	☑	**OTHER** Pinching, VR Nausea
☐	Biological or microbiological hazards	☐			

RISK RATING MATRIX:

	RISK SEVERITY/CONSEQUENCE			
LIKELIHOOD	**CRITICAL** *(severe injury or fatality - >2 weeks lost time, major property damage)*	**MAJOR** *(injury resulting in at least one day lost time, moderate property damage)*	**MINOR** *(medical aid only, minor property damage)*	**NEGLIGIBLE** *(first aid treatment, minimal threat)*
VERY LIKELY *(likely to occur in a short period of time, expected to occur frequently)*	**High**	**High**	**Medium**	**Medium**
LIKELY *(quite likely to occur in time)*	**High**	**Medium**	**Medium**	**Low**
UNLIKELY *(not likely to occur, but possible)*	**Medium**	**Medium**	**Low**	**Very low**
VERY UNLIKELY *(Not likely to occur, even over time)*	**Medium**	**Low**	**Very low**	**Very low**

Risk priority	Definitions of priority	Time frame
High	Situation critical, stop work immediately or consider cessation of work process. Must be fixed today, consider short term and/or long term actions.	**Now**
Medium	Is very important, must be fixed urgently, consider short term and/or long term actions.	**1 – 3 weeks**
Low	Is still important but can be dealt with through scheduled maintenance or similar type programming. However, if solution is quick and easy then fix it today.	**1 - 3 Months**
Very low	Review and/or manage by routine processes	**Not applicable**

C.2 Safety Clearance

For Office Use Only
Project#:

EQUIPMENT OR DEVICE SAFETY RISK ASSESSMENT REVIEW FORM

Purpose: The purpose of this risk assessment form is to ensure that a risk assessment has been conducted when a device or piece of equipment which will be used on or tested with humans **(a)** has not been commercially obtained by the University **(b)** has been modified prior to being used.

Process: whenever the activity is occurring **under the auspices of UWaterloo** and will be tested or used on humans, and where the device or piece of equipment has been manufactured or modified, the equipment or device must first be assessed to ensure it is safe to be used on humans. In cases where this is **research requiring REC review**, the risk assessment must be provided with the **ethics application**. The risk assessment process will be proportionate, i.e. devices or equipment which present low risks should receive less scrutiny than those presenting high risks.

This form should be completed and submitted to the Safety Office (**safety@uwaterloo.ca**). The Safety Office will review the information contained on the form and assess the degree of risk involved with the device or equipment and recommend additional scrutiny or expertise if required. If the device or equipment presents above minimal risks, the Safety Office may request that the Laboratory Safety Committee (LSC) or external expert review and approve the device or equipment before it can be tested or used on humans.

DIRECTIONS:

1) Complete this form ensuring that all required supplementary information is provided as outlined in 5) below.
2) Approval **and** inspection may be required before testing or use may occur. Allow 3-5 days after submission for contact from the Safety Office regarding questions and scheduling of the inspection if one is required.
3) In the case of students, the faculty advisor **must** submit this completed Equipment or Device Safety Review Form along with any additional supporting materials to the Safety Office.
4) The "Submitter" , i.e. the student, should be cc'd if the form is submitted by a faculty supervisor;
5) The following applicable attachments accompany this form:
    a. ☑Project Definition Document (for undergraduate and graduate students)
    b. ☑Detailed device information including photographs or drawings
    c. ☑Manufacturer's device electrical/mechanical safety documentation (for devices being modified)
    d. ☑Electrical Safety Testing documentation
    e. ☑Standard Operating Procedure which will be used with the device or piece of equipment
    f. ☑Any other documentation that would assist the committee in determining the level of risk posed by the device
6) Subject line **must** read "Equipment or Device Safety Review From for [submitter's name]".

