Virtual Reality (VR) in Occupational Training: Enhancing Training Performance and Overcoming Challenges in Forklift Driving

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ABSTRACT

The rapid advancement of technology has transformed occupational training, with virtual reality (VR) emerging as a promising tool, particularly for high-risk environments like forklift driving. VR enables immersive, hands-on learning in a safe, controlled setting, reducing real-world hazards. However, current VR-based occupational training often falls short in preparing novice operators for complex, real-world tasks requiring advanced skills. Additionally, cybersickness remains a critical barrier to broader adoption.

To address these challenges, our research pursued three interconnected goals. First, we aimed to enhance training effectiveness through real-time multimodal feedback in VR forklift-driving training. In the initial phase of our first study, we gathered expert strategies from 12 experienced forklift drivers and identified common errors among 20 novices. Based on these observations, we developed visual and haptic feedback methods. In the second phase, 15 novices completed training modules incorporating these feedback types. Haptic feedback significantly reduced training completion time compared to either visual or combined feedback (visual and haptic), but not significantly different from no feedback in the fork-pallet engagement module. Visual and combined feedback, however, increased completion times compared to providing no feedback. Haptic feedback also reduced perceived mental demands compared to visual or no feedback. Semi-structured interviews provided further user experience feedback and design considerations for future feedback systems.

During the first study, we observed high dropout rates due to cybersickness, especially among older adults and female participants. This led to our second study, which examined the impact of demographic factors, i.e., age and sex, on cybersickness susceptibility during VR-based forklift training. Using the Simulator Sickness Questionnaire (SSQ) and survival analysis on data from 20 participants, we found that older adults were universally more vulnerable to cybersickness, while sex showed no significant effect.

Our third study explored the role of head rotations and elevated height in cybersickness onset. We recruited 26 participants to perform controlled head rotations (pitch, yaw, and roll) from both ground level and elevated positions within a VR forklift driving environment. Subjective reports indicated that three-axis head rotations and elevated height significantly increased the risk of cybersickness.

Together, these findings inform the design of more effective and inclusive VR-based training systems for forklift driving. By integrating tailored feedback and accounting for demographic and movement-related factors, we can improve training outcomes while reducing cybersickness and enhancing accessibility for diverse users.

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GENERAL AUDIENCE ABSTRACT

Virtual reality (VR) is revolutionizing the way people learn complex job skills, such as forklift driving. It offers a safe and immersive way for trainees to practice without the risks of real-life training. But while VR training has many benefits, it also comes with challenges. Many trainees struggle with tasks that involve real-world complexity, and a substantial number experience cybersickness—a form of motion sickness caused by the virtual environment. Our research focused on improving VT forklift training by exploring two key questions: How can feedback help learners perform better? And why do some people experience cybersickness more than others?

In our first study, we looked at how different types of feedback–such as visual cues and haptic (vibration-based) signals–could support learning. We started by interviewing twelve experienced forklift drivers to learn the strategies they use on the job. We also observed twenty novices to understand common mistakes. From these observations, we designed a VR training system that provided different types of real-time feedback. We then tested the system with fifteen novice users. We found that haptic feedback alone helped users complete tasks faster and with less mental effort. In contrast, visual feedback–whether alone or combined with haptics–actually slowed users down.

While testing this system, we noticed that some participants, particularly older adults and women, experienced severe cybersickness and had to stop training. This led us to a second study focused on understanding who is most affected by cybersickness. We recruited twenty participants and measured their susceptibility to cybersickness during typical forklift-driving tasks. The results indicated that older adults were more vulnerable to cybersickness, while biological sex did not make a significant difference.

In our third study, we investigated how head rotation and scene height–an important part of driving a forklift–might contribute to cybersickness. We asked twenty-six participants to move their heads in different directions (up and down, side-to-side, and tilting) while using the VR simulator, both at ground level and from an elevated height. We measured their self-reported symptoms using two scales. Our findings showed that head rotations in all three directions and elevated height significantly increased the risk of cybersickness.

Taken together, these studies provide essential knowledge into how VR training can be made more effective and inclusive. By designing feedback systems and understanding what causes cybersickness, we can create VR-based occupational training that benefits all users—regardless of age or sensitivity to motion. Our ultimate goal is to make VR-based occupational training not just innovative, but also comfortable, accessible, and impactful for all users.

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Specific Aims

The rapid advancement of technology has significantly transformed occupational training, with virtual reality (VR) emerging as a promising tool in this domain. VR-based forklift training, though relatively new, has gained traction due to its cost and time efficiency. However, many existing VR-based training programs primarily focus on basic operational skills, often failing to prepare trainees for real-world challenges that demand advanced skills. Additionally, while VR holds great potential, the occurrence of cybersickness—characterized by dizziness, nausea, and disorientation—remains a major challenge in its implementation. To maximize VR's benefits, it is crucial to address these challenges by incorporating personalized feedback and investigating cybersickness in depth, ensuring an inclusive and effective training environment for all users.

Proper training is critical to enhance both the safety and efficiency of forklift truck operation. While most VR-based forklift training programs emphasize fundamental operational skills and safety protocols, they often fall short in preparing drivers for complex challenges, i.e., precise maneuvering in confined spaces requiring a high level of hand-eye coordination and spatial awareness–skills. These are not always adequately addressed in current training programs. As a result, novice drivers may struggle with these challenges when transitioning from virtual to real-world environments. Learning advanced skills through guidance from experienced drivers has been shown to be an effective approach. Targeted feedback modeled by experienced drivers' strategies can accelerate skill development, enhance safety awareness, and improve learning efficiency. However, there is limited research on how to effectively integrate such feedback into VR-based forklift training, warranting the need to investigate it further.

VR-based training can also have a limited impact on trainees and deter them due to cybersickness, which remains a significant obstacle, limiting VR's broader implementation. Several factors contribute to a person's susceptibility to cybersickness, including sensory conflicts, screen resolution and latency, and individual characteristics. Sensory conflict, particularly between the visual and vestibular systems, is a common cause. Head rotation exacerbates this conflict by creating a mismatch between the vestibular system and the proprioceptive system. This disparity between expected and actual sensory input leads to cybersickness symptoms. Forklift training often involves dynamic head rotations to navigate the virtual environment, potentially intensifying sensory conflict. In addition to this, our previous studies have found a significant occurrence of cybersickness among participants. Specifically, 58% of older adults and 57% of females were unable to complete the experiment due to severe cybersickness. These percentages are substantially higher than the 10-15% cybersickness rates reported in other VR-based training programs, such as driving simulators. Individual factors, including age and biological sex, appear to influence susceptibility to cybersickness during VR forklift training. If certain demographic groups are disproportionately affected, it could create inequities in workforce training, limiting some individuals' ability to benefit from the advanced training tools. Therefore, it is critical to better understand the factors contributing to cybersickness in VR-based occupational training. Specifically, how individual factors and dynamic head rotations may aggravate cybersickness. Understanding these factors' effects can potentially help to develop more effective VR training systems.

This dissertation aims to address these challenges with two primary goals. First, we will evaluate the performance and learning outcomes of novice drivers using multimodal feedback modeled after experienced drivers' strategies. Second, we will investigate factors contributing to cybersickness, focusing on the effects of individual characteristics (e.g., age and biological sex) and head rotations on its occurrence and severity. To achieve these goals, we propose the following three studies:

Specific Aim 1: Develop and Evaluate Multimodal Feedback Systems to Aid VR Forklift Training for Novice Drivers.
We will develop multimodal feedback systems using experienced drivers' strategies and analyze novice drivers' common mistakes. We will recruit 10 experienced and 20 novice participants to perform two fundamental forklift tasks in a VR environment. We will use the retrospective think-aloud protocol to obtain experienced drivers' strategies. Based on these strategies, we will evaluate the developed feedback (no feedback, visual, haptic, and combined visual and haptic) with an additional 15 novice drivers.
Hypothesis 1: Combined visual and haptic feedback will have higher usability than the other feedback modalities.

Specific Aim 2: Understand the Impact of Age and Sex on Cybersickness Susceptibility during VR Forklift Training.
We aim to understand how age and biological sex influence cybersickness susceptibility during VR-based forklift driving. To this end, we will recruit 20 participants to complete a series of forklift operation tasks (e.g., fork-pallet engagement, pallet loading/unloading, and load pickup) in a VR simulator. Cybersickness will be measured using the Simulator Sickness Questionnaire (SSQ). Survival analysis and the Cox proportional hazard model will be used to assess susceptibility to cybersickness among different age and sex groups during VR forklift training.
Hypothesis 2: Older adults and female participants will experience more severe cybersickness compared to younger adults and males.

Specific Aim 3: Investigate the Impact of Head Rotation and Forklift Truck Platform Height on the Occurrence of Cybersickness.
We will investigate how dynamic head rotation influences cybersickness, particularly across different demographic groups (age and sex). We will recruit 24 participants, balanced by age and sex, to perform a visual box-tracking task in a VR warehouse environment. In this task, participants will perform controlled head rotation by moving their heads along different axes (pitch, yaw, and roll) and from different heights (ground and elevated). We will measure self-reported cybersickness severity.
Hypothesis 3: Cybersickness severity will be greater during three-axis head rotations compared to one- or two-axis head rotations.

Chapter 1: Introduction

1.1. Use of Virtual Reality in Occupational Training

Virtual reality (VR) has rapidly become a cost-effective and efficient tool for occupational training across various industries (Abbas et al., 2023; Villiers & Blignaut, 2016). Its immersive environments allow trainees to practice critical skills in realistic scenarios (Norris et al., 2019; Stavroulia et al., 2019) while minimizing risks and costs (Patle et al., 2019; H.-T. Wu et al., 2020). This technology is particularly beneficial for training in hazardous fields such as forklift operations (M. S. Islam et al., 2024b; Zawadzki et al., 2019), firefighting (Narciso et al., 2020; Wheeler et al., 2021), military operations (Bhagat et al., 2016; Gawlik-Kobylińska et al., 2020), and construction safety (Jeelani et al., 2020; Sacks et al., 2013). It also offers cost-effective solutions for training in fields where equipment and procedures are expensive, including surgical procedures (Desselle et al., 2020; Gasco et al., 2014; Tsai et al., 2001), aviation (Brown et al., 2023; Eschen et al., 2018), assembly and maintenance (Gavish et al., 2015; Randeniya et al., 2019), and driving (Goedicke et al., 2018; Lang et al., 2018). The integration of VR into training programs is substantially improving how professionals acquire and refine their skills (Gallagher et al., 2005; Lohre et al., 2020; Orser & Spadafora, 2022). VR training also helps to enhance learning outcomes (Goode et al., 2013), safety (Bhide et al., 2015), and productivity (M. S. Islam et al., 2024b). As VR technology advances, its role in occupational training is expected to expand, offering innovative solutions to more industries (Choi et al., 2015; Naranjo et al., 2020; Radhakrishnan et al., 2021; Zhang & Aslan, 2020).

1.2. Cybersickness in VR Training

Despite its advantages, a major limitation of VR training is cybersickness, an adverse reaction characterized by symptoms such as nausea, dizziness, and other discomforts (Davis et al., 2014a). Cybersickness is mainly triggered by sensory conflicts such as mismatched visual and vestibular cues (H. Kim et al., 2021). It significantly impacts user experience, making it harder for people to use VR for training (Yildirim, 2020). Multiple factors influence its occurrence and severity, including physiological (Bruck & Watters, 2011; Kim et al., 2005), psychological (Freiwald et al., 2020; Yang et al., 2023), and technological factors (Rebenitsch & Owen, 2021; Stauffert et al., 2020). For example, factors known to contribute to the risk of cybersickness during VR training include prolonged postural instability (Litleskare, 2021; Risi & Palmisano, 2019; Widdowson et al., 2021), no prior VR experiences (Garrido et al., 2022), technological limitations in the VR system [e.g., latency (Caserman et al., 2019; Stauffert et al., 2018), resolution (Oh & Son, 2022) and field of view constraints (Rebenitsch & Owen, 2016; Teixeira & Palmisano, 2021)].

1.3. Potential Factors Impacting Cybersickness Occurrence

1.3.1. Age and Sex

Research, particularly within the driving simulation, suggests that cybersickness susceptibility varies with demographic factors, particularly age and sex (Loeb et al., 2019; Maxwell et al., 2021). Older adults report higher levels of discomfort and cybersickness in VR (Arns & Cerney, 2005) due to age-related declines in sensory processing and motor control (Ebaid et al., 2017; Hofer et al., 2003). Females tend to experience more severe cybersickness than males (Kim et al., 2021; Munafo et al., 2017), potentially due to hormonal fluctuations (Jasper et al., 2023) and differences in vestibular function (Melo et al., 2021; Paillard et al., 2013). As both age and sex can significantly affect the VR experience, it is essential to account for demographic diversity when designing VR training systems to ensure inclusivity and accessibility in workforce development.

1.3.2. Head Rotation

Occupational training, such as forklift operation and firefighting (to name a few), requires frequent head and torso movements, creating sensory conflicts in VR (Li et al., 2021). Sensory conflicts can be noticeable with dynamic movements involving frequent or excessive head and torso rotations (Porcino et al., 2020; Salehi et al., 2024). Movement along multiple axes (pitch, yaw, and roll) can intensify cybersickness. For example, Li et al. (2021) found that head rotation along the yaw axis (head axial rotation) was more comfortable and incurred less cybersickness than the pitch axis (head flexion/extension). In another study, rotation along the roll axis (head abduction/adduction) caused the most severe cybersickness (Budhiraja et al., 2017). If multiple axes of head rotation are performed, i.e., tilting the head while rotating, it could trigger more severe cybersickness symptoms (Dai et al., 2003). For example, dual-axis (pitch and roll) or triple-axis (pitch, roll, and yaw) head rotation caused significantly higher cybersickness compared to single-axis pitch only head rotation (Keshavarz & Hecht, 2011a). Understanding how these dynamics affect cybersickness can inform the design of more comfortable and effective VR training protocols.

1.3.3. Prior VR Experience

Prior experience with VR tends to reduce cybersickness symptoms, as experienced users are developing coping mechanisms (Dennison & D'Zmura, 2017; Teixeira & Palmisano, 2021) and better able to adapt to sensory conflict (Munafo et al., 2017; Palmisano & Constable, 2022; Ya et al., 2017). For example, experienced users showed improved hand-eye coordination, spatial awareness, and overall comfort (Enders et al., 2024; Houweling et al., 2024; Rutkowski et al., 2021; Shin et al., 2015). In the context of VR occupational training, having prior VR experience or gradually acclimatizing novice users can enhance the effectiveness of training programs (Burigat & Chittaro, 2007) by mitigating the risk of cybersickness (Kennedy et al., 2000; Stanney et al., 1998).

1.4. Measuring Cybersickness

Measuring cybersickness in VR is crucial for assessing its impact on VR-based training (Chang et al., 2020). Previous studies have utilized both subjective and objective measures to quantify cybersickness and compare it's severity across different demographic groups (Chattha et al., 2020; Keshavarz et al., 2017; Séba et al., 2023; Tychsen & Foeller, 2020). Subjective measures of cybersickness capture the perceived severity of symptoms experienced (Mazloumi Gavgani et al., 2018; Yeo et al., 2022). Simulator sickness questionnaire (SSQ) is one of the most widely used subjective measures of cybersickness (Kennedy et al., 1993), consisting of 16 items grouped into three subscales: nausea, oculomotor, and disorientation. Another subjective measure is the Fast Motion Sickness (FMS) scale (Keshavarz et al., 2019; Keshavarz & Hecht, 2011b), a quick, single-item assessment where users rate their symptoms from 0 to 20 (Keshavarz & Hecht, 2011c), allowing for rapid evaluations of symptom changes (Czeisler et al., 2023; Reinhard et al., 2017).

Objective measures of cybersickness allow a continuous assessment of cybersickness (Wibirama & Hamamoto, 2014; Zużewicz et al., 2011). For instance, heart rate (HR) and heart rate variability (HRV) are commonly used, with an increase in HR and a decrease in HRV linked to more severe cybersickness symptoms (Chattha et al., 2020; Malińska et al., 2015). Electrodermal activity (EDA) or galvanic skin response (GSR) measures skin conductance, which can be used to infer discomfort and arousal (Schneider et al., 2022; Smyth et al., 2021). Increased skin conductance level often indicates cybersickness onset (Chiossi et al., 2022; N. Martin et al., 2020a). A decrease in skin temperature, particularly in peripheral areas like the hands and feet, indicates vasoconstriction, which is a response to cybersickness (Arnold et al., 2019; Smyth et al., 2021).

Kinematic measures such as head and neck movements can also be used for assessing cybersickness (Salehi et al., 2024). Excessive head and neck movements can disrupt the vestibular system, which could lead to cybersickness (Li et al., 2021). While measuring such excessive movements itself is not a direct measure of cybersickness, monitoring them can help identify problematic VR scenarios; thus informing the design of more comfortable VR experiences.

1.5. Research Needs for Forklift Driving Training Using VR

Forklift trucks play a major role in warehouse and distribution center operations (Fazlollahtabar et al., 2019; Vanheusden et al., 2020). The growing warehousing and distribution sector has created a high demand for skilled forklift truck drivers, who are essential for ensuring smooth and timely operations (Lustosa et al., 2018). Driving a forklift often involves navigating through narrow spaces, and skillful maneuvering around obstacles, pedestrians, and other vehicles. Drivers often need to undergo regular training and certification updates. Given the complexities of forklift driving, providing operators with efficient, effective, and safe training is essential for achieving peak efficiency and productivity in warehouse operations (M. Choi et al., 2020; Horberry et al., 2004). Since accident and fatality rates in forklift operations are relatively high (Marsh & Fosbroke, 2015), training could reduce accident rates and injuries.

VR-based training has emerged as a cost-effective and space-saving alternative to conventional forklift training (Abbas et al., 2023; Villiers & Blignaut, 2016). Conventional forklift training is typically conducted on-site, requiring a dedicated training area and time coordination between trainers and trainees during work. This method is often limited by trainer availability, facility access, and other logistical constraints (Herrera et al., 2018). It is a resource-intensive, time-consuming, and costly process (Vahdatikhaki et al., 2019). It can also increase the risk of equipment and property damage, as well as the potential for injuries (Yuen et al., 2010). To address these limitations and challenges, several commercial VR systems are being used for forklift driver training (Zawadzki et al., 2019), including the Raymond VR Forklift Simulator (*The Raymond Corporation, USA*), Wolter VR Forklift Simulator (*Wolter Inc, USA*), Virtual Forklift VR Simulator (*Virtual Forklift, USA*), Forklift-Simulator (*FL-Simulator Inc, USA*), CM Labs Forklift Simulator Training (*CM Labs, Canada*), and Humulo Forklift VR Training (*Humulo Engineering, USA*). These systems offer companies and drivers the opportunity to train and operate virtual forklift trucks in a safe and immersive learning environment.