I. GENERAL INFORMATION	
Project Title: Linear Acceleration VR Study (Max: 142 Characters)	
Submitter/ Lead Contact: Justin Zhou	**Submitter Phone:** [redacted]
Submitter E-mail: J64zhou@uwaterloo.ca	**Faculty Advisor:** Dr. David Wang **Department:** Electrical & Computer Engineering
Students involved with project:	

II. DESCRIPTION	
A.	This project is: ☑ Student thesis/dissertation ☐ Student class project ☐ Faculty or staff research proposal ☐ Product development ☐ OTHER (specify):
B.	This project is: ☐ Not funded or self-funded ☑ Funded Name of sponsor: NSERC Tri-Council ☐ Non-federally funded ☐ OTHER (specify):
C.	Check all that apply: ☑ Testing or use will occur with **uWaterloo employees or students** involving: a) a new device that was manufactured by the submitter; or b) a commercially bought device that was modified in some way. ☐ Testing or use will occur with persons who are **external** to the University Involving: a) a new device that was manufactured by the submitter; or b) a commercially bought device that was modified in some way. ☐ I intend to commercially market the device ☐ NONE OF THE ABOVE
D.	Date you plan to test or use the device: May 10 - June 28
E.	Date and location of where the device or equipment will be available for inspection. Approval/inspection must occur prior to any testing or use on humans: E7 - 1437
F.	Provide a brief description of **(a) the device**, **(b) its intended purpose**, and **(c) why it is needed**: (Note: If more space is required, please provide an attachment to this form) The device is a custom built electric GoKart under the supervision of Dr. Chris Rennick's team. It's intended purpose is to be used as a research GoKart that can drive autonomously. It is needed for this research as we are investigating the Just Noticable Difference (JND) for how users percieve the differences between physical linear acceleration (from the gokart) and visually percieved linear acceleration (from VR). Participants will be placed into the kart and experience both physical and visual linear acceleration.

G.	Provide a description of the demographics of who the device is being tested on or those who will use it. Include information such as age, mental or physical status, and any other relevant physical or social factors (e.g., specific medical conditions, prisoners, pregnant women, homeless, family or other factors which may create risks). University of Waterloo undergraduate and/or graduate students. Participants must be between the ages of 18 - 40, with no major health conditions or hearing/visual impairments. The purpose of these exclusion criteria is because the study is to verify if the proposed test methods can be used for general study/testing. Health conditions and hearing/visual impairments would hinder the participants ability to perceive the acceleration and visual aids presented in the study, thus not providing us with valid/expected information and data. Participants must have experience with Virtual Reality (VR) and driving simulators.
H.	Describe the setting in which the device will be used. For instance, possible locations, and any special considerations related to the environmental setting (flat surface, large room, another person to assist, quiet area, etc.): Flat surface room in E7 - 1437 with no obstructions or tables so that the kart can drive in a straight line. Another person will be present (trained) to assist in the research.
I.	Describe any **(a) mechanical safety**, **(b) electric safety**, and **(c) other risks** associated with the device. Include how these **risks will be minimized**. (Note: If more space is required, please provide an attachment to this form) Please view the provided Equipment Risk Assessment

II. DETERMINATION *(For office use only)*

A.	**Reviewed by:** Dhananjai Borwankar **Signed:** DSBorwankar **Date:** Sept 13 2024	
B.	☑ Testing or use may proceed within proposed use, standard operating procedures and conditions.	☐ Other conditions:
	☐ Testing or use may NOT proceed	☐ External review required. Resubmit upon completion. ☐ Insufficient information. Resubmit as per comments below. ☐ Risk is not acceptable.
C.	**Comments/Recommendations:** No other requirements are necessary	

Appendix D

Participant Screening

D.1 Participant Screening

D.1.1 Verbal Recruitment Script

Linear Acceleration Perception on a Moving VR Environment Verbal Recruitment Notes.

Main Points to Mention:

- Recruiting participants for a VR study.
- This is a study that has been reviewed and received clearance from the University of Waterloo Research Ethics Board.
- VR study while placed into a moving environment (Go Kart)
- We are looking for participants who have the following:
    - VR Experience
    - Driving Experience
    - Driving Simulation Experience
    - Go-Kart Experience
- Participants shouldn't have any pre-existing health problems
- Aid in research of how people perceive VR while in a moving environment
- Participants will be remunerated for their participation as appreciation, and have the ability to opt out at any time.
- Participant confidentiality will be kept and not released. (Deleted upon conclusion of the research, projected to end Aug 2024).

Where to signup:

- Sign the QR code provided -> Which will link to the recruitment screening questionnaire.