Although VR in forklift training shows great potential for improving skill acquisition, enhancing safety, and increasing cost and time efficiency, it still doesn’t adequately prepare novices for challenging tasks. So, there are scopes to improve the existing VR simulator training platforms. In addition to this, cybersickness remains a significant barrier to fully realizing these benefits (Islam & Lim, 2024). Forklift training using VR is still on the rise and is a relatively new research area. This presents a unique opportunity to contribute to an emerging field, as the immersive nature of VR forklift training makes it particularly susceptible to cybersickness. To reduce the effect of cybersickness in VR-based forklift training, it is critical to identify and address the specific factors contributing to cybersickness. One of the characteristics of forklift driving training VR, which is different from a passenger car simulator, is its complex and dynamic movements. Forklift driving also often requires the operator to maintain a standing posture, which can amplify sensory conflicts during VR training. Operators frequently rotate their heads to check for obstacles, lean forward to adjust their view, and rotate their torsos to maintain spatial awareness of the load, all while navigating tight spaces and interacting with both stationary and moving objects. These dynamic movements are essential for safe forklift operation but pose unique challenges in VR due to the mismatch between visual and vestibular signals. For instance, when an operator visually experiences forward motion while remaining physically stationary, the inner ear perceives a lack of movement, creating a conflict (Koch et al., 2018). Detailed research is needed to explore whether these dynamic movements (especially the ones associated with the head) contribute to sensory conflicts, leading to severe cybersickness.

Individual factors such as age and sex have been shown to influence cybersickness susceptibility, yet there is limited research on how these factors interact with VR forklift training. For example, younger individuals may adapt more quickly to VR environments due to their higher exposure to digital technology, whereas older adults often report greater levels of discomfort and prolonged recovery times from cybersickness due to age-related changes in vestibular function and sensory processing. This discrepancy is very critical to address in VR forklift training, or, broadly in any occupational training using VR. The mean age of forklift truck drivers in the US is 42 years (Islam et al., 2023), and with the aging workforce, they may be more vulnerable to cybersickness, potentially reducing the VR training's accessibility and effectiveness for this group. Understanding these demographic influences is crucial for developing inclusive training programs that cater to diverse populations in workforce training.

1.6 Research Goals and Hypotheses

My overall research goal is to improve the existing VR forklift training by implementing multimodal feedback designed after experienced drivers' strategies to make training effective for novices, and to investigate the factors that contribute to cybersickness during VR-based forklift training. Specifically, my research will focus on designing multimodal feedback to aid novice drivers, and investigating the effects of head rotation and individual demographic factors (i.e., age and sex) on cybersickness occurrence and severity during VR forklift training. The overarching hypothesis is that multimodal feedback designed after experienced drivers will significantly improve novice's performance, and specific factors, such as head rotations, age, and biological sex, significantly impact cybersickness susceptibility.

1.7 Implications

Investigating the impact of multimodal feedback as training aid and factors contributing to cybersickness has significant implications for efficiency and safety in virtual occupational training. Cybersickness can impair cognitive and motor functions, potentially leading to health concerns, i.e., nausea, dizziness, disorientation, and fatigue, which can compromise learning outcomes and user well-being during training. This research aims to improve trainee safety by identifying the key contributors to these adverse effects and addressing them. This is particularly important in high-risk industries such as construction, aviation, and forklift operations, where the margin for error is minimal, and the consequences of mistakes can be severe. Training programs can ensure better skill retention and promote safer practices, ultimately reducing the risk of accidents and injuries by reducing the negative effects of cybersickness.

The findings from this research will significantly shape the future of workforce training. As VR becomes more sophisticated and widespread, improving existing training platforms and understanding cybersickness will be key to unlocking their full potential for occupational training. Based on these findings, effective mitigation strategies can be made for future VR-based training, making them more accessible and acceptable to a broader range of individuals, including those demographics who are currently susceptible to cybersickness. This inclusivity will ensure that all workers, regardless of age, sex, or prior experience with virtual environments, can benefit from advanced training technologies.

1.8. Innovation

The proposed research is innovative in several ways. First, it focuses on developing multimodal feedback designed after experienced forklift drivers to aid novice drivers with their training. Second, it fills a significant gap in the literature by focusing specifically on cybersickness occurrence within the context of VR occupational training. While cybersickness is a well-documented phenomenon in other domains, including gaming, its implications for occupational training have received limited attention. This study will contribute new information to an emerging area of research, paving the way for the development of tailored interventions and best practices. This research not only advances theoretical understanding but also offers an evaluation of practical solutions for quantifying cybersickness discomfort and enhancing user experience in VR training environments. Methodologically, this study will use the Cox Proportional Hazard Model and Survival Analysis to estimate the time until cybersickness onset based on individual factors such as age and sex, which introduces a novel, data-driven approach to understanding individual variability in cybersickness susceptibility. The findings of this study have the potential to impact the VR forklift training industry by providing solutions and guidelines on the design and implementation of forklift training programs.

Chapter 2: Development and Evaluation of Multimodal Feedback to Enhance Virtual Reality Forklift Training

2.1. Introduction

Forklift trucks are integral to efficient warehouse operations (Ebrahimi et al., 2023). Ensuring high productivity while adhering to safety standards is essential for forklift truck drivers. However, forklift-related incidents remain a substantial source of workplace injuries and fatalities in the warehousing industry, with 614 fatal and 7,000 non-fatal injuries reported between 2011-2017 (*BLS,* 2017). Proper training is critical to enhance both the efficiency and safety of forklift truck operation.

Virtual Reality (VR) technology offers new opportunities for training forklift drivers in a controlled simulation setting (M. S. Islam et al., 2024b). Such immersive training allows trainees to develop their skills without the risks or costs associated with physical training setups (Yuen et al., 2010). While most VR forklift training programs emphasize fundamental operational skills and safety protocols (Abbas et al., 2023), they often fall short in preparing drivers for the complex, real-world challenges that demand advanced skills (Sarupuri et al., 2016; Naranjo et al., 2020). For example, precise maneuvering in confined spaces requires high levels of hand-eye coordination and spatial awareness, which are not always adequately addressed in current VR training programs. As a result, novice drivers may struggle with these challenges when transitioning from virtual to real-world environments.

Learning advanced skills through coaching from experienced drivers is an effective training approach (Underwood, 2007). Novices can benefit greatly from the expertise of experienced drivers, allowing them to quickly learn and avoid common mistakes. However, providing real-time, in-person guidance during forklift training can be costly and resource-intensive (Moser, 2017). Alternatively, if such feedback can be provided within a simulated environment, it could enhance learning efficiency and effectiveness. Previous studies in other domains (e.g., motor skill training and driving) have demonstrated that targeted feedback can accelerate skill development, enhance safety awareness, and improve learning efficiency (Hodges et al., 2011; Underwood, 2007). However, there is limited practical evidence regarding how to effectively develop and integrate such feedback into VR forklift training.

Real-time multimodal feedback—combining visual, auditory, and haptic cues—has been found effective in various domains such as teleoperation, vehicle driving, and assembly tasks (Hong et al., 2017; Hong et al., 2022; Islam & Lim, 2022). In driving simulations, both visual and haptic feedback have proven valuable for maintaining user engagement (Pietra et al., 2021) and alerting drivers to potential hazards. If not used appropriately, though, multimodal feedback can cause cognitive overload, distraction, or decreased learning efficacy (Birrell et al., 2013; Cockburn & Brewster, 2005). Therefore, it is crucial to assess the efficacy of multimodal feedback within the context of VR forklift training, especially since the simulated training environment is already overloaded with multimodal sensory information. Learning efficacy using multimodal feedback systems has been measured using various metrics, including time efficiency (M. S. Islam et al., 2022), task score (Blustein et al., 2018), dwell time (Bolarinwa et al., 2021), NASA Task Load Index (D. S. Lee et al., 2023), the System Usability Scale (F. Machado et al., 2023), and subjective user preferences (Oviatt, 2003). EEG-based measures can offer real-time insights into cognitive load variations, helping to optimize feedback modalities for enhanced training outcomes (Zahabi et al., 2023).

To enhance the efficacy of multimodal feedback for VR forklift training, we completed two sequential studies to: 1) develop multimodal feedback for VR training based on both advanced skills and strategies adopted by experienced forklift truck drivers and common mistakes made by novice drivers; and 2) evaluate the performance and preference of novice drivers on multimodal feedback. The overall structure and method for each study are summarized in Figure 2.1. These studies were intended to provide critical design considerations for the future development of real-time multimodal feedback systems for VR forklift driving training to enhance learning effectiveness.

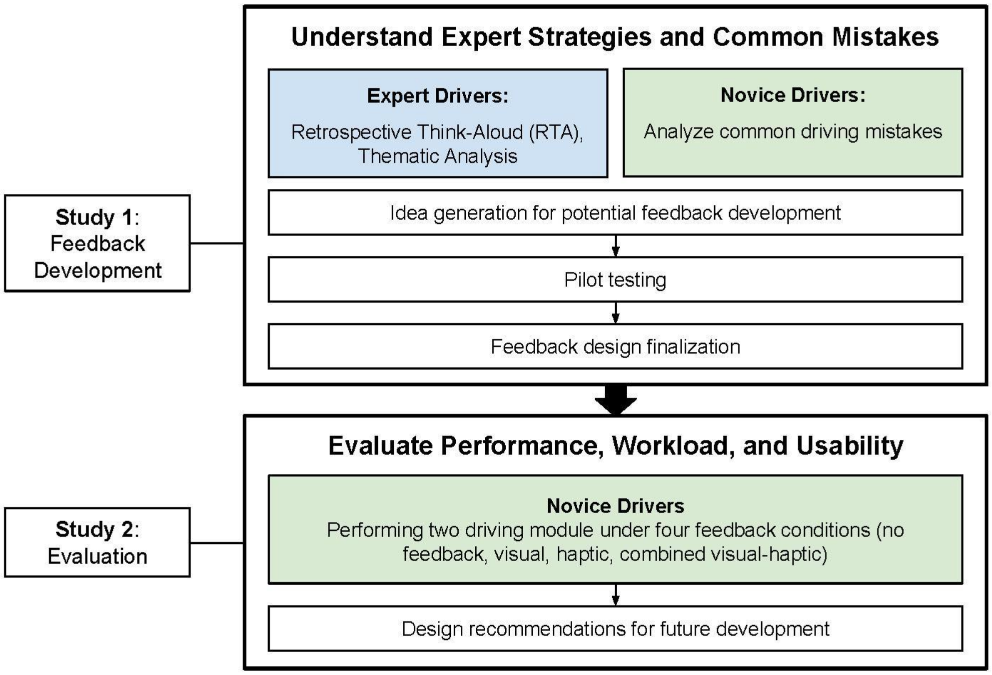


Figure 2.1: Summary of the methods used in two sequential studies to develop and evaluate multimodal feedback methods.

2.2. Study 1: Developing Multimodal Feedback

This study employed two complementary approaches to inform the design of real-time multimodal feedback for forklift driving training to be tested in the subsequent study (see Figure 2.1). In one approach, we used a retrospective think-aloud (RTA) protocol to obtain the strategies of experienced drivers in specific driving scenarios. These drivers reviewed their performance videos post- VR training and verbalized their strategies and decision-making processes. In the other, we observed and coded frequent mistakes made by novice drivers. Since experienced drivers are unlikely to commit the typical mistakes of novices, our dual approach was designed to complement both groups' insights. By integrating these inputs, we sought to create multimodal feedback that would effectively address the learning needs of novice drivers and enhance their training experience. The following sections detail the methods used for each group.

2.2.1. Participants

Twelve experienced forklift drivers (>2 years of forklift truck driving experience; 3 female, 9 male) were recruited through flyers and newspaper advertisements. These participants had a mean (SD) age of 48.4 (9.7) years and 14 (10.6) years of forklift driving experience. Seven participants dropped out of the study due to VR simulator-induced cybersickness: three withdrew after the practice session, three after the first trial, and one approximately 30 minutes into data collection. Ultimately, five participants (1 female, 4 male) completed the study and their data were used for analysis. They had a mean (SD) age of 43.6 (9.2) years and 11.4 (7.1) years of forklift driving experience.

Additionally, 20 novice drivers (6 female, 14 male) completed the study, as reported in our prior work (Islam et al., 2024). Their mean (SD) age was 23.9 (5.0) years. All novices were university students with a valid motor vehicle driver's license. Except for two novices who reported less than one month of forklift experience, the rest had no prior forklift driving experience. All participants provided written informed consent, following procedures approved by the Institutional Review Board at Virginia Tech (IRB 22-341).

2.2.2. Experimental Procedures

We used a high-fidelity, VR, order-picker forklift simulator (The Raymond Corporation, NY, USA; Figure 2.2). This simulator had a highly realistic simulation of warehouse environments with physical buttons and controls from an actual order picker truck that is connected to. A Vive Pro Eye headset (HTC Corporation, Taiwan) coupled with a Leap Motion controller (Leap Motion Inc., USA).

Figure 2.2: Participant operating the physical interface of the simulator.

Before starting the main driving modules, we provided 10 minutes of practice for all participants so they could get familiar with the VR simulator. Then, the participants completed two standard training modules in the VR, the order-picker forklift simulator (Figure 2.3). The first training module, M1 (fork-pallet engagement), required participants to engage a pallet with the fork and drive with it. Learning backward driving and enhancing depth perception were the main goals of the module. The second training module, M2 (load pickup), involved maneuvering the truck between aisles of elevated racks, parking close to racks, and using hands to pick up boxes. This module was to train precise parallel parking and height manipulation skills. Each module was repeated three times, with two-minute rest breaks between replications.

Following the training, a retrospective think-aloud (RTA) protocol (Elling et al., 2011) was performed with the experienced drivers. First-person views from the VR simulator during their training were recorded using Open Broadcast Software (OBS Studio, USA). Eye gaze data were captured with the Vive Pro Eye headset, and this gaze data was then overlaid on the recorded videos for the RTA (Figure 2.4). The experienced drivers reviewed their performance videos (replayed as necessary) and explained their driving strategies. We used semi-structured interview questions (see Table A.1) to guide the discussion. All videos of RTA sessions were recorded for further analysis.

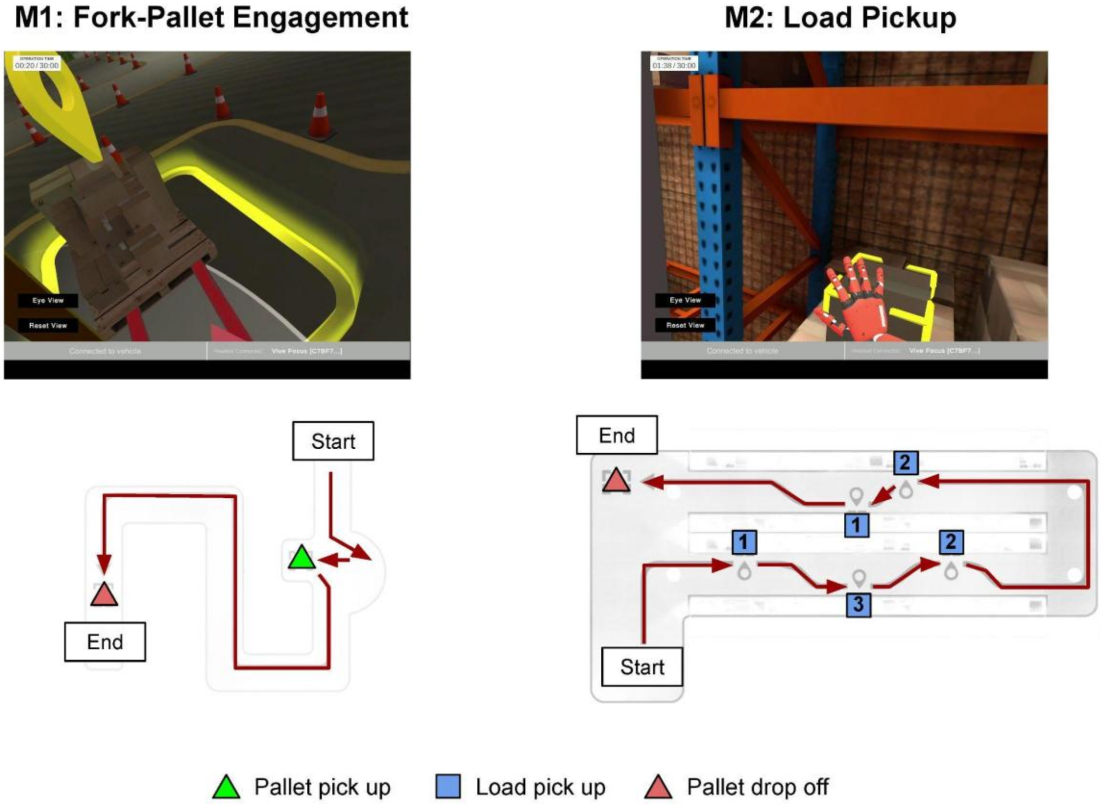


Figure 2.3: Two driving training modules used in this study: 1) fork-pallet engagement (M1); and 2) load pickup (M2).

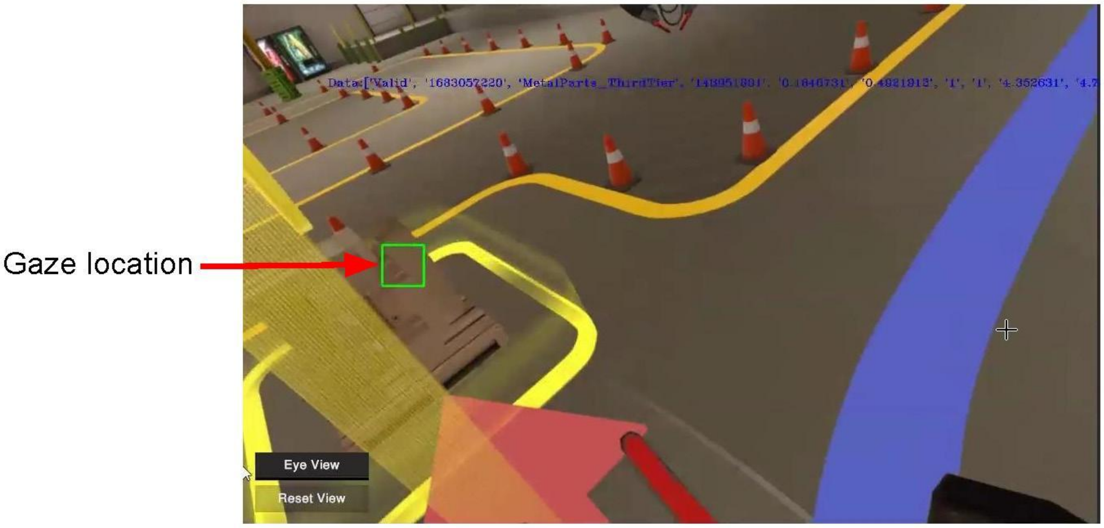


Figure 2.4: A snapshot of eye-gaze location (green box) overlaid on a recorded first-person view video for the retrospective think-aloud (RTA).

2.2.3. Analysis

The recorded RTA sessions were transcribed verbatim using Otter.ai (California, USA) and were reviewed by the first and last authors. The transcripts were analyzed to identify experienced drivers' knowledge and strategies. The first author thoroughly reviewed the transcripts to become familiar with the data and its contents. Sentences or phrases describing performance-enhancing strategies or mistakes to avoid were labeled and categorized according to the training modules and subtasks and were finalized iteratively by discussing and reviewing with the last author. The responses of the experienced drivers from the RTA sessions are provided in Table A.1 (Appendix A).

We analyzed the novice participants' data for errors by annotating their first-person driving videos. Some of their mistakes were marked automatically in the system as errors (i.e., dragging the pallet, hitting the rack), but some mistakes were not (e.g., driving without lifting the pallet, attempting to pick up load without reaching the correct height). Given the practical importance of such unmarked errors based on our discussion with the experienced drivers through RTA, we also annotated such mistakes manually. Both the type and frequency of mistakes were recorded for further analysis.

After obtaining results from both approaches (experienced drivers' knowledge and strategies and novices' common mistakes), we had multiple discussions to brainstorm potential feedback design ideas with an industry partner (i.e., developer of the VR forklift training system). We then prioritized several feedback design ideas, discussed their feasibility and importance, and then implemented and pilot-tested them.

2.2.4. Results

The driving strategies and mistakes of participants are summarized in Table 1, along with associated visual and haptic feedback designs and their trigger conditions. Considering that the driving environment is already auditorily-cluttered (e.g., noise from the forklift truck and the warehouse environment), we developed only visual and haptic feedback. Due to the differing nature of the strategies and mistakes, we could not implement all of them with both modalities. Instead, we matched the most intuitive modality for each specific module, ensuring that the feedback was intuitive and actionable. We also sought to avoid overloading users with both visual and haptic feedback for every mistake or strategy, which would risk causing confusion or reducing effectiveness. As a result, a total of six visual and four haptic feedback designs were selected for subsequent testing based on their importance, feasibility, and potential effectiveness for novice learning (Study 2). The haptic feedback design was customized for a Tactsuit X40 (Bhaptics, Korea), which was used in the evaluation study (Study 2). The suit contains 40 tactors—20 in the front and 20 in the back—arranged in four rows by five columns on each side. Using Bhapatics

Studio software (Bhaptics, Korea), we designed vibration patterns by location, direction, duration, and intensity across those 40 tactors. In the following section, we summarize key feedback obtained from experienced drivers and common driving mistakes observed in novices.

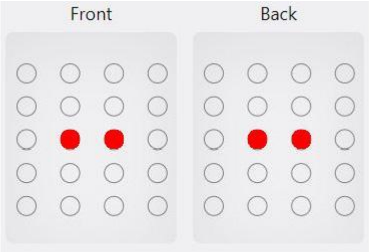
Driving Strategies Identified from Experienced Drivers. In M1, experienced drivers indicated that fork-pallet engagement is a challenging maneuver for many drivers. Even experienced drivers often made multiple attempts to complete this module successfully. They highlighted that this module requires intense focus, because misalignments between the fork and pallet could damage the assets on the pallet. Immediately after engaging the pallet, drivers must lift the pallet approximately two inches to prevent dragging against the ground. Although this step was not explicitly required in the current training module, experienced drivers were accustomed to this maneuver and routinely lifted the pallet before driving. Additionally, making safe turns at corners was identified as particularly challenging, especially when a pallet is attached to the forklift, extending the length of the truck. To ensure safety while turning, experienced drivers paid close attention to corners when carrying a pallet. Some drivers used personalized techniques, such as “Squaring” or “Shouldering,” which involves aligning their shoulder with a specific reference point before initiating the turn.

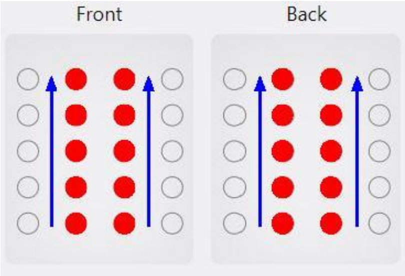
In M2, participants had to position the truck precisely, both vertically and horizontally, to pick up a box from the rack. The task was easier when the box was within arm's reach. Experienced drivers were skilled at parking their trucks close to the rack (horizontal alignment) and stopping at the proper height (vertical alignment), making the load pick up smooth and efficient. They mentioned relying on their intuition and experience to align the truck parallel to the racks while moving closer. They also lift the truck’s sidebars to extend their arm’s reach for picking up boxes. Similar to M1, before driving to the next pickup location, experienced drivers consistently lifted the pallet slightly off the ground as part of their regular practice.

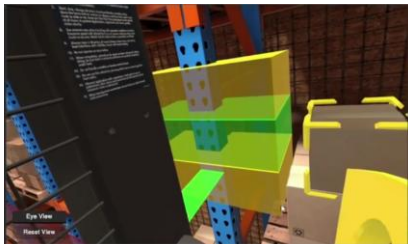
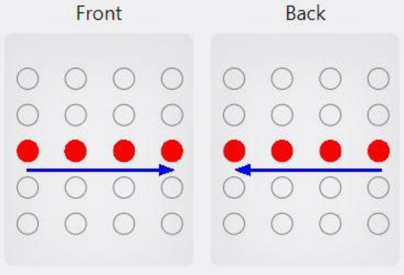
Across all driving modules, experienced drivers emphasized the importance of observing their surroundings and ensuring proper fork positioning. While driving with a load on the back of the truck, they made a point to slow down during turns, emphasizing the risks of turning too quickly with a loaded pallet. They especially cautioned that uneven load distribution on the pallet could affect stability.

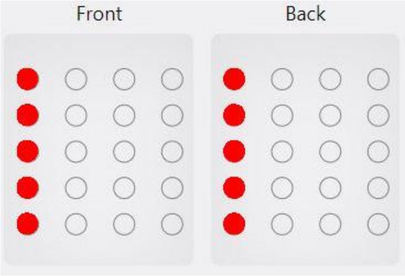
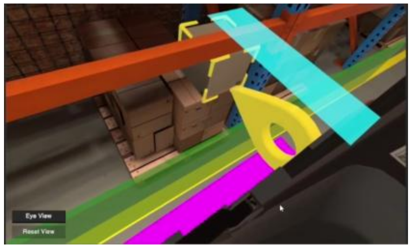
Common Driving Mistakes Observed among Novices. Several critical driving mistakes were observed exclusively among novices. The most common mistakes included misaligning the fork with the pallet (31.7%), failing to lift the pallet before driving, resulting in pallet dragging (28.3%), stopping at an incorrect vertical height during load pickup (e.g., too low or high) (38.3%), and crashing into racks (28.3%).

Table 2.1: Summary of driving strategies, mistakes, and associated visual and haptic, real-time feedback designs with their trigger conditions.

Module	Strategies or Mistakes identified	Potential Feedback Design	Visual Feedback	Haptic Feedback
Fork-Pallet Alignment	**Experienced**: Identified as a challenging task; Often required multiple attempts **Novice**: Misalignment errors (31.7%)	Provide a visual overlay to guide fork-pallet alignment	 Visual extension at the end of the forks (green) and an alignment zone for the chamfer under the pallet (green) **Trigger condition**: Always	N/A
		Provide feedback upon successful pallet engagement	N/A	 Vibrate two tactors at the center of both the front and back of the vest **Duration:** 100 ms twice, with a 100-ms gap (total cycle: 300 ms) **Intensity**: 30% of the manufacturer's default setting

				Trigger condition: correct alignment
Fork-Pallet Lifting	**Experienced:** Always lifted forks before driving **Novice:** Lifting errors (28.3%)	Provide a reminder to lift forks before driving	N/A	 Vibrate two columns of tactors at the center of both the front and back of the vest **Duration:** 200 ms **Intensity:** 30% of the manufacturer’s default setting **Trigger condition:** After fork-pallet engagement and before driving

Techniques for Safe Turning	**Experienced:** Used the “shouldering” method **Novice:** Struggled with turning (28.3%)	Provide a visual aid for vehicle orientation	 Compass (pink box) indicating how parallel the vehicle is with respect to the environment (e.g., aisle) **Trigger condition:** Always	N/A
Vertical Height Alignment	**Experienced:** Stopped at the correct height based on their intuition; lifted the side-arm bar to extend reach **Novice:** Incorrect reach distance and height (38.3%)	Provide feedback when the driver reaches the appropriate height for box pickup	 Match the green bar (from the forklift truck) to the green reference zone (on the vertical axis of the rack) **Trigger condition:** within the reach distance from the box	 Vibrate the middle row of both front and back sides in a circular motion **Duration:** 500 ms **Intensity:** 50% of the manufacturer’s default setting **Trigger condition:** correct height

Horizontal Truck Alignment	**Experienced:** Used yellow-marked lines for alignment and had no collisions **Novice:** Collision (28.3%)	Provide feedback to aid truck alignment within a safe and close distance from the rack	 Virtual wall (transparent green) changes color based on proximity (green: safe; red: too close) **Trigger condition:** When the vehicle is close to the rack	 Continuous vibration when in close proximity to the wall **Duration:** 100 ms per cycle **Intensity:** 30% of the manufacturer's default setting **Trigger condition:** Vehicle interacting with the virtual wall
		Provide a distance indicator to aid proper positioning	 Distance indicator (sky blue bar) between vehicle and aisle showing the optimal pickup distance **Triggering condition:** Always	N/A
Weight Distribution	**Experienced:** Concerned about maneuvering with uneven weight distribution **Novice:** Unaware of the issue due to lack of experience	Provide feedback to alert drivers to slow down while turning	Not implemented in this study due to technical infeasibility	

2.3. Study 2: Evaluating Multimodal Feedback

The real-time multimodal feedback designs developed in Study 1 were evaluated with a new sample of novice participants to assess their efficacy. To objectively measure changes in novice behaviors, we collected various performance metrics (e.g., completion time, task/penalty scores), a workload measure (i.e., NASA-TLX), and eye tracking metrics (i.e., dwell time, gaze entropy). The latter were included since gaze fixation on different areas of interest (AOIs) can reveal how participants interact with a system while being exposed to multimodal feedback (Bolarinwa et al., 2021). By analyzing eye-tracking metrics, we aimed to investigate whether novices effectively utilized visual feedback to improve their performance (Minen et al., 2023; Oviedo-Trespalacios et al., 2019).

2.3.1. Participants

Twenty novice participants (seven female, 13 male) were recruited. Four female participants withdrew after a 10-minute practice session due to cybersickness, and data from one male participant were discarded due to calibration errors with the simulator. In total, 15 participants (three female, 12 male) completed the study. The mean (SD) ages were 21.7 (5.8) years for females and 22.9 (3.9) years for males. All participants were university students with valid motor vehicle driving licenses, no prior forklift truck driving experience, and no self-reported musculoskeletal disorders, pain, or medical conditions that could affect their participation in the VR simulator. All participants signed an informed consent form, and the study was conducted in accordance with the procedures approved by the Institutional Review Board at Virginia Tech (IRB 23-776).

2.3.2. Experimental Procedures and Data Collection

The same VR simulator from Study 1 was used (Figure 2.2). Also, as in Study 1, participants began with a 10-minute practice time before the experiment trials. They performed the same two driving modules (M1 and M2), each replicated here four times under different feedback conditions: No Feedback (NF), Visual only (V), Haptic Only (H), and combined Visual and Haptic feedback (VH). The feedback conditions were presented in a partially counterbalanced order to reduce potential confounds due to learning effects. The custom visual and haptic feedback designs from Study 1 (detailed in Table 1) were integrated into the VR simulation, with some feedback provided by default (e.g., extended fork) while other feedback was triggered by participant actions. Raw gaze X-Y coordinates were captured at 60 Hz using the built-in eye tracker in the HTC VIVE Pro Eye (VIVE Pro Eye Overview, VIVE, Southeast Asia) and the provided SDK (v. 1.3.6.8) in the Unity game engine (2021.3 LTS). The eye tracker was calibrated using the system dashboard prior to data collection.

Participants were allowed up to three attempts to complete each driving module under each feedback condition. If a participant accumulated a penalty score exceeding 100 (on a 0-100 scale), the simulator terminated the training, and the participant had to retry from the beginning of the module. After each trial, participants completed both the NASA-TLX (Hart & Staveland, 1988) and the System Usability Scale (SUS) questionnaire (Bangor et al., 2008). Upon completing all trials (2 learning modules x 4 feedback conditions), participants were asked to share their preferred feedback types for different usability dimensions (Appendix A.2) and participated in a semi-structured interview (Appendix A.3).

2.3.3. Data Processing

Completion times for each trial were recorded by annotating the start and end times of the driving trials using Elan software (v6.2; Wittenburg et al., 2006). We retrieved simulator penalty scores, which were incurred for various reasons, such as failing to check surroundings while entering or exiting aisles or dragging the pallet along the ground. Participants received up to three attempts to complete a trial, and penalty scores from all attempts were summed for each module. The NASA-TLX raw scores from the six subscales were used for analysis. The SUS questionnaire was scored following the guidelines by Lewis (2018).

Responses from the semi-structured interviews were transcribed manually from the recordings. The transcriptions were summarized based on the feedback conditions.

2.3.4. Statistical Analysis

Separate mixed-factor analyses of variance (ANOVAs) were used to evaluate the effect of *Feedback Condition* on each dependent variable (i.e., task completion time, penalty score, NASA-TLX scores, overall SUS score). Significant main effects were followed by Tukey's HSD post hoc pairwise comparisons. Participant responses to the feedback preference questionnaire were analyzed using a nonparametric Chi-square test of independence (McHugh, 2013). JMP (*v.18*) software was used to conduct the analysis, and statistical significance was concluded when $p < .05$.

2.3.5. Results

Completion Time and Penalty Score. Descriptive statistics (Table A.4) and pairwise comparisons (Table A.7) are provided in Appendix A. A significant main effect of *Feedback Condition* was found for completion time in both driving modules (M1 [$F_{3,60} = 4.1$, $p = .013$], M2 [$F_{3,60} = 5.38$, $p = .004$]). Participants completed M1 fastest with haptic feedback compared to the V and VH (Figure 2.5). For M2, participants completed the module faster when there was no feedback compared to V and VH (Figure 2.5). For the penalty score, no significant effects of feedback type were found for either M1 or M2.

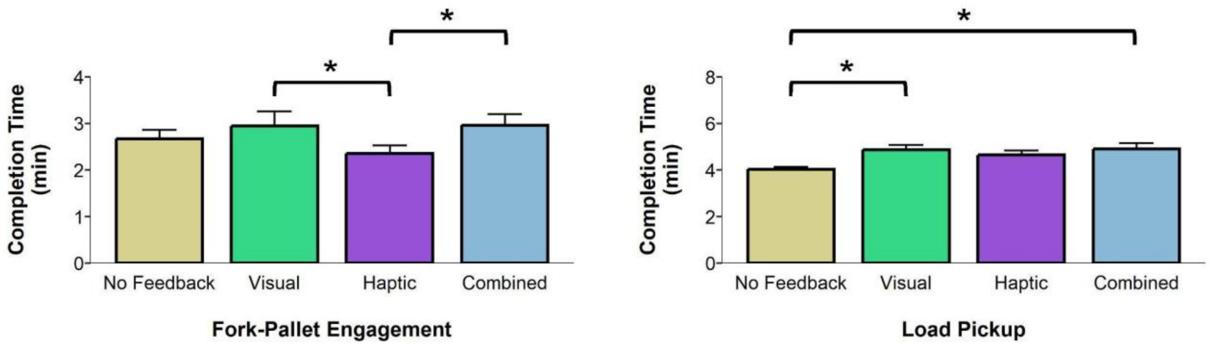


Figure 2.5: Completion time in driving modules M1 and M2, in response to different feedback modalities. Error bars represent standard errors, and the symbol * indicates a significant pairwise difference (p < .05).

Subjective Measures (NASA-TLX, SUS). Descriptive statistics (Table A.5) and pairwise comparisons between feedback conditions (Table A.7) are reported in Appendix A. In M1, haptic feedback yielded a lower mental demand than NF and V (Figure 2.6). No significant difference was observed in M2 for the NASA-TLX scores. No significant differences were found for the Overall SUS score in either M1 or M2.

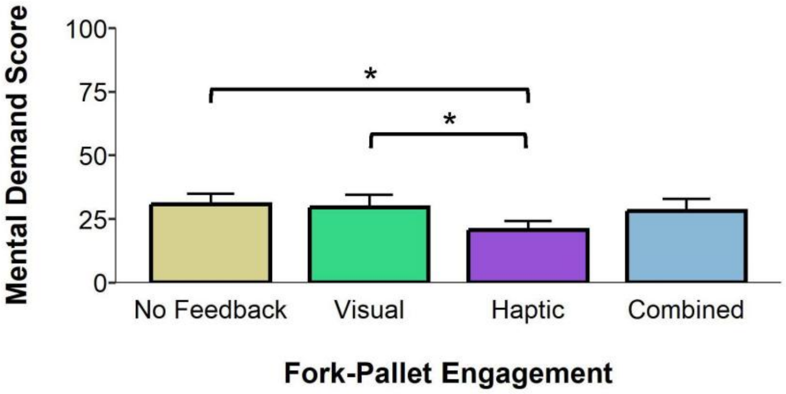


Figure 2.6: Mental demand in driving module M1 using different feedback modalities. Error bars represent standard errors, and the symbol * indicates a significant pairwise difference (p < .05).

Feedback Preference. Among the eight preference questions, visual feedback was the most preferred choice except for the “collision information,” in which the combined feedback was the most preferred. However, there was no statistically significant difference in these preference counts.

The semi-structured interview provided insights into their perceptions and usability of the different feedback modalities. A summary of these responses is presented below.

No Feedback (NF). A few participants preferred no feedback due to its simplicity and minimal distractions. However, most participants reported feeling less confident and comfortable without any feedback. For example, P9 stated, "*It felt like you're thrown into the things, and you're forced to just drive around and use all your senses without having any extra help*." This reliance on personal judgment– without the guidance of visual or haptic cues– raised their concern about making mistakes, particularly impending collisions. Participants expressed a need for external signals to confirm their actions were correct.