D.1.2 Screening Survey

VR Research Screening Survey

Thank you for your interest in VR Research.

Please fill out this survey to see if you are eligible to participate.

If you have any questions, please let the investigator know at J64zhou@uwaterloo.ca

Sign in to Google to save your progress. Learn more

* Indicates required question

How often do you use VR? *

	1	2	3	4	5	6	7	8	9	10	
Not Very Often	○	○	○	○	○	○	○	○	○	○	Very Often

Have you used a Driving Simulator Before? *

- ○ Yes
- ○ No

How often do you use a Driving Simulator? *

	1	2	3	4	5	6	7	8	9	10	
Not Very Often	○	○	○	○	○	○	○	○	○	○	Very Often

Do you have any impairments with musculoskeletal (back or body), vestibular (balance), hearing/visual, neurological (seizures, Parkinson's, etc.)? *

- ◯ Yes
- ◯ No

Do you have any medical implants (e.g. pacemaker)? *

- ◯ Yes
- ◯ No

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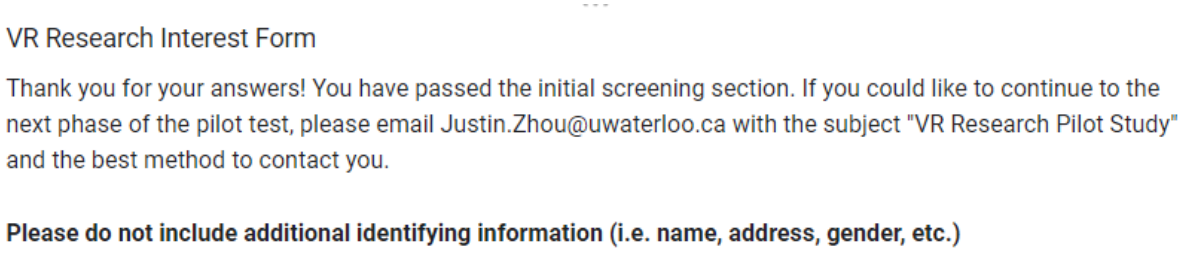


Figure D.1: Screening Survey Pass Screen

D.2 Pretest Forms

D.2.1 Written Consent Form

WRITTEN CONSENT FORM

Study Title: Linear Acceleration Perception on a Moving VR Environment

By providing your consent, you are not waiving your legal rights or releasing the investigator(s) or involved institution(s) from their legal and professional responsibilities.

I have read the information presented in the information letter about the study being conducted by David Wang and Justin Zhou from the Department of Electrical and Computer Engineering at the University of Waterloo. I have had the opportunity to ask any questions related to this study, to receive satisfactory answers to my questions, and any additional details I wanted.

I am aware that I have the option of allowing my interview to be audio recorded to ensure an accurate recording of my responses.

I was informed that I may withdraw my consent at any time without penalty by advising the researcher. Data cannot be withdrawn after results have been published.

I am aware that if I have any major health conditions that I may be excluded from participation from this study. Health conditions include but are not limited to, musculoskeletal, vestibular, hearing/visual, neurological, or medical implants.

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB #45573). If you have questions for the Board, contact the Office of Research Ethics, toll-free at 1-833-643-2379 (Canada and USA), 1-519-888-4440, or reb@uwaterloo.ca.

For all other questions contact Justin Zhou, justin.zhou@uwaterloo.ca .

☐YES ☐NO I agree and consent to any/all audio recording during the duration of the study. Prior to audio recording, the researchers will verbally notify of the recording start.

☐YES ☐NO I agree, of my own free will, to participate in this study.

Participant Name: _____ (Please print)

Participant Signature: _____

Date: _____

D.2.2 Information Consent Letter

Information-Consent Letter

Study Title: Linear Acceleration Perception on a Moving VR Environment

Principal Investigator/Faculty Supervisor:
David Wang
dwang@uwaterloo.ca
(519) 888 4567 x33968
University of Waterloo Department of Electrical & Computer Engineering

Student Investigator:
Justin Zhou
J64zhou@uwaterloo.ca
University of Waterloo Department of Electrical & Computer Engineering

To help you make an informed decision regarding your participation, this letter will explain what the study is about, the possible risks and benefits, and your rights as a research participant. If you do not understand something in the letter, please ask one of the investigators before agreeing to participate in the study. You will be given a copy of this information-consent letter if you choose to participate in the study for your records.