Visual (V). Visual feedback was the most preferred modality given its clarity, ease of use, and non-intrusive nature. Participants found the visual feedback intuitive and effective in guiding their actions while reducing errors, such as collisions. P4 remarked, *"The reminders were gentle and there were there when I needed, but they weren't overstimulating."* The absence of physical discomfort and distraction, unlike the haptic feedback, made visual feedback a more relaxing and efficient tool. Participants appreciated that the helpful cues without adding to their cognitive load.

Haptic (H). Haptic feedback received mixed reviews. While some participants valued its ability to provide immediate physical alerts, such as warnings about obstacles, others found it redundant, distracting, overwhelming, or even panic-inducing. Unlike visual cues that could be selectively ignored, haptic feedback was perceived as intrusive and sometimes difficult to interpret. P17 noted, *"Haptics helped me avoid danger, and warned me if I made any mistakes that I should avoid."* However, some participants found the overlap between success and warning signals confusing. P10 described this problem, stating, *"Sometimes it felt contradictory, cause when I got into the pallet it gave me a notification (for noting the successful completion) but also gave me warning if I was about to crash, so it was both warning and success."*

Combined visual and haptic (VH). The combination of visual and haptic feedback was the least comfortable option for most participants due to sensory overload and the challenge of processing simultaneous cues. Unexpected vibrations and the physical discomfort of wearing a haptic device further contributed to their discomfort. While participants acknowledged the effectiveness of combined feedback in preventing collisions, since visual cues provided alerts and haptic cues reinforced spatial awareness, the dual-modality approach often felt overwhelming. P1 explained, *"Visual made me realize like there's danger there, and haptics made my body come into sense."* Overall, while some participants appreciated the comprehensive coverage of VH, others found it distracting, particularly during complex tasks.

2.4. Discussion

2.4.1. Feedback Effectiveness

Time efficiency. Completion time was shorter with haptic feedback (H) in M1 and NF in M2 compared to visual (V) and combined visual and haptic (VH) feedback (Figure 2.5). In general, tasks involving visual feedback took longer, likely due to the additional cognitive effort required to process visual cues, integrate them into the task context, and make motor adjustments accordingly (Hebart et al., 2018). While visual feedback can increase cognitive load (Rego & Montague, 2023), some studies have reported benefits in reducing task completion time, particularly in scenarios requiring swift decision-making during critical situations (Huang et al., 2024). However, our driving modules focused on precise control, rather than rapid responses to safety-critical situations, which we believe explains why the added visual feedback was not as effective as anticipated. Similarly, the combination of visual and haptic feedback resulted in slower task completion, possibly due to increased cognitive overload for the drivers (Paden et al., 2024).

In M1, the faster completion time with haptic feedback may be attributed to its role in enhancing sensorimotor integration and reducing cognitive load, since haptic cues can be processed more rapidly by the brain (Thomas et al., 2021). For example, in a study on teleoperating mobile robots, operators receiving haptic feedback completed navigation tasks more quickly and with fewer collisions compared to those without feedback (Corujeira et al., 2017). In M1, haptic feedback may have allowed novices to focus on the primary driving task without relying on visual cues, and thus streamlining information processing and enhancing task execution.

The longer completion time with any type of feedback in M2 suggests that, in certain contexts – particularly for cognitively demanding tasks – the absence of feedback may allow drivers to focus more effectively on their primary task without unnecessary distractions. In our previous study investigating cognitive workload using the same simulator, the M2 driving module induced more cognitive workload than M1 (Zahabi et al., 2023). Given these higher cognitive demands, the addition of external feedback may have further increased cognitive load, making task execution more challenging.

Research on multimodal feedback in driving simulations has yielded mixed results regarding task completion time. Some studies have reported performance improvements with multimodal feedback. For instance, a driving simulator study showed that haptic feedback in the form of steering wheel vibrations improved reaction times and reduced lane departure errors (Frissen & Mars, 2024). Similarly, another study demonstrated that combined visual and auditory feedback enhanced situation awareness and reduced completion times in complex driving scenarios (Ju et al., 2022). However, other studies have reported contradictory findings. For example, Naujoks et al. (2021) found that adding auditory and visual feedback in a driving simulator increased cognitive load and led to longer completion times. Although we cannot draw definitive conclusions from our study regarding when real-time multimodal feedback enhances task efficiency, our findings do suggest that feedback can have adverse effects when task complexity is high. Indeed, excessive or additional feedback can sometimes interfere with task performance by overwhelming the user with unnecessary information (Lurie & Swaminathan, 2009).

Cognitive workload. In M1, haptic feedback yielded the lowest mental demand among all feedback conditions, which aligns with previous evidence of cognitive benefits from haptic feedback in virtual environments (Boessenkool et al., 2013). It appears that the immediacy and precision of haptic cues facilitate more efficient motor responses and faster decision-making, thereby reducing perceived mental workload during task execution (Baker & Rolf, 2020; Ramírez-Fernández et al., 2015). However, in M2, no significant differences were observed in mental demand or any other NASA-TLX scores across different feedback conditions. The effects of feedback modality on subjective experiences may thus vary between different stages or complexities of forklift driving tasks, highlighting the importance of designing multimodal feedback carefully based on the task characteristics (M. Choi et al., 2020; Froland et al., 2023; P. Martin et al., 2012). For instance, in simpler or more familiar tasks (such as M1), haptic feedback might provide a clear advantage by reducing cognitive load. In contrast, in more complex or unfamiliar tasks (such as M2), the benefits of haptic feedback might be less pronounced, with users relying more on higher-level cognitive strategies or prior experience to navigate the task, regardless of the feedback modality. Some previous studies have shown that visual feedback can reduce perceived mental workload (Vitenese et al., 2003), but the lack of significant differences in M2 may be due to the higher complexity that was involved. In this case, additional feedback may not have significantly altered workload perception because participants were already operating near their cognitive limits.

Another potential explanation for the lack of significant differences in perceived workload between different feedback modalities is that the designed feedback may have been supplementary rather than essential. Feedback may only significantly affect perceived workload if users perceive it as providing crucial task information (Machado et al., 2023). Similar findings have been reported in other VR-based applications, such as VR assembly training (Yin et al., 2019), driving simulations (J.-H. Lee & Spence, 2008), and VR manipulation tasks (Nuamah et al., 2019). Results from these studies, together with ours, suggest that the effectiveness of feedback in reducing perceived workload may depend on whether it provides essential task-relevant information.

2.4.2. Suggestions for Alternative Feedback Designs

Participants provided valuable feedback for improving the current feedback designs for forklift driving training in VR. We summarize their suggestions for refining the visual and haptic feedback systems in Table 2.2.

Table 2.2: Future Design Suggestions for Feedback Modalities stratified by Specific Driving Tasks.

Task	Future Design Suggestions	
	Visual	Haptic
Fork-Pallet Alignment and Pallet Lifting	**Increase the Offset of Visual Overlay for Fork and Pallet Alignment**: Expand the green zone for fork alignment to reduce mental demand, allowing for slight offsets in fork placement while still achieving accurate alignment **Curve Fork Extension While in Rotation**: Allow the virtual fork extension line to rotate with the vehicle's movement, similar to parking assistance technology, to provide predictive path **Improve Visibility of Visual Overlays**: Change the color or make the fork extension more transparent to distinguish it from the designated zone for better visibility	**Lifting Pallet Reminder after Fork-Pallet Engagement**: Some participants preferred the current haptic reminder for lifting pallets, while others suggested reducing its duration and exploring the use of auditory cues as additional reminders
Forklift Navigation Inside Aisles and Truck Alignment (Horizontal or Vertical)	**Virtual Wall**: Adjust the virtual wall height, especially for ground-level load pickups, as participants found it too low (currently ~2 ft from the ground). Consider a more transparent see-through augmented visualization to prevent obstruction of pickup locations **Wall Sensitivity and Visibility**: Increase the sensitivity of the virtual wall, triggering the red warning at a closer distance. Some participants questioned the need for the wall altogether, feeling that the existing floor markings were sufficient. **Compass Feature**: Improve the compass by changing its color to red or blue, making it transparent, or using a different shape (e.g., arrow). A few participants suggested removing the feature entirely as they found it unnecessary	**Collision Avoidance**: Reduce the frequency of haptic feedback when the forklift is stationary to avoid distractions, ensuring it remains effective only when drivers are actively moving **Optimal Vertical Height**: Adjust the intensity or pattern of the haptic feedback to improve clarity and help users differentiate when they are at the correct vertical height or too close to the shelves

2.4.3. Limitations and Future Work

This study had several limitations. First, the study contained two specific forklift driving modules: fork-pallet engagement and load pickup. While these modules represent fundamental forklift operations, they do not capture the full range of forklift driving scenarios. Our findings cannot be generalized to other tasks, such as operating in environments with other vehicles or pedestrians. Second, the visual and haptic feedback we used were not always functionally equivalent. For example, the visual feedback in the fork-pallet engagement module provided guidance for alignment. However, in the fork-pallet engagement module, visual feedback provided direct alignment guidance, whereas haptic feedback served only as a notification or reminder. This discrepancy stemmed from the inherent characteristics and constraints of each feedback modality, which may have influenced participant perceptions, performance, and preferences. Third, we did not include auditory feedback or combinations of auditory, visual, and haptic feedback. Auditory feedback was excluded primarily due to concerns about masking effects in noisy work environments. Future research should explore the integration of auditory feedback and refine existing feedback patterns based on the qualitative feedback provided by participants (as discussed in section 2.4.2).

2.5. Conclusions

We developed and evaluated different real-time multimodal feedback designs for forklift truck training in a virtual environment. We completed an initial study to observe the behaviors of experienced and novice forklift drivers in two selected driving modules. Experienced participants' expertise and strategies were extracted using the retrospective think-aloud method, whereas common mistakes by novices were identified. Based on these findings, we designed and implemented three feedback designs of visual, haptic, and combined visual-haptic modalities for comparison against no feedback with a new sample of novice drivers. We found shorter completion times with haptic feedback during load-pallet engagement, but with no feedback during the load pickup module. A lower level of mental workload was reported using haptic feedback in the load-pallet engagement task, and eye-tracking metrics indicated more attention to obstacles and hazards with haptic feedback. Though not effective for improving completion time or mental demand, visual feedback was most preferred by the participants. Findings from our study, along with future feedback design suggestions, can aid in the further development of real-time multimodal feedback to enhance VR forklift training and improve its effectiveness.

Chapter 3: Cybersickness Susceptibility in Virtual Reality Forklift Driving: Impact of Age and Sex

3.1. Introduction

Forklifts are integral to efficient warehouse operations (Neira-Tovar et al., 2022). Forklift operators are required to take proper driving training and certification (Sarupuri et al., 2016), following the Occupational Safety and Health Administration (OSHA 1910.178 (i)(6)) standards. A traditional certificate training course involves truck driving with the guidance of dedicated trainers and also requires dedicated forklift trucks and space, all of which are resource-intensive and costly (Islam et al., 2024a). To address these challenges, virtual reality (VR) simulators have emerged as a cost-effective and safe alternative for forklift driving training (Villiers & Blignaut, 2016). These simulators can replicate real-world scenarios, allowing operators to practice in a controlled environment without the associated risks of physical training (Abbas et al., 2023). However, there is a substantial challenge associated with VR experiences, specifically concerning cybersickness during virtual training (Froland et al., 2023; Rebenitsch & Owen, 2021).

Cybersickness in VR arises primarily from a perceptual conflict between visual stimuli and vestibular sensations, leading to sensory mismatch and disorientation (Oman, 1990; Warwick-Evans et al., 1998). In simpler terms, the eyes perceive movement in the virtual world, but the body remains stationary, leading to a conflict in sensory information that the brain struggles to reconcile. The underlying mechanisms of cybersickness are complex and multifaceted, involving both technological and individual factors (Jasper et al., 2023). Various factors, such as field of view (Bos et al., 2010), latency (Stauffert et al., 2020), display resolution (Wang et al., 2022), and movement speed (Chattha et al., 2020), can intensify symptoms of cybersickness. Despite advancements in VR technology, the frequent experience of cybersickness and its associated symptoms during VR training is a concerning issue (Abotaleb et al., 2023; Líndal et al., 2018).

The occurrence of cybersickness in VR could restrict the widespread adoption of this convenient and innovative form of job training, disproportionately disadvantaging specific demographics (such as older or female workers). Individual attributes, such as age and sex, may impact susceptibility to cybersickness due to variations in vestibular sensitivity (Abouzari et al., 2020), hormonal influences (Bannigan et al., 2024), and cognitive processing (Park et al., 2022). In driving simulator studies, older adults and females have shown more cybersickness symptoms (Keshavarz et al., 2018; Smyth et al., 2019). These symptoms may include nausea, dizziness, sweating, and disorientation, all of which can significantly impair the performance and overall experience of the users (Davis et al., 2014b). Consistently across various studies, older adults reported severe cybersickness that led them to discontinue driving tasks prematurely (Matas et al., 2016; Stoffregen et al., 2017). To ensure inclusivity and accessibility in forklift driving training using VR for diverse worker populations, it is essential to understand whether specific user populations are more susceptible to cybersickness.

Although prior studies have investigated the impact of individual attributes, such as age and sex, in diverse VR applications, including passenger vehicle driving (Almallah et al., 2021; Brooks et al., 2010), forklift driving simulation is unique in terms of its navigational and operational requirements (i.e., standing driving). Given that forklift driving involves dynamic upper body movement and standing posture (Islam et al., 2023), participants might show more vulnerability toward cybersickness due to postural instability (Stoffregen & Smart, 1998; Villard et al., 2008). Therefore, we examined the influence of age and sex on cybersickness susceptibility within a virtual reality forklift simulation. The outcomes of our study are expected to provide substantial evidence for developing targeted interventions and design strategies for VR-based forklift driving training based on user demographics, to enhance both user experience and training effectiveness.

3.2. Methods

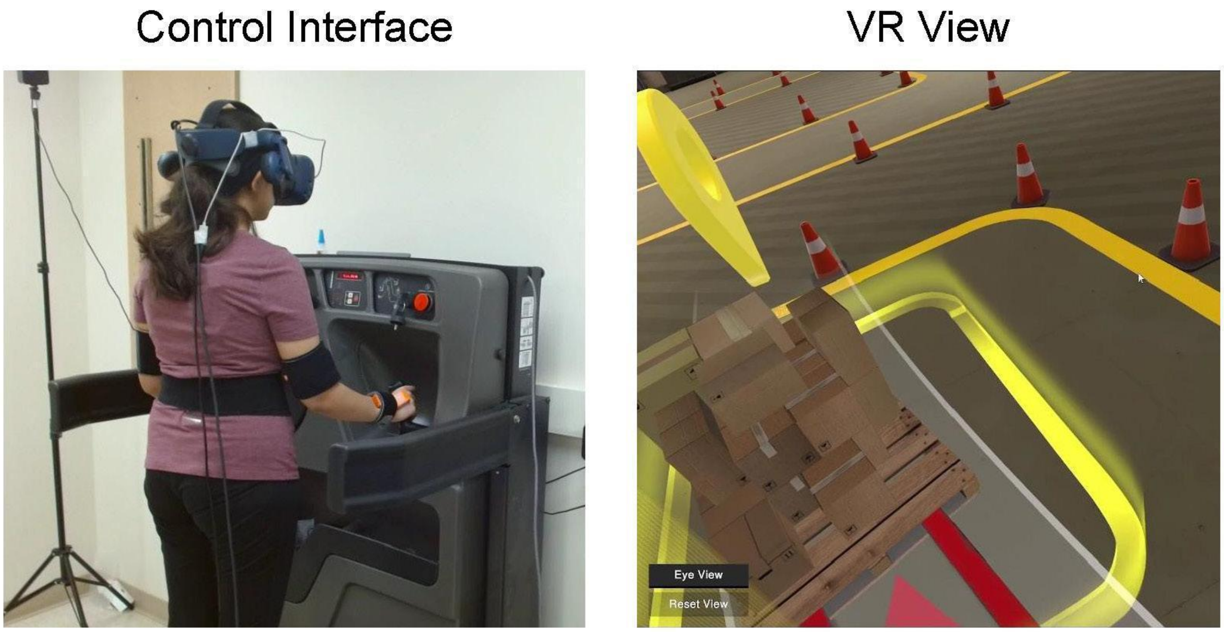
3.2.1. Participants

Twenty individuals (9 female, 11 male) were recruited and completed the study. Participants were recruited by distributing flyers and emails to the university email groups and also by publishing advertisements in a local newspaper. Participants were divided into two age groups: a younger adult group (18-40 years old; F = 7, M = 4) with a mean (SD) age of 26.3 (5.1) years, and an older adult group (>40 years old; F = 2, M = 7) with a mean (SD) age of 51.8 (8.6) years. The age of 40 was selected as the split between young and older groups, modeling previous work comparing skill acquisition between the age groups (Park, 1994; Zandri & Charness, 1989). All older participants had prior forklift-driving experience, averaging 14.3 (SD = 10.6) years. In contrast, only one young adult had four years of forklift-driving experience, while the others had none. None of the older adults had VR experience. Among young adults, two had no VR experience, five used VR monthly, three used it weekly, and one used it almost daily. Prior to any data collection, participants provided written informed consent. This research complied with the Declaration of Helsinki and was approved by the Institutional Review Board (IRB) of Virginia Tech (IRB-22-341).

3.2.2. Experimental Procedures

We used a VR-based order picker forklift simulator (The Raymond Corporation, NY, USA) equipped with a Vive Pro Eye headset (HTC Corporation, Taiwan), and a Leap Motion controller (Leap Motion

Inc., USA), all linked to the physical truck control panel (Figure 1). This order picker truck requires operators in a stand-up position while driving. Participants initially participated in a 10-minute try-out session. During the try-out session, the experimenter demonstrated how the buttons on the physical control work and allowed participants to practice them. The training session was performed in a free-roam warehouse environment, where participants could explore the VR environment and control without specific goals.



Control Interface

VR View

Figure 3.1: VR training environment showing: (a) the control interface of the truck simulator; and (b) participant view of the virtual environment.

After the try-out, participants received rest breaks until they were comfortable to start the main trials. Participants completed a total of eight trials, performing two repetitions of the four driving lessons in a fixed order. Each of the repeated lessons was performed consecutively. The driving lessons for this study increased in complexity. A fixed-order sequence allowed participants to progressively develop the skills needed for subsequent tasks. This was done to minimize the likelihood of task failure and ensure participants could effectively complete all trials. The driving lessons consist of common and basic forklift driving tasks: driving along a designated path, engaging a pallet to the fork, driving in a wide aisle, and emergency stopping when there are blocks ahead of the truck. Mean (SD) trial completion time for each task were 2.4 (1.0), 4.2 (2.5), 7.8 (4.4), and 2.0 (0.9) mins. Participants were instructed to stop at any time if they felt severe cybersickness and could not continue further. Up to five minutes of rest break was provided between each trial. After each trial, participants were allowed to remove the VR headset during rest breaks and were asked to complete the paper-based Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). SSQ is a 16-item questionnaire that assesses the effects of VR on an individual's symptoms, categorized into three components: nausea, oculomotor discomfort, and disorientation. We used the paper-based method to avoid exposing participants to additional screen time.

3.2.3. Data Processing

SSQ responses (on a scale of 0-4) were subsequently converted into four subscales (Nausea, Oculomotor, Disorientation, and Overall), following the method described in previous literature (H. K. Kim et al., 2018). The four subscales had a maximum value of 267.2 (Nausea), 212.2 (Oculomotor), 389.8 (Disorientation), and 314.5 (Overall), with higher scores indicating stronger sickness symptoms. Each trial was labeled as either a cybersickness occurring trial (COT) or a no COT (nCOT), based on the SSQ scores. Any trials with >50% of the SSQ subscales (133.6, 106.1, 194.9, and 157.25, respectively) were deemed as COT, following a similar approach taken by previous research that used a 50% threshold from the reported subjective motion sickness scale (Keshavarz et al., 2017).

Survival time was calculated for later use in the Kaplan–Meier (Dudley et al., 2016) and Cox Proportional Hazards models (F. E. Harrell, 2015) by summing all active VR time (excluding the try-out session and breaks between trials) until participants had a COT. For participants who completed all eight trials without experiencing moderate to severe cybersickness (did not cross 50% of the SSQ scores), the time for all eight trials was calculated as the survival time.

3.2.4. Statistical Analysis

A success rate (%) was calculated based on the number of participants surviving for each trial. Chi-square tests of independence (McHugh, 2013) were used to determine if the proportion of success rate differed significantly between different age and sex groups. The Mann-Kendall, which is a non-parametric test, was used to assess if there was a monotonic upward or downward trend in the success rate between different age and sex groups over time (Yue et al., 2002). The SSQ score during the COT (or the eighth trial for participants who did not experience cybersickness) was labeled as a "final SSQ score" and used for comparison between different groups (age, sex). Separate mixed model repeated measures Analysis of Variance (ANOVAs) were used to investigate the effect of *Age* and *Sex* on the final SSQ score and the survival time. Survival analysis (Kaplan–Meier) and Cox Proportional Hazards models were used to examine *Age* and *Sex* differences in the SSQ scores. The Kaplan-Meier method is a non-parametric statistical approach used to estimate the survival function from lifetime data, providing the probability of surviving beyond specific time points (Dudley et al., 2016). This method was used to estimate survival probabilities over time, enabling comparisons of survival curves (time until cybersickness) between different age and sex groups. The Cox proportional hazards model, a semiparametric regression technique, assesses the effect of various covariates on the hazard or risk of an event occurring, assuming that the hazard/risk ratios between groups remain constant over time. This model was used to calculate risk ratios for each age and sex group.

3.3. Results

Cybersickness symptoms and success rate. Seven older participants could not complete all eight trials and quit prematurely due to severe cybersickness. Among them, four quit after the try-out training session and did not want to continue with the main driving trials. We observed severe physical symptoms of cybersickness among these participants, i.e., feeling dizzy and nauseated, unable to maintain a steady posture, sweating around the forehead and neck, and vomiting. No visual symptoms were observed among the young participants, though four participants reported feeling slightly dizzy.

The success rate (%) during each trial (including the training period) is shown in Figure 2 for each age and sex group. The Chi-square test of independence showed no significant difference in the success rate between the age groups ($\chi^2 = 6.64$, $p = .687$) and the sex groups ($\chi^2 = 1.24$, $p = .999$). The success rate (%) gradually declined over the trials and the Mann-Kendall test showed a significantly decreasing trend for all the groups tested, i.e., older adults ($\tau = -0.73$, $p = .010$), young adults ($\tau = -0.83$, $p = .003$), females ($\tau = -0.68$, $p = .022$), and males ($\tau = -0.80$, $p = .004$).

SSQ score and survival time. The Overall SSQ scores of each participant are represented in Figure 3 for each trial until they experience severe cybersickness. ANOVA results using the final SSQ score and survival time are reported in Table 3.1. Only *Age* showed a significant difference for both final SSQ score and survival time. Older adults showed a 257.2% higher overall final SSQ score compared to young (Figure 3.4). Survival time was also 66.3% lower among older adults (Figure 4). There was no main effect of sex or interaction.

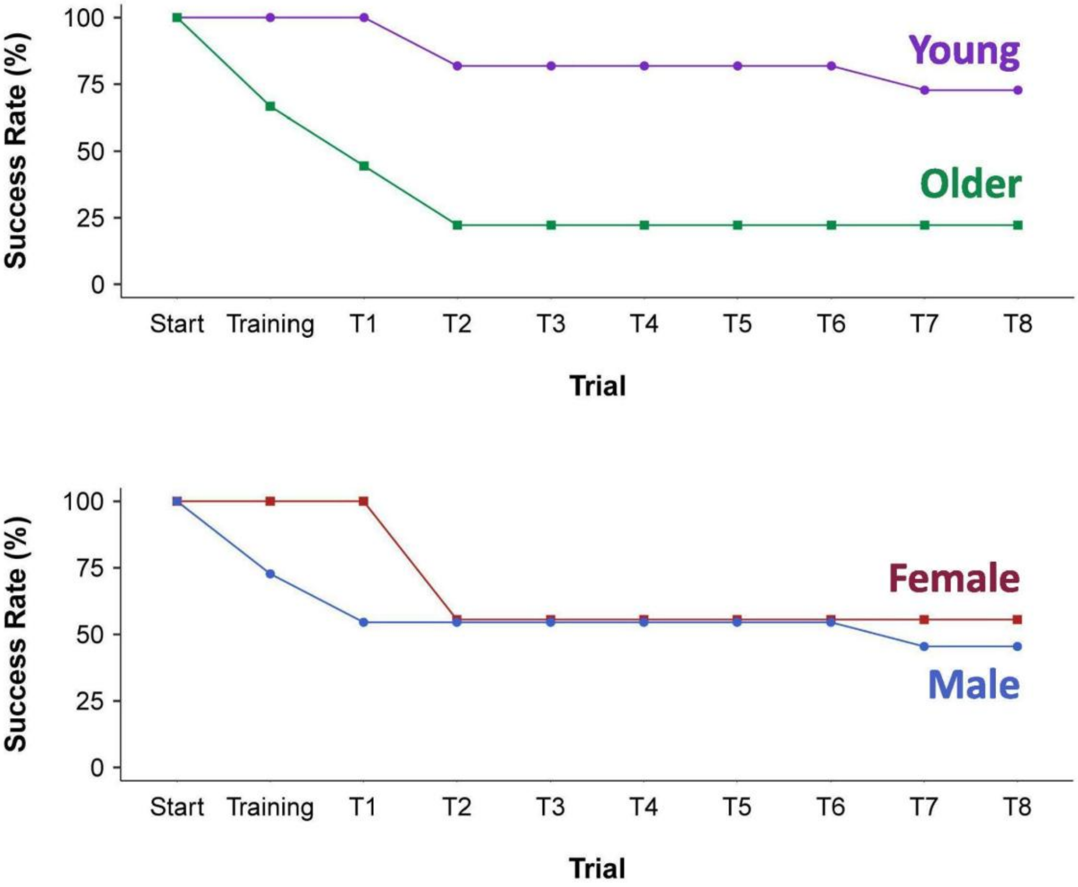
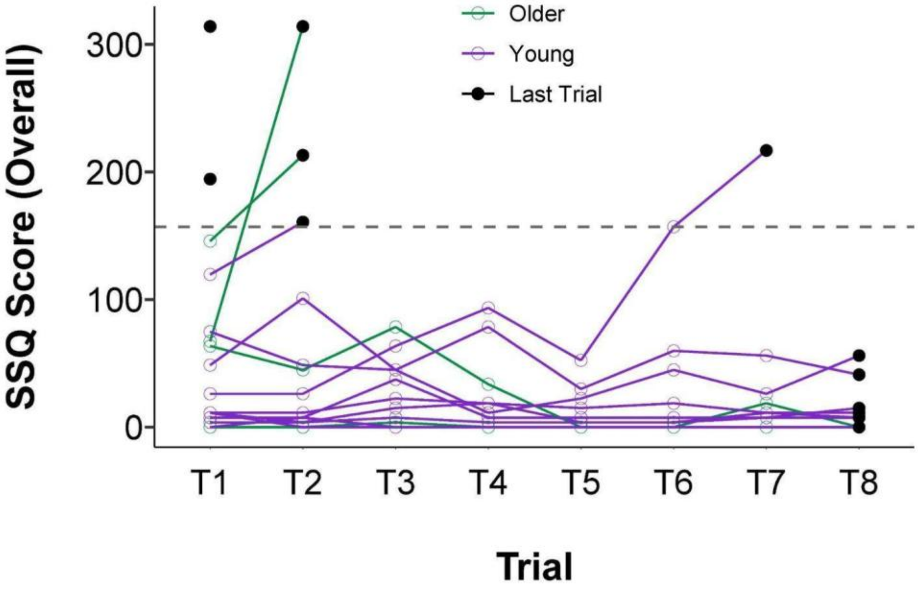


Figure 3.2: Success rate (%) of different age and sex groups over repeated trials.

Table 3.1: Summary of ANOVA results for the effects of *Sex* and *Age* on the final SSQ scores and Survival Time [*F* value (*p*-value, η^2_p)]. Significant effects are in bold font.

Effect	**Final SSQ Score**			
	Overall	Nausea	Oculomotor	Disorientation
Age (A)	**9.05 (.008, 0.241)**	**5.59 (.031, 0.067)**	**7.47 (.015, 0.101)**	**5.03 (.039, 0.057)**
Sex (S)	0.06 (.816, 001)	0.87 (.364, 0.003)	0.23 (.641, 0)	0.87 (.365, 0.003)
A × S	0.33 (.574, 0)	0.60 (.448, 0.001)	0.24 (.629, 0)	0.21 (.651, 0)
	Survival Time			
Age (A)	**5.58 (.031, 0.067)**	**9.00 (.009, 0.130)**	**6.51 (.021, 0.084)**	**4.55 (.049, 0.049)**
Sex (S)	0.55 (.469, 0.001)	1.06 (.319, 0.004)	0.14 (.711, 0)	0.28 (.603, 0)
A × S	0.03 (.859, 0)	0 (.993, 0)	0.11 (.741, 0)	0.14 (.709, 0)



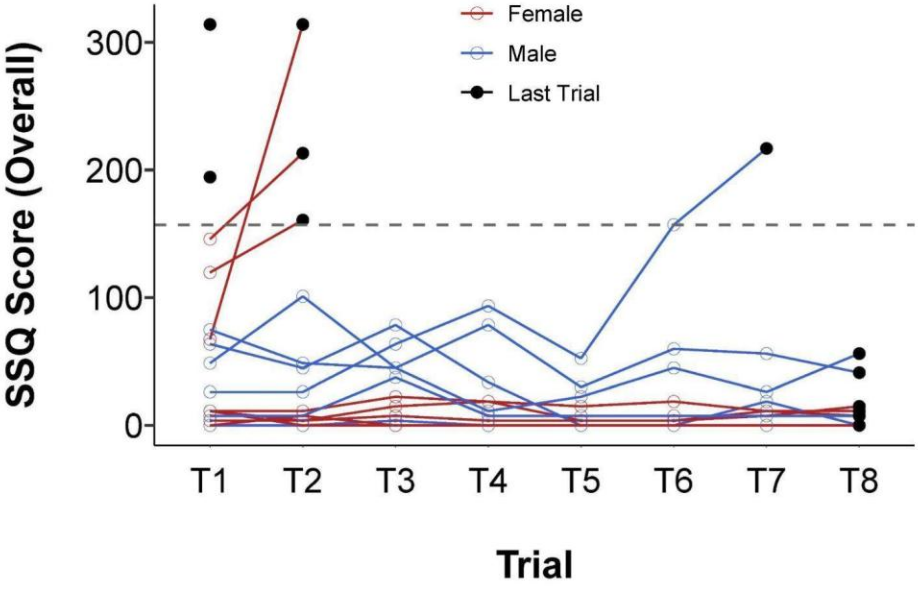


Figure 3.3: Overall SSQ score across different trials for each participant. Filled circles represent the last trial of each participant, which was either a cybersickness occurring trial (COT) or an nCOT if the participant did not experience severe cybersickness until the last trial (T8). Dotted horizontal lines represent 50% of the SSQ score (Overall) criteria.

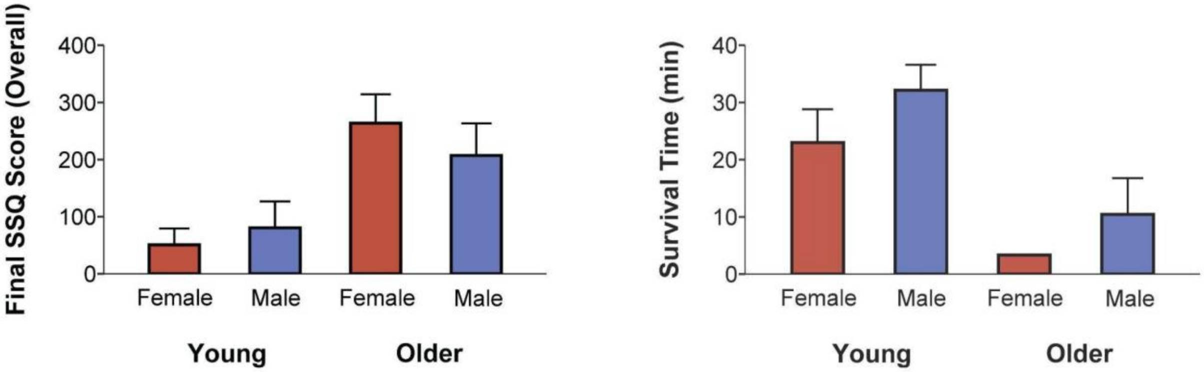


Figure 3.4: (a) Final SSQ score (overall); and (b) Survival time for different age and sex groups. The error bar represents the standard error.

3.3.3. Survival Analysis

Summary results from the Cox proportional hazard model, including risk ratios (95% CI), are summarized in Table 2. Age was the only significant predictor across the overall SSQ score and three subscales. The risk ratio showed that older participants had a 4.2 to 7.8 times greater risk of experiencing VR-induced sickness compared to their younger counterparts, based on the SSQ scores (overall and subscales). There was no main effect of sex or interaction. Figure 5 depicts the estimated survival probabilities of different sex and age groups for the overall SSQ scores. For older adults, the survival probability drops down to 22.2% within the first five minutes of the training. Males showed lower overall probability, but this was not statistically significant.

Table 3.2: Cox proportional hazard model and risk ratio for sex and age on SSQ scores.

SSQ scores	Variable	Estimate	Risk Ratio (95% CI)	*p*-value
Overall	*Age*	0.86	**5.69** (1.28, 25.31)	**.022**
	Sex	0.17	1.41 (0.32, 6.17)	.651
Nausea	*Age*	1.02	**7.83** (1.65, 37.19)	**.007**
	Sex	0.22	1.57 (0.35, 7.01)	.553
Oculomotor	*Age*	0.72	**4.22** (1.21, 14.79)	**.029**
	Sex	0.11	0.81 (0.24, 2.76)	.729
Disorientation	*Age*	0.73	**4.35** (1.15, 16.41)	**.032**
	Sex	0.01	1.03 (0.28, 3.79)	.965

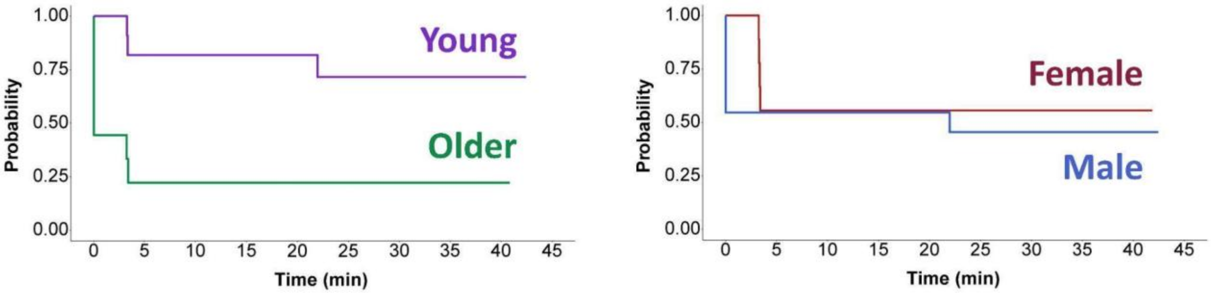


Figure 3. 5: Estimated probability of successful VR forklift training completion without experiencing severe cybersickness symptoms based on the Kaplan-Meier survival analyses by different age (left) and sex (right) groups.

3.4. Discussion

We investigated the impact of age and sex on cybersickness susceptibility in a virtual reality (VR) forklift driving simulator. The results indicated that age is a significant factor influencing the occurrence and severity of cybersickness symptoms, while sex did not show a significant impact. We will discuss the implications of these findings in the context of occupational VR training, explore the potential mechanisms underlying the observed age-related differences, and provide recommendations for mitigating cybersickness in VR applications.

3.4.1. Age and Cybersickness

Older adults had higher scores across all SSQ subscales and shorter survival times before experiencing symptoms severe enough to discontinue the task. This finding aligns with previous research suggesting that older adults are more susceptible to cybersickness and related symptoms in virtual environments (W.-T. Chang, 2020; G. D. Park et al., 2006). The absence of interaction effects between sex and age further implies that the impact of age on cybersickness risk remains consistent across both sexes, indicating a universal vulnerability among older individuals (Drazich et al., 2023).

The greater risk ratio (4.2 to 7.8) among older adults experiencing VR-induced sickness has substantial implications for the widespread adoption and future design of VR-based forklift driving training, especially if considered as a replacement or alternative to traditional hands-on training. About 75% of older participants could not continue beyond the first driving trial, with survival probability dropping to 22.2% within the first five minutes of training. In practical terms, if a training program excludes three-fourths of older adults (age > 40 years) due to cybersickness, it could undermine its original purpose of being cost-effective. This problem could cause diminished participation and raises significant concerns regarding age-based discrimination. Given that the aging workforce is a crucial societal problem in logistics and warehousing industries (Gekara et al., 2019; Sgarbossa et al., 2020), attracting or retaining older workers will be essential in the next decade. Companies using this type of new training technology might struggle to attract older workers if they feel alienated by the technology (Caspi et al., 2019; Selwyn, 2004). This exclusionary effect also contradicts the growing societal emphasis on creating inclusive work environments and promoting lifelong learning opportunities for all employees, regardless of age (Alves et al., 2023; Burns, 2020).