Invitation to participation/What is the study about?

You are invited to participate in a research study about the link between visual cues in Virtual Reality (VR) and a physically moving mobile platform.

Virtual reality (VR) is like putting on goggles and feeling like you're in a different world. The main way it does this is through what you see. Developers have been working hard to make it feel as real as possible. Some of the latest gadgets even let you walk around or use special shoes to feel like you're moving in this virtual world. But, most of the time, you stay in one spot. The magic happens because the virtual world changes as you move. But there's a catch: the virtual world can't change too fast or too slow, or you'll feel like something's off.

Our research wants to figure out the balance between how you move and what you see in VR. Specifically, we're curious about how it feels when you're in a moving car and the VR world is changing around you. We want to study how fast or slow the virtual world can change before it feels weird.

Our goal is to find out the limits of what people can see in VR versus what they're actually doing. Why? Because understanding this can help businesses use VR better. Imagine a VR game that makes you feel like you're running or turning, even when you're not. It would save a lot of space!

What does participation involve?

Participation in the study will consist of one 60-minute test session in which you will be asked to:

- Complete an orientation of the VR and mobile platform system.
- Placed into the platform and run a calibration test without VR.
- Wear a VR headset and perform general linear acceleration tests.
    - After each test you will be asked to answer a question prompted by the VR headset
- Once the test concludes, you will remove the headset and exit the platform.
- To conclude, you will be asked to complete a quick questionnaire about the test and your experience.

Who may participate in the study?

Participants must be between the ages of 18 - 40, with no pre-existing major health conditions or hearing/visual impairments. Health conditions include but are not limited to, musculoskeletal, vestibular, hearing/visual, neurological, or medical implants. Participants must have experience with Virtual Reality (VR), and driving experience or driving simulators.

The purpose of these exclusion criteria is because to our best efforts, the vast majority of VR research doesn't follow standard sample size calculations. This is due to the large variety of VR users and the large use case scenarios.

For this study, we will be testing with participants who are familiar with and have used VR and Driving simulators best to quantify the Just Noticeable Difference for linear acceleration perception. We are testing to see if experienced users in the field can be "tricked" or "fooled”.

Health conditions and hearing/visual impairments would hinder the participant's ability to perceive the acceleration and visual aids presented in the study, thus not providing us with valid/expected information and data.

There is an exclusion on people with visual/hearing impairments due to the nature of the investigation. VR relies on complete stereoscopic 3D to create proper immersion effects. Furthermore, the moving platform and VR is only rated for healthy participants with no health conditions/disabilities.

Is participation in the study voluntary?

Your participation in this study is voluntary. You may decide to leave the study at any time by communicating this to the researcher at any moment during the test.

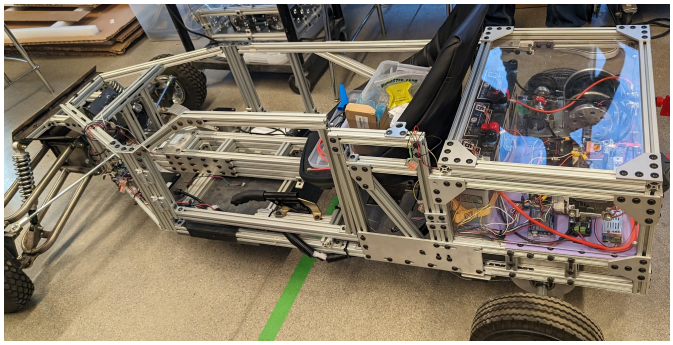
Will I receive anything for participating in the study?

In appreciation of your time, you will receive $25 for your participation. You will receive the full amount regardless of if you complete the entire session or choose to withdraw.

The amount received is taxable. It is your responsibility to report this amount for income tax purposes.

Photos of the Kart:





What are the possible benefits of the study?

The primary potential benefit of the study is an understanding of what effect visual cues play on the perception of linear acceleration.

There are no direct benefits to the participants.

What are the risks associated with the study?