Thus, discussing potential mitigation strategies to accommodate aging workers in VR-based occupational training is important. First, designers and developers of VR-based occupational training programs should ensure that older users are adequately considered early in the design process to alleviate cybersickness and discomfort in virtual environments (N. Lee et al., 2021). By involving these target users early on, designers could identify and prioritize design features that are essential to accommodate older users. For example, individuals experience more severe cybersickness in a standing posture compared to a seated posture due to reduced postural stability, increased reliance on visual cues for balance, and greater vestibular disturbances when upright (Chattha & Shah, 2018; Clifton & Palmisano, 2020). In a standing posture, the body's center of gravity is more dynamic, and minor shifts in VR visuals can trigger a stronger mismatch between visual, vestibular, and proprioceptive inputs, leading to heightened symptoms of cybersickness (Keshavarz et al., 2015; Riccio & Stoffregen, 1991). Considering that our participants performed all trials while standing due to the design of the simulator, older participants may have experienced more discomfort and cybersickness (Bonnet et al., 2008; N.-E. Kim et al., 2018). So, providing older adults with a seat may help reduce discomfort associated with cybersickness (Marengo et al., 2019), but this will require substantial design modifications in the simulator hardware. Future designs of VR forklift simulators could be improved to accommodate both standing and seated postures so that older adults can start their training in seated postures and gradually adapt to the virtual environment.

Head rotations are also recognized as significant factors contributing to the sensory conflicts that often result in cybersickness in virtual environments (Li et al., 2021). In forklift driving, operators consistently need to look around to assess their surroundings to avoid accidents. During excessive and fast head rotations, participants' vestibular system and proprioceptive feedback experience more sensory mismatch, leading to cybersickness (Koch et al., 2018). Thus, starting the training with a relatively simple driving task with little head rotation (i.e., forward driving without no extreme turns) and acclimatizing older adults into the environment could be effective.

Several software-based modifications could also be considered to reduce the cybersickness. Peripheral blurring and field-of-view reduction are useful techniques that have been shown to provide visual comfort and help reduce cybersickness symptoms in the virtual environment (Groth et al., 2021; F. Wu & Suma Rosenberg, 2022). High-resolution displays with faster refresh rates can minimize latency and visual distortions, both of which are key factors in causing cybersickness (Wang et al., 2022). Changing the locomotion method also impacts the severity of cybersickness. For example, the snap-turning locomotion technique can be used, which rotates the user's viewpoint instantaneously in fixed increments rather than smoothly (Kronemberger et al., 2024; Onuki & Kumazawa, 2019). This technique can be less nauseating for some individuals, as it minimizes the perception of continuous motion (Onuki & Kumazawa, 2019).

If physical or software-based design modifications are too costly or impractical, there are alternative mitigation approaches that could be considered. Increased postural sway is known to heighten the cybersickness experience (Rebenitsch & Quinby, 2019). In a passenger car driving simulation study, the use of passive restraints on the head and the chest has been found to be effective in reducing cybersickness among older adults (Keshavarz et al., 2017). Similar approaches could be explored with the forklift driving simulation in a standing posture using passive restraints that could potentially help with increasing postural stability and proprioception.

The Kaplan-Meier survival plots revealed intriguing patterns in the temporal dynamics of cybersickness occurrence. Older adults exhibited a significantly rapid decline in survival probability within the first five minutes, followed by a plateau phase where few additional participants crossed the set threshold for cybersickness. This observation suggests that the majority who are prone to cybersickness will exhibit symptoms quickly, while those who do not experience it during the early stage are less likely to do so later in the exposure. We have also observed early visible physical symptoms from older adults who eventually quit the study prematurely. Thus, we should particularly target those people who show an early sign of cybersickness for potential mitigation. Detecting such signs early on, and acclimating older users to the virtual environment by starting with shorter sessions and gradually increasing the training length can be beneficial in reducing cybersickness susceptibility (Bendixen et al., 2023; Schmidt et al., 2021). By doing so, users could adapt to the sensory stimuli and reduce the likelihood of experiencing cybersickness (Dużmańska et al., 2018). Real-time monitoring of physiological signals, such as heart rate and skin conductance, could be useful in detecting discomfort and cybersickness symptoms (N. Martin et al., 2020b; Recenti et al., 2021).

3.4.2. Sex and Cybersickness

Although previous research had suggested potential sex-based differences in cybersickness susceptibility (Fulvio et al., 2021; Hou et al., 2019), our exploratory findings suggest that within the context of VR forklift simulation training, sex may not be a significant determinant. The absence of sex-based differences in our study might indicate that the physical demands of forklift operation, such as standing and upper body movement, could overshadow any inherent sex-based predispositions to cybersickness. The biological and cognitive factors influencing cybersickness (Kuiper et al., 2020; Riecke et al., 2006) do not differ substantially between sexes in this particular VR context. However, due to the small sample size used in this study, further research with larger and even more diverse samples is needed to explore this aspect in greater detail.

3.4.3. Future Research and Limitations

Our study motivates several areas for future research investigation. While age and sex are important demographic factors to consider (which is also practically easy to obtain at the training site), an individual's susceptibility to cybersickness could stem from multiple other individual factors. Thus, it would be beneficial to investigate other individual factors that might influence cybersickness susceptibility, such as previous experience with VR, baseline vestibular function, and cognitive processing speed. As discussed in Section 4.1, tailored training plans could be built for each individual based on their demographics, or their baseline functions so that the cybersickness mitigation can be more effective and personalized. Future studies would also explore the long-term effects of repeated VR exposure and the potential for habituation to cybersickness symptoms over time.

The limitations of this study should be acknowledged. The small sample size ($N = 20$) and the convenience sampling method might limit the generalizability of the findings. Moreover, the limited sample size may have reduced the statistical power to detect significant effects, particularly in examining potential sex-based differences. We did not control the total trial and break times, which could have influenced participant fatigue and recovery, potentially affecting performance and cybersickness symptoms. Additionally, while the study found that older adults experienced greater difficulty due to cybersickness, this may be attributed to their lack of prior VR experience rather than purely age-related effects. Most younger participants reported regular VR use (monthly, weekly, or even daily), which may have aided their adaptation to the VR training. The lack of control for prior VR experience is a limitation of this study. This study did not control forklift driving experience as most of the young adults did not have any prior forklift driving experience. Including forklift driving experience as a potential factor in a future study may reveal how this affects VR adaptation. Another limitation is that all participants completed tasks in a fixed sequence, which may have introduced potential task order effects, as experiences from earlier tasks could have influenced performance in later ones. However, a fixed order was necessary due to the progressive complexity of the forklift-driving lessons. The use of a single VR forklift truck simulation platform might limit the generalizability of the findings to other VR simulator systems or other types of forklift trucks.

3.5. Conclusions

Our study helped to understand cybersickness within a virtual forklift training environment by investigating the effects of age and sex. The significant impact of age emphasized the importance of designing VR training programs that accommodate older adults' needs to ensure an accessible and effective training experience. While sex was not a significant factor in this context, further research is necessary to explore this aspect comprehensively. Implementing effective mitigation strategies can optimize and enhance user experience and training outcomes. This approach will support the broader adoption of VR for occupational training and other applications, ensuring that users across various demographics can benefit from this innovative technology without discomfort or adverse effects. Since this was an exploratory study, for future study, adding more subjective and objective measures of cybersickness measurement can provide stronger evidence of the true nature of the impact that sex and age play in virtual forklift training.

Chapter 4: Investigate the Impact of Head Rotation and Forklift Truck Platform Height on the Occurrence of Cybersickness

4.1. Introduction

Cybersickness, a common adverse effect in virtual reality (VR) environments, arises from sensory conflicts primarily involving the vestibular, visual, and proprioceptive systems (Gallagher & Ferrè, 2018; J. Kim et al., 2020). One of the key contributors to these conflicts are head rotations–particularly rotational motions along the pitch, yaw, and roll axes–which intensify the mismatch between visual stimuli and vestibular feedback. Rapid or complex head rotations amplify these discrepancies, often resulting in symptoms such as nausea, dizziness, and visual discomfort.

Research has consistently demonstrated that users who engage in frequent or rapid head rotations experience significantly higher levels of cybersickness compared to those in static or minimal movement conditions (Li et al., 2021; Park & Koo, 2025). Among these movements, yaw rotation–movement around the vertical axis–has been identified as a major contributor to sensory conflict, often resulting in cross-coupled stimuli that the brain struggles to reconcile between the visual and vestibular systems (Holly et al., 2016). Pitch rotation, which involves nodding the head up and down, can also intensify sensory conflict due to its association with gravitational cues, exacerbating the mismatch between sensory inputs (Holly & Harmon, 2012). Roll movements, involving lateral tilting of the head, also contribute to cybersickness through direction-dependent processing of vestibular information in the brain (Ertl et al., 2023). Simultaneous movement across multiple axes–such as combined pitch, yaw, and roll–has been shown to intensify these conflicts even more than isolated movements, leading to a greater likelihood of cybersickness (Keshavarz & Hecht, 2011a).

Height or position of the user in the virtual environment can have a measurable impact on users' postural control, psychological state, and sensory integration, factors that collectively contribute to cybersickness (LaViola, 2000). For instance, elevated VR environments often introduce a heightened sense of threat or anxiety, particularly due to fear of falling, which in turn activates autonomic responses such as increased heart rate and skin conductance (Zhu et al., 2023). Bzdúšková et al. (2022) reported increased distress and discomfort during the VR experience when participants were placed at an elevated height. Similarly, Ang & Quarles (2024) informed that participants who experienced moving through virtual terrain with elevation changes reported more cybersickness than flat terrain. Despite preliminary evidence, the role of virtual platform height remains underexplored in the context of cybersickness.

Existing commercial VR-based forklift training simulators, provide an immersive training environment with actual forklift operation for the user to try and learn. Forklift operations such as environmental scanning, hazard detection, precise execution of loading and unloading tasks, and retrieval of pallets/products from an elevated height are an essential part of forklift training. These tasks require dynamic head rotations and vehicle manipulation at an elevated height, which can potentially challenge the vestibular system's ability to integrate multisensory cues, increasing the likelihood and severity of cybersickness observed in our earlier work (Islam & Lim, 2025). However, relatively little research has systematically explored how simple to complex head rotations–across different axes such as pitch, yaw, roll, and their combinations, contribute to cybersickness, especially in combination with heights. Understanding of how specific head rotations and heights impact cybersickness is critical for enhancing VR training design, improving user interaction strategies, and developing mitigation strategies that minimize discomfort and enhance overall user experience.

To investigate the factors contributing to cybersickness, particularly the role of dynamic head rotations and heights, it is essential to adopt reliable and sensitive measurement techniques. Prior research has explored various subjective assessment tools, validating their effectiveness in capturing the multifaceted nature of cybersickness (Gonçalves et al., 2024; Kourtesis et al., 2023; Sevinc & Berkman, 2020). Among subjective approaches, standardized self-report instruments remain the most practical and widely used in VR research due to their ease of administration and direct insight into participants' perceived symptoms. Two of the most widely used self-reported assessment tools are the Simulator Sickness Questionnaire (SSQ) and the Fast Motion Sickness Scale or FMS (Keshavarz & Hecht, 2011c). The SSQ, developed by Kennedy et al. (1993), has become a gold standard, widely adopted for evaluating symptoms induced by simulator-based environments, including VR applications. Its strong reliability and sensitivity to changes in exposure make it especially valuable in controlled studies (Kourtesis et al., 2023). However, the SSQ also has practical limitations–namely, its length and complexity–which can contribute to participant fatigue and reduced compliance, particularly when repeated measurements are required during VR sessions (Bouchard et al., 2021; Kourtesis et al., 2023; Somrak et al., 2021). To overcome these limitations, the Fast Motion Sickness Scale (FMS) was introduced as a streamlined alternative (Keshavarz & Hecht, 2011). The FMS consists of a single-item visual analog scale (VAS) ranging from 0 (no sickness) to 20 (severe sickness), allowing participants to quickly report their current level of discomfort. This efficiency makes it especially useful in experimental designs that require frequent, real-time assessments of cybersickness during dynamic VR interactions.

While the gold standard subjective tool, like the SSQ is widely used to assess cybersickness, it requires pausing the experience for self-reporting at the end of a certain period. This interruption can interfere with immersion and may not capture real-time symptom fluctuations. In contrast, the FMS scale offers the potential for more frequent, real-time monitoring without disrupting the user's experience. Integrating these two scales can provide a more holistic understanding of users' responses to VR training. This multimodal approach is especially valuable in occupational VR training, where minimizing interruptions and maximizing realism are essential.

This study will systematically investigate the occurrence and severity of cybersickness resulting from head rotations involving one, two, or three axes (pitch, yaw, and roll) within a simulated VR warehouse environment at different height settings (ground level vs. elevated height). Two subjective reporting methods—the FMS and SSQ—will be used to assess cybersickness. We hypothesize that more complex head rotations (involving all three axes) will elicit significantly greater cybersickness symptoms compared to rotations involving only one or two axes. We also hypothesize that head rotations performed during trials at elevated heights will induce greater cybersickness than those at ground level. Finally, consistent with findings from Chapter 3, we hypothesize that older adults will report higher levels of cybersickness compared to younger adults. Confirming these hypotheses would highlight the impact of complex head rotations and heights on user comfort and support the development of best VR occupational training, such as limiting or gradually introducing multi-axis head rotations, to improve VR system design and enhance user experience, training outcomes, and inclusivity.

4.2. Methods

4.2.1. Participants

Twenty-six individuals (15 female, 11 male) were recruited via flyers and university email groups. Younger adults group (18-40 years; 8 female, 7 male) had a mean (SD) age of 22.1 (3.5) years, and older adult group (>40 years; 7 female, 4 male) had a mean (SD) age of 51.4 (5.8) years. Among younger adults, one participant had never used VR, 12 reported rare but prior use, one used it weekly, and one used it daily. Among older adults, nine had no prior VR experience, and two reported limited exposure.

After the training session, four participants (2 female from the younger adults group, 1 female and 1 male from the older adults group) withdrew from the study due to severe cybersickness. Thus, a total of 22 individuals completed the study, corresponding to 86.7% of younger adults and 81.8% for older adults. Younger adults group (6 female, 7 male) had a mean (SD) age of 22.4 (3.7) years, and the older adult group (6 female, 3 male) had a mean (SD) age of 51.3 (6.4) years. Prior to data collection, all participants provided written informed consent. This research complied with the declaration of Helsinki and was approved by the Institutional Review Board (IRB) of Virginia Tech (IRB-25-008).

4.2.2. Experimental Procedures

A virtual warehouse environment was created using the Unity game engine (*version 2021.3 LTS,* Unity Technologies, CA, USA). A virtual order picker forklift truck was placed within this environment, and participants experienced being transported through the warehouse aboard the forklift truck (Figure 4.1). We used an order picker truck as it is one of the commonly used forklift truck for warehouse operations. The movement of the truck was pre-programmed by the experimenter; participants were not required to drive or control the vehicle. The VR experience was delivered using a Meta Quest 3 head-mounted display (Meta, CA, USA). The forklift truck was positioned at two heights: ground level and elevated height, simulating the vertical mobility of a real forklift. Actual order picker forklift truck can move up to 38 feet vertically. In the elevated height condition, the platform of the truck was raised to the level of the fourth shelf from the ground. During each height condition, participants performed head rotations along one, two, or three axes. In the 1-axis condition, participants performed head rotations along the yaw axis (axial rotation). Yaw rotation was selected as the primary movement in the 1-axis condition due to its fundamental role in environmental scanning during forklift operation, as operators must frequently perform lateral visual sweeps to monitor aisles, assess obstacle clearance, detect pedestrians, and align the forklift with pallets or shelves. In the 2-axis condition, they combined yaw and pitch movements (axial rotation and flexion/extension). Combined yaw and pitch movement models a common compound motion that is used in forklift navigation and load placement tasks. In the 3-axis condition, head rotations included yaw, pitch, and roll (axial rotation, flexion/extension, and abduction/adduction). Though roll is less frequent during routine driving, it can occur when operators lean to improve sightlines, or inspect loads from oblique angles. Figure 4.2 illustrates the head rotation for each axis condition.

Prior to the start of the session, participants received a short training of up to 5 minutes to familiarize themselves with the VR device, the environment, and the tasks that they would be performing. Each participant completed six randomized trials (three axis-specific head rotation conditions x two height conditions) using a balanced Latin square design. Adequate rest breaks were provided between trials, with participants self-selecting when to proceed. We asked FMS score prior to the start of each trial (Pre-FMS), and a trial would proceed only if the Pre-FMS score was below 5. During each trial, the virtual forklift truck stopped at 15 locations within the VR warehouse. At each location, participants were instructed to rotate their head to align with a red-marked target box in the designated axis direction, while minimizing movement of the torso and lower extremities as much as possible. After every third location (checkpoints), participants rated their cybersickness using the 0-20 FMS scale, resulting in a total of five FMS scores per trial. Following each trial, participants also completed the SSQ (Figure 4.3).

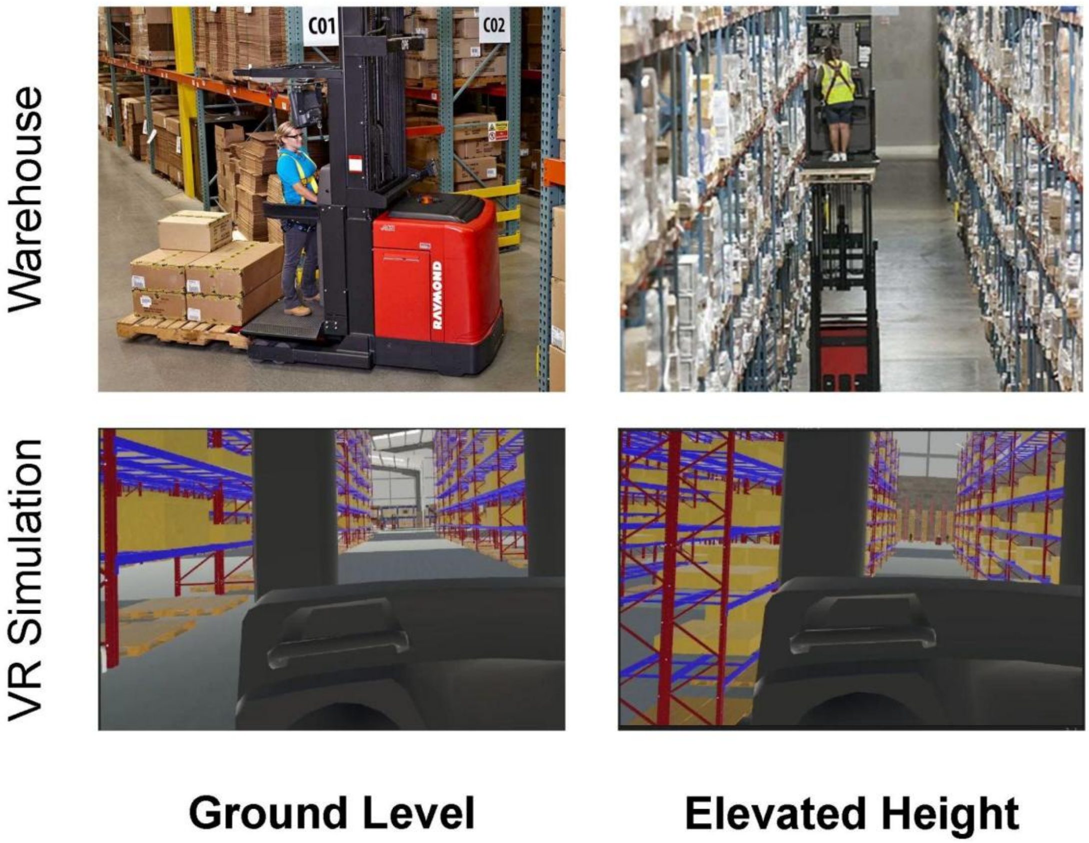


Figure 4.1**:** Different height of forklift truck in real warehouse (Order Pickers, The Raymond Corporation, 2025) and the virtual warehouse simulation used in this study showing the ground level (left) and elevated height (right) condition.

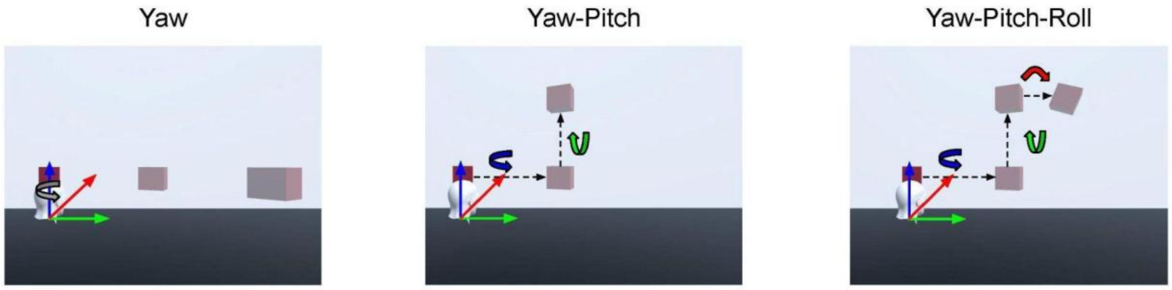


Figure 4.2: Head rotation directions along the yaw, pitch, and roll axes.

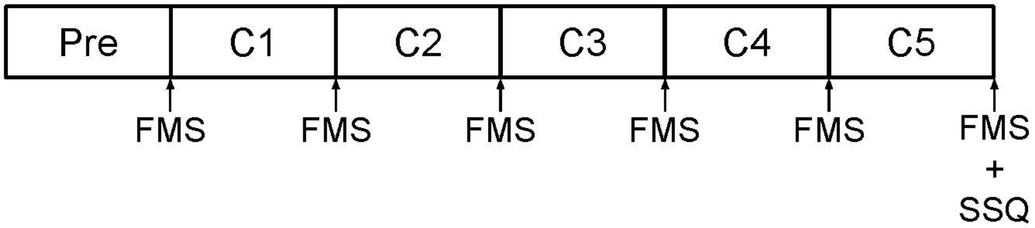


Figure 4.3: Timeline of each trial, indicating five checkpoints (C1-C5) and the timing of FMS and SSQ completion.

4.2.3. Data processing

We used FMS scores to label each trial as either a cybersickness-occurring trial (COT) or a no-cybersickness-occurring trial (nCOT). A trial was labeled as COT if an FMS score greater than 10 was reported in any checkpoint. FMS scores were used for COT/nCOT labeling instead of SSQ scores because FMS scores were collected more frequently, at pre-trial (Pre-FMS) and five checkpoints per trial, providing a more temporally dense and precise measure of when cybersickness occurred during a trial. In contrast, SSQ was administered only once after each trial. The mean FMS score for each trial was calculated by averaging the five checkpoint FMS values within that trial. SSQ responses were converted into four subscales following the same method described in Chapter 3. Additionally, as in Chapter 3, we calculated a success rate (%) based on the number of participants who survived the checkpoints (FMS $\leqq$ 10) in each trial. The four participants who withdrew from the experiment due to severe cybersickness were counted as failures by default in the success rate (%) calculation.

4.2.4. Statistical Analysis

Chi-square tests of independence were used to examine whether the proportion of success rates differed significantly across age group, sex, head rotation, and truck height conditions. Separate mixed-model repeated measures Analysis of Variance (ANOVAs) were used to investigate the effect of *Age*, *Sex, Head rotation, Height, Trial order* (block), and *Prior VR experience* (covariate) on survival time and subjective cybersickness scores (FMS and SSQ subscales). Survival analyses using Kaplan–Meier curves and Cox Proportional Hazards models were performed to examine differences across *Age*, *Sex*, *Head rotation,* and *Height* conditions. Significant main effects were followed by Tukey's HSD post hoc pairwise comparisons. Additionally, Pearson correlations were computed between different subjective responses (FMS at C5 vs. SSQ scores). All statistical analyses were performed using JMP Pro (v18.0.0, SAS, NC, USA). For the ANOVAs, we used the restricted maximum likelihood (REML) method, and statistical significance was concluded when $p < .05$. Effect sizes are reported using partial eta squared (η^2_p).

4.3. Results

4.3.1. Success Rate

The success rate (%) during each trial for different age groups is represented in Figure 4.4. We observed a slight decrease in success rate over the course of checkpoints, with a substantial decline across all age groups during complex head rotations, particularly when the truck was at an elevated height. However, these trends did not reach statistical significance based on the Chi-square analyses.

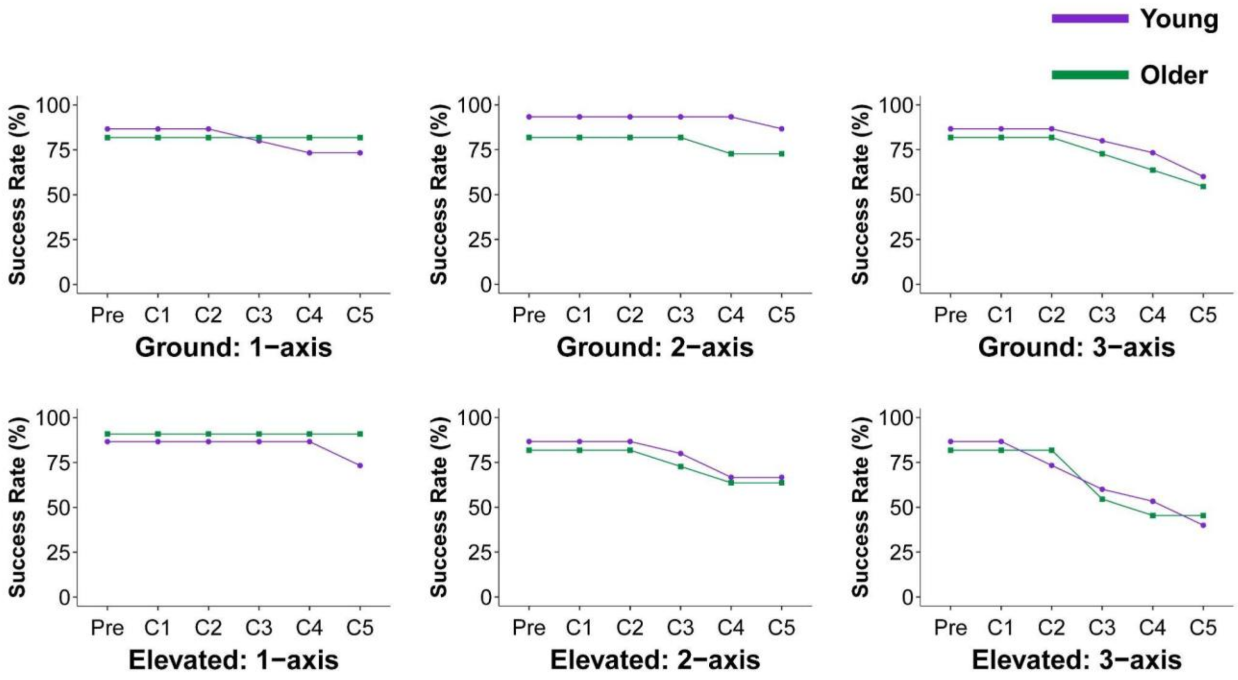


Figure 4.4: Success rate (%) across different age groups prior to the trial (Pre) and at each checkpoint, stratified by head rotation (1-, 2-, and 3-axis) and truck height (ground level, elevated) conditions.

4.3.2. Subjective Assessment of Cybersickness

ANOVA results for the subjective scores (FMS and the four SSQ subscales) showed an interaction effect of *Age* and *Head rotation* for the SSQ Disorientation subscale, and a main effect of *Head rotation* for all subjective scores. We also observed a main effect of *Height* for FMS, SSQ Overall, and Oculomotor subscales. Older adults reported significantly more Disorientation during 3-axis trials compared to 1-axis trials (151.1%). During the 3-axis rotation, participants reported significantly greater FMS compared to 1-axis (121.4%) and 2-axis (47.9%) rotations, with FMS scores for 3-axis trials also greater than for 2-axis trials (49.6%). In the SSQ overall subscale, scores during the 3-axis rotation were greater than in the 1-axis rotation trials (67.1%). Participants reported greater Nausea during 3-axis rotations compared to 1-axis (95.5%) and 2-axis (39.6%) rotations. Similarly, Oculomotor discomfort was greater during 3-axis rotations compared to 1-axis (54.9%) and 2-axis (35.0%) rotations. Participants reported significantly greater FMS (31.3%), SSQ Overall (24.3%) and Disorientation (22.9%) scores in the elevated height condition compared to the ground level condition. The results of this ANOVA are summarized in Table 4.1 and illustrated in Figure 4.5.

Table 4.1: Summary of ANOVA results for the effects of *Age*, *Sex, Head rotation, Height,* and *Trial* on the FMS and SSQ subscales [*F* value (*p*-value, η^2_p)]. Significant effects are in bold font.

Effect	***FMS***	***SSQ***			
		Overall	Nausea	Oculomotor	Disorientation
Age	2.07 (.169, 0.013)	0.05 (.820, 0)	0.02 (.901, 0)	0.32 (.579, 0)	0.03 (.867, 0)
Sex	0.17 (.686, 0)	2.76 (.116, 0.022)	2.60 (.126, 0.020)	3.03 (.101, 0.025)	2.25 (.153, 0.015)
Head rotation (R)	**39.63 (<.001, 0.336)**	**9.49 (<.001, 0.032)**	**11.54 (<.001, 0.045)**	**7.05 (.001, 0.018)**	**6.29 (.003, 0.015)**
Height (H)	**13.66 (<.001, 0.015)**	**4.71 (.037, 0.002)**	2.29 (.134, 0.001)	**6.43 (.013, 0.004)**	3.41 (.068, 0.001)
Age × R	4.94 (.009, 0.009)	2.74 (.069, 0.003)	2.12 (.126, 0.002)	2.09 (.128, 0.002)	**3.19 (.045, 0.004)**
Age × H	0.80 (.372, 0)	0.31 (.580, 0)	1.65 (.202, 0)	0.01 (.908, 0)	0.01 (.889, 0)
H × R	1.11 (.334, 0.001)	0.38 (.688, 0)	0.85 (.429, 0)	0.64 (.530, 0)	0.00 (.999, 0)

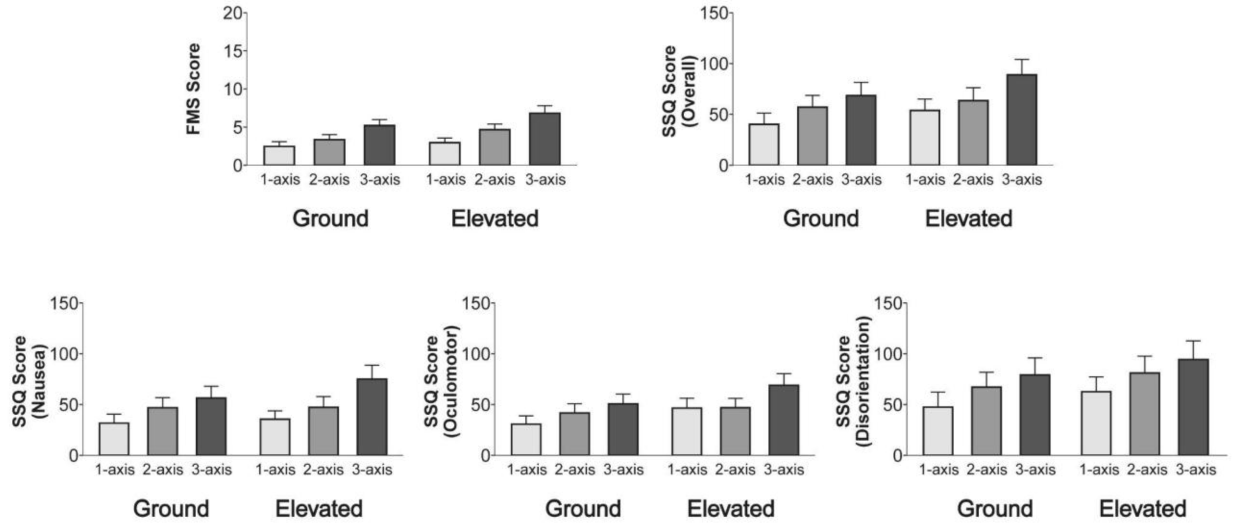


Figure 4.5: FMS, SSQ Overall, Nausea, Oculomotor, and Disorientation subscales across different head rotation and height conditions.

4.3.3. Survival Analysis

Summary results from the Cox proportional hazards model based on FMS scores, including risk ratios (95% CI), are summarized in Table 4.2. Older adults showed a significantly greater risk of experiencing cybersickness compared to younger adults (risk ratio = 1.65). We also observed a significantly higher risk with more complex head rotations (3-axis > 2-axis > 1-axis). Compared to 1-axis rotation, the risk ratio for cybersickness was 5.09 for 3-axis rotation and 2.44 for 2-axis rotation. Similarly, compared to 2-axis rotation, 3-axis rotation showed a risk ratio of 2.08. No significant differences in risk were observed based on sex or height. Figure 4.6 depicts the estimated survival probabilities of different age groups across head rotation conditions.

Table 4.2: Cox proportional hazards model and risk ratios for sex, age, head rotation, and truck height based on FMS scores.

Variable	**Level 1**	**Level 2**	**Risk Ratio (95% CI)**	***p*-value**
Age	*Young*	*Older*	**1.65 (1.02, 2.65)**	**.039**
Sex	*Male*	*Female*	1.16 (0.77, 1.78)	.471
Head rotation	*1*	*2*	**2.44 (1.49, 4.01)**	**<.001**
	1	*3*	**5.09 (2.81, 9.19)**	**<.001**
	2	*3*	**2.08 (1.23, 3.51)**	**.006**
Height	*Ground level*	*Elevated height*	1.23 (0.83, 1.81)	.308

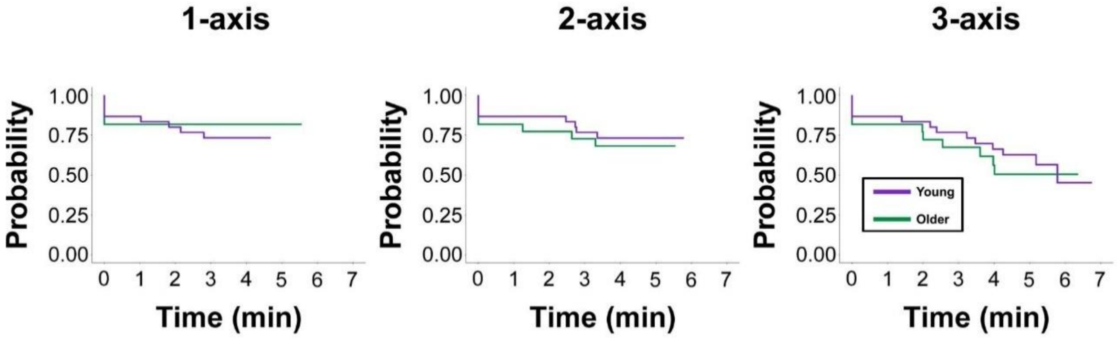


Figure 4.6: Estimated probability of successful VR task completion without experiencing severe cybersickness symptoms based on FMS scores. Kaplan-Meier survival curves for each head rotation axis condition, stratified by age group.

4.3.4. Correlation among Different Subjective Measures

We computed Pearson correlation coefficients to examine the associations among the different subjective measures. The FMS (at C5) and the four SSQ subscales showed moderate positive correlations (Table 4.3).

Table 4.3: Summary of Pearson Correlation results for FMS and SSQ subscales [*r*-value (*F*-value, *p-value*)]. Significant effects are in bold font.

Variable	SSQ Subscales			
	Overall	Nausea	Oculomotor	Disorientation
FMS Score	***r* = .73** **(149.24, <.001)**	***r* = .73** **(148.51, <.001)**	***r* = .67** **(107.04, <.001)**	***r* = .69** **(115.18, <.001)**

4.4. Discussion

4.4.1. Overall Impact of Head Rotations on Cybersickness

The findings of this study confirmed the relationship between head rotation complexity and the occurrence and severity of cybersickness during VR-based forklift training. We observed a significant elevation in subjective cybersickness ratings under conditions involving multi-axis head rotations. In Particular, simultaneous pitch, yaw, and roll head rotations in the 3-axis condition significantly increased subjective discomfort, reflecting the cumulative challenge these movements impose on sensory integration mechanisms. Prior research supports that multi-axis head rotations exacerbate visual-vestibular conflicts, intensifying cybersickness symptoms (Bonato et al., 2009; Palmisano et al., 2017). For example, Palmisano et al. (2019) demonstrated that simultaneous rotations along multiple axes significantly disrupted the vestibular system's ability to interpret spatial orientation, worsening cybersickness severity. Similarly, Keshavarz & Hecht (2011a) emphasized that complex head rotations heighten cognitive demands for sensory reintegration, thereby amplifying discomfort.

In VR-based occupational training, such as forklift training, the requirement for rapid and dynamic head rotations to monitor surroundings may heighten susceptibility to cybersickness (Żukowska et al., 2019). While we hypothesized that complex head rotations would be a major cause of severe cybersickness symptoms during VR-based forklift training as observed in Chapter 3, no prior study had confirmed this within this specific occupational context. Our findings contribute important new evidence by explicitly demonstrating the impact of complex head rotations on cybersickness during practical, occupation-specific VR training. Consequently, this highlights the importance of carefully managing or limiting complex rotational head rotations in VR systems intended for prolonged occupational use, such as in search and rescue (Carrozzino et al., 2023), firefighting (Barbosa et al., 2017), or repair and maintenance tasks (Rodrigues et al., 2022).