There are two low-risks associated with the study:

1. There is little chance of the moving platform hitting a stationary object such as a wall or a pole. This is mitigated as there is a dead-man trigger to be operated by the test operator. This trigger will shut off any movement and remove power to the mobile platform in the

event that the test operator senses that the platform will hit a wall or a pole. Furthermore, the platform is moving in pre-planned and coded routines, which further reduces the chances of it hitting a stationary object.

2. Simulation / Motion sickness (Short-Term), this is low-risk and low-severity as is a well-known potential common side effect of VR and simulator use. If the participant starts to feel nauseous, then they can request a short break or leave the study entirely.

Will my identity be known?

Your participation in the study and the association of your identity with the study data will remain confidential.

An audio recording will be kept from the interview. This will occur before and after the study. The purpose is to record any feedback from the test procedures. You are not required to have this audio recorded, and the researchers will verbally confirm with you before any recording happens.

Will my information be kept confidential?

Individual results will not be shared in this study. Only the research team will have access to study data. Your information will be securely stored in a password protected file only accessible to the research team. Research data will be retained for a minimum of 1 year after August 31, 2024.

Future Data Use

There are no plans for future data use

Who is sponsoring/funding this study?

This study is funded by the NSERC Tri-Agency Grant.

Has the study received ethics clearance?

This study has been reviewed and received ethics clearance through a University of Waterloo Research Ethics Board (REB #45573) If you have questions for the Board, contact the Office of Research Ethics, toll-free at 1-833-643-2379 (Canada and USA), 1-519-888-4440, or reb@uwaterloo.ca.

Who should I contact if I have questions regarding my participation in the study?

If you have any questions regarding this study or would like additional information to assist you in reaching a decision about participation, please contact **Justin Zhou** by email at **J64Zhou@uwaterloo.ca**

Appendix E

Post Test Questionnaire

Acceleration VR Research Post-Exam Form

Thank you for completing in VR Acceleration Research.

Please fill out this questionnaire to finalize the research session

If you have any questions, please let the investigator know.

justinzhou8@gmail.com Switch account

Not shared

* Indicates required question

Please scale how immersive the experience is *

	1	2	3	4	5	6	7	8	9	10	
Not Immersive	○	○	○	○	○	○	○	○	○	○	Very Immersive

Please scale how realistic the acceleration felt *

	1	2	3	4	5	6	7	8	9	10	
Not Realistic	○	○	○	○	○	○	○	○	○	○	Very Realistic

Please scale how much fun you had *

	1	2	3	4	5	6	7	8	9	10	
Not much fun	○	○	○	○	○	○	○	○	○	○	Very fun

Please indicate if you felt any of the following regarding motion sickness (choose all that apply) *

- [ ] Sick to Stomach
- [ ] Queasy
- [ ] Nauseated
- [ ] Upset Stomach
- [ ] Stomach Ache
- [ ] Dizzy
- [ ] Spinning
- [ ] Faint-Like
- [ ] Lightheaded
- [ ] Blurry Vision
- [ ] Head Rush
- [ ] Disoriented
- [ ] Sweaty
- [ ] Cold Sweat
- [ ] Hot/Warm
- [ ] Annoyed/Irritated
- [ ] Tired/Fatigued
- [ ] Uneasy
- [ ] No Symptoms N/A
- [ ] Other:

How much did the visuals affect your acceleration perception? *

	1	2	3	4	5	6	7	8	9	10	
Not much	○	○	○	○	○	○	○	○	○	○	A Lot

Would you want to participate again? *

- ○ Yes
- ○ No

How often do you use VR? *

	1	2	3	4	5	6	7	8	9	10	
Not Very Often	○	○	○	○	○	○	○	○	○	○	Very Often

Have you used a Driving Simulator Before? *

- ○ Yes
- ○ No

How often do you use a Driving Simulator? *

	1	2	3	4	5	6	7	8	9	10	
Not Very Often	○	○	○	○	○	○	○	○	○	○	Very Often

Do you have any impairments with musculoskeletal (back or body), vestibular (balance), hearing/visual, neurological (seizures, Parkinson's, etc.)? *

- ◯ Yes
- ◯ No

Do you have any medical implants (e.g. pacemaker)? *

- ◯ Yes
- ◯ No

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