4.4.2. Age-Related Differences in Cybersickness Experience

Although older adults demonstrated an elevated risk of cybersickness in the Cox proportional hazard model, no significant difference emerged in their overall subjective scores from the ANOVA across various conditions compared to younger participants. The only notable different between age groups was that older adults reported significantly greater disorientation during 3-axis rotation compared to 1- axis rotation compared to younger adults. Additionally, it is noteworthy that the same number of participants (two from each age group) withdrew from the study due to severe cybersickness, suggesting that there was no substantial difference in the occurrence of early and severe cybersickness symptoms between younger and older adults during initial VR exposure.

The greater risk ratio (1.65) of experiencing cybersickness among older adults aligns with known age-related declines in sensory processing and vestibular function, which may reduce the ability to resolve multisensory conflicts in VR (Inagaki et al., 2024). Munafo et al. (2017) indicated that older adults' susceptibility to cybersickness may stem from decreased multisensory integration efficiency, emphasizing the role of sensory integration deficits in aging populations. Age-related degeneration of vestibular sensory organs and a reduction in vestibular-ocular reflex efficiency might result in earlier or more intense symptoms among older adults compared to younger adults (Allen et al., 2016; Garrido et al., 2022).

In our earlier study (Chapter 3), we observed a risk ratio for older adults that was 4.2 to 7.8 times higher than that for younger adults, a substantially greater risk compared to the current study, which showed a risk ratio of 1.65. One potential explanation for the relatively lower risk ratio in the current study is the difference in the realism of the virtual environments. The commercially available forklift simulator used in chapter 3 was more immersive and visually realistic than the custom-built environment developed by our research group for study 4. Visual realism has been identified as a contributing factor to cybersickness in VR environments. Studies suggest that environments with higher graphical fidelity can intensify sensory mismatches, thereby increasing discomfort. For instance, Pouke et al. (2018) found that greater visual realism, due to more pronounced visual flow and deeper sensory conflicts, can lead to heightened levels of cybersickness. Another potential explanation for the lower risk ratio in this study could be forklift driving experience among the older adults. In chapter 3, all the older adults had prior forklift driving experience, while the older adults in chapter 4 didn’t have prior experience. This experience may have created stronger and more deeply ingrained expectations about the sensory and proprioceptive feedback associated with real-world forklift operation. When those expectations are violated, such as when the virtual environment fails to replicate the vestibular, haptic, or kinesthetic feedback that experienced operators are accustomed to, this could exacerbate the sensory conflict that underlies cybersickness. More specifically, experienced drivers likely rely on a well-developed internal model of forklift operation, which includes expectations of inertia, engine vibration, resistance in the controls, and environmental response. When immersed in a virtual environment that offers high visual realism but lacks corresponding physical and vestibular cues, this discrepancy may create a heightened sense of sensory dissonance (Jung et al., 2021), especially in individuals whose prior real-world experience is extensive. This could lead to more intense cybersickness symptoms in these users than in older adults without experience, who may not yet have firm sensorimotor expectations tied to forklift driving. In addition to this, the simulator used in chapter 3 requires actively driving and navigating the forklift, causing increased cognitive load. Whereas the simulator in chapter 4 doesn’t require active driving input by the participants, giving them a passive role in terms of driving and reduced cognitive load. The increased cognitive load in chapter 3's participants may have led to an increased cybersickness ratio compared to chapter 4's participants (Breves & Stein, 2023).

These findings are essential for the design of inclusive VR systems, as they emphasize the need for demographic-sensitive approaches. Adaptive strategies such as prolonged acclimation phases and simplified head rotation tasks could be employed in the early stages of training to accommodate older users. Given that older adults experienced more severe disorientation during complex head rotation (3-axis), occupational VR training could be redesigned to minimize tasks that require such movements. For example, in forklift driving training, tasks like checking the clearance between the vehicle and the rack by looking at the back and bottom of the truck while at an elevated height involve complex head rotations and could be modified to reduce discomfort. Additionally, gradual exposure protocols and supportive multisensory feedback or guidance systems may help enhance adaptation while minimizing discomfort (Grassini et al., 2021). For occupational training, where older workers represent a growing segment of the workforce (Davies et al., 2017), failing to address these disparities could inadvertently marginalize this population and reduce the efficacy of VR-based training interventions.

4.4.3. Influence of Elevated Height on Cybersickness

Our findings indicated that cybersickness symptoms were more pronounced during elevated height conditions compared to ground level, particularly in FMS, SSQ Overall, and the Oculomotor subscale scores. This supports our hypothesis that elevated heights amplify perceived environmental instability, thus producing more severe cybersickness symptoms. Typically, higher elevations induce greater perceived instability due to clearer visual indicators of height and reduced environmental references (Stefanucci & Proffitt, 2009; Wuehr et al., 2019). At greater heights, users may struggle to anchor themselves visually, resulting in increased cognitive and oculomotor demands to maintain orientation. Since some type of forklift trucks (e.g., order picker) requires users to perform tasks from different height conditions, which may go up to 38 feet from the ground, the findings from this study are crucial for better VR training development. Future VR-based forklift training environments should consider our findings by incorporating carefully designed visual stability cues, particularly at extended height conditions. Strategies such as enriching ground texture detail, adding peripheral visual anchors, or implementing subtle environmental cues (e.g., horizon lines or static reference points) can reduce sensory mismatch and enhance perceived stability (Cao et al., 2018; Nguyen-Vo et al., 2018; Park et al., 2023). Similar to the approach recommended for complex head rotations, elevated height could also be introduced gradually during occupational VR training. Users could first acclimate to tasks at ground level before progressing to tasks at greater heights, allowing for a more comfortable transition. Example tasks include retrieving loads from elevated risks, which involve increased visual and vestibular demands. A progressive training strategy may help users better adapt to height-related sensory challenges and mitigate cybersickness symptoms.

4.4.4. Complementary Use of FMS and SSQ

Our study employed both the Fast Motion Sickness Scale (FMS) and the Simulator Sickness Questionnaire (SSQ) to assess subjective cybersickness experiences. We observed similar patterns in the effects of head rotation and forklift height across both scales. Although both measures yielded consistent results with moderate positive correlations, prior research suggests the FMS may be less sensitive to subtle differences compared to the multidimensional nature of the SSQ (Bimberg et al., 2020). Nevertheless, the ease of use and real-time applicability of FMS make it a valuable tool for continuous cybersickness monitoring without disrupting tasks. Further, we examined associations between FMS and the SSQ measures using Pearson correlation coefficients. The moderate positive correlations observed between the FMS and SSQ scales indicate consistency among subjective self-reported measures, reinforcing their reliability in representing perceived cybersickness. As these scales provide a complementary approach, one offering immediate practical monitoring (FMS) and the other one offering robust retrospective analysis (SSQ), researcher can select either scale based on specific research need and goal for the cybersickness measurement.

4.4.5. Future Work and Limitations

While this study offers critical insights into how head rotation complexity and elevated platform height affect cybersickness in VR-based occupational training, future research should further investigate strategies that can dynamically adjust to users' real-time physiological and behavioral responses. Future research could include physiological signals (e.g., heart rate, skin temperature), postural sway, or subjective reports, forming a closed-loop system for mitigating cybersickness. Expanding this research to include more potentially cybersickness-inducing VR tasks, such as dynamic navigation or vehicle control, may offer further insights into cybersickness dynamics.

This study had several limitations. Our relatively small sample size and controlled VR environment may limit the generalizability of the results to broader occupational contexts. Additionally, the short trial durations may not fully capture the effects of extended VR exposure during occupational trainings. Future studies should include larger, more diverse participant samples, investigate longer training sessions, and explore varying task complexities to enhance ecological validity.

4.5. Conclusions

This study provides compelling evidence that the complexity of head rotations in virtual reality (VR) environments significantly influences the severity and onset of cybersickness symptoms, particularly in immersive forklift training simulations. Through a systematically controlled manipulation of head rotations across one, two, and three axes, and across two forklift platform heights, we demonstrated that three-axis head rotations elicited markedly higher subjective discomfort and posed a significantly greater risk of cybersickness onset. These effects were particularly pronounced among older adults, who exhibited heightened disorientation and increased susceptibility, emphasizing the role of age-related sensory processing differences in VR experiences. Elevated platform height contributed to increased subjective discomfort—particularly in the FMS, oculomotor and overall SSQ subscale scores. The FMS proved effective for detecting real-time fluctuations in symptom severity during task performance, while the SSQ provided a more comprehensive post-experience assessment. The moderate correlations observed between these measures support their complementary use, particularly in training contexts where continuous monitoring without disrupting immersion is critical. Design interventions targeting discomfort at elevated heights should embed stable visual reference cues, such as horizon lines or environmental landmarks, to support spatial orientation and reduce oculomotor fatigue. For older users, personalized calibration procedures and adaptive systems such as gradual exposure to training and complex head rotation or elevated height tasks may enhance safety and comfort, thereby improving accessibility and training effectiveness.

Chapter 5: Theoretical and Practical Contributions

In this dissertation, we investigated the effectiveness of multimodal feedback (visual and haptic) in virtual reality (VR) forklift training, and the impact of demographic factors and dynamic head rotation on cybersickness. The study in Chapter 2 expands the application of multimodal feedback theories in occupational training within virtual reality environments. It provides new insights into the cognitive load implications of multimodal feedback, showing how feedback types influence task efficiency and mental workload. It also demonstrates how expert knowledge and novice mistakes can inform real-time feedback mechanisms in VR training. The study offered evidence-based design recommendations for integrating real-time multimodal feedback in VR-based forklift training. It introduced a systematic method for designing and evaluating multimodal feedback in virtual forklift training.

Chapter 3 investigated the impact of age and sex on cybersickness susceptibility in a VR-based forklift driving simulation. The study highlighted the need for age-inclusive design considerations in VR-based occupational training, particularly for mitigating cybersickness among older workers. It advanced the understanding of individual differences in cybersickness susceptibility, particularly regarding aging and occupational VR training. The study utilized survival analysis (Kaplan-Meier) and Cox Proportional Hazards models to quantify cybersickness susceptibility, offering a novel approach for studying cybersickness. The findings from this study will help to develop age-friendly VR training solutions, reducing occupational barriers for older workers and preventing workplace exclusion.

Chapter 4 systematically examined the impact of dynamic head rotations (single-axis yaw rotations vs. multi-axis combinations involving yaw, pitch, and roll) as well as different height conditions on cybersickness in VR-based forklift training. The findings of this study quantified how sensory conflicts induced by specific types of head rotation (single vs. multi-axis rotations) influence cybersickness severity. Theoretically, this study integrated FMS and SSQ to comprehensively evaluate cybersickness. The comparison of a robust subjective tool (Simulator Sickness Questionnaire) with simpler real-time tool (Fast Motion Sickness Scale), emphasized their complementary roles. Overall, the findings from this study can be used to improve accessibility and usability of VR-based occupational training by reducing cybersickness-related discomfort, potentially increasing adoption and retention among diverse user groups, including older adults.

Chapter 6: General Conclusion

In this dissertation, we have comprehensively investigated the application of virtual reality (VR) technology for enhancing occupational training effectiveness, particularly in the context of forklift driving, while systematically addressing key barriers such as inadequate skill acquisition and cybersickness. As virtual reality continues to evolve as a robust training tool, understanding its capabilities and limitations is vital for effectively integrating this technology into professional settings. The primary objective of this research was twofold: firstly, to optimize learning outcomes by implementing real-time multimodal feedback based on strategies utilized by experienced forklift operators, and secondly, to explore the significant demographic and factors relating to head rotation influencing cybersickness susceptibility among VR users.

Through three studies, this research has achieved the objectives of this dissertation. The initial study focused on developing and evaluating multimodal feedback, specifically visual and haptic feedback mechanisms, derived from a thorough analysis of experienced drivers' practices and novices' errors. Results demonstrated that haptic feedback effectively reduced task completion time and cognitive workload, suggesting that haptic cues can provide intuitive guidance without significantly burdening trainees' cognitive resources. Conversely, visual feedback, whether used independently or combined with haptic cues, was associated with longer task completion times and higher cognitive load. This finding suggests that visual feedback may unintentionally divert users' attention or increase cognitive processing demands, especially in complex tasks requiring precise motor coordination. Interestingly, while visual feedback generally received positive subjective ratings for clarity and intuitiveness, participants frequently expressed that visual cues alone were less effective in situations requiring immediate responses, i.e., collision detection and avoidance. Haptic feedback uniquely addressed this need by offering instant, tangible alerts that effectively heightened awareness, thereby reducing errors related to collision judgment and control. Despite its benefits, haptic feedback occasionally introduced distraction. These mixed experiences underline the importance of carefully calibrating feedback designs to ensure clarity and avoid cognitive overload or distraction, thus informing future multimodal feedback development.

The second study explored demographic factors in cybersickness susceptibility, particularly focusing on the effects of age and biological sex during VR forklift training tasks. We used survival analysis and Cox proportional hazard modeling, identifying that older adults consistently exhibited higher vulnerability to cybersickness than younger individuals, regardless of sex. These results inform a critical consideration for occupational training design—demographic inclusivity. Given the aging workforce, it is essential to create VR training programs adaptable to older users' physiological sensitivities and perceptual processing limitations. Interestingly, the anticipated sex-based differences in cybersickness susceptibility were not observed, suggesting that other factors might moderate or mask sex-related differences in virtual environments. These findings expand current knowledge by providing empirical evidence against a commonly presumed gender-based disparity in cybersickness susceptibility within occupational training contexts.

The third investigation examined the impact of head rotations—rotational motions along pitch, yaw, and roll axes—and forklift heights during VR forklift operations. Controlled experimental conditions demonstrated that three-axis head rotations substantially increased cybersickness risk, corroborating prior research indicating that sensory conflicts stemming from complex vestibular stimuli significantly contribute to motion-induced discomfort in VR environments.

This dissertation addresses a critical safety concern in industrial environments by investigating the potential causes of cybersickness and its impact to diverse populations. A deeper understanding of cybersickness can inform the development of effective mitigation techniques to reduce its impact, thereby facilitating the broader adoption of VR for workforce training. VR-based training has the potential to decrease workplace accidents by minimizing human error during skill acquisition. Findings from the studies presented here also highlight that certain demographic group–particularly older adults–are more susceptible to cybersickness. As workforce training increasingly incorporates advanced technologies like VR, there is a risk that older adults may be excluded due to these challenges. Therefore, this dissertation emphasizes the importance of accessibility and inclusivity in VR design, offering specific recommendations to better accommodate older adults in training applications.

Collectively, the empirical insights generated from these studies yield substantial implications for the design of VR-based occupational training. Furthermore, this dissertation highlights significant opportunities for future research. The relationship between demographic characteristics, head rotation patterns, and susceptibility to cybersickness warrants further exploration across various occupational tasks and virtual environments. From a broader perspective, these contributions significantly advance theoretical understanding and practical methodologies for integrating VR into occupational training. The emphasis on user-centered design principles ensures that VR training platforms can meet diverse user needs, reduce dropout rates due to discomfort, and facilitate effective skill transfer from virtual simulations to real-world performance. Given the growing reliance on advanced technologies for workforce training, these findings are timely and critical.

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Appendices:

Table A.1: Responses of experienced participants from the retrospective think-aloud protocol

Module	Question	Response
Fork Pallet Engagement (M1)	What were you doing before the driving started?	PE3: I'm getting oriented to VR to physical in this aspect. Looking down making sure that I can feel what I'm looking at, which is awesome. Then you tell me which one to hit. So I'm looking over there. And now I'll wiggle fingers Come on, little later. Oh, here we go.
		PE4: So when we walk in, we're clipping down here, instead of clipping a lanyard to the top the lanyards are common for everyone but the belts, you have your own safety equipment and you don't share it. So that's something a little different for us. We're trying to clip in, clip down and we found that and I guess I'm trying to find my controls. And I think I'd probably check my fork height every time right? I wasn't used to not having the height limiter so I've repeatedly checking out anyway
		PE7: I will look behind me and look down and what's behind me and my forks. Also, I use the horn a lot. Safety. Anytime the truck goes in motion, whether forward or backwards. from a standstill, whether you're coming out of an hour or not, you should always want more. Lets anyone in the area know that the truck is in motion or getting ready to be.
	What action did you take during turning and loading the pallet?	PE3: Now, this one. This one one, the one that I tried to deal with 360 on earlier. That was right, that was early. This one was the one where you had the glitch. And it didn't look like the pallet was all the way on the forks. So I'm starting I'm looking ahead eventually move up here here in this area. The picker should be able to do a 360 where I can pull up rotate 90 degrees and being lined up on the power. It didn't do it early. And there's no way to be able to line up. This I thought was good, too. I thought I had a good goal. Until Okay, I'll admit, driving backwards. And steering is not a strong point of mine at all. This should have been a straight shot and been fine. I don't remember if I lowered my forks, which probably caused a problem. Okay. Now, I don't know what's going on here. I didn't raise the forks. But they look like they're going in straight enough that they should have gone all the way in and swung the back into that palette. This is a very dangerous maneuver in real life. Don't do it at home. But it did let me I'm trying. I'm trying. I'm trying. Okay, well. I got penalized. which which is fair, but if it would have gone in Yeah, that wouldn't have happened, I would have never let it go. So when it came back out, what I ended up doing was just picking it up, which was odd because it would have been it would have been back in heavy, it would have not. the boxes are tied down. And it would have applied pressure, pressure to the forks actually pulling the forks down depending on heavy. But that's why I'm gazing back and forth, back and forth, back and forth, because the forks just wouldn't go in, then I just went, Okay, let's just do it.
		PE4: We're just checking to the left make sure with the got some space pretty much looking. Looking ahead and then we're really going to focus on the palate. (Do you remember to lower down your fork?) On the third one, I did the

		very first one, I had a lot of trouble. But this one, I dropped it on the floor. Got a pretty bad angle, actually, but we're getting lined up. We're getting lined out for it. And I'm completely focused on the forks and the pallets here. And the machine was pretty forgiving. Finally, like, Finally, let me hook up there. And I was just struggling to get it perfectly even. Because when we're doing stuff in the building, you know, I want that pallet to be on even. And it's actually I think that's a maneuver that was easier to do and in real equipment than on the on the virtual sim simulator. So we've we've got it, I think we remember to pick it up.
		PE7: Just lining them up for itself with the slots on the pallet to be able to get in there without pushing out around. Because if you hit that power too hard, all those boxes will spill, you know, and then that's extra one. So now so that's where you're at. The part that I was a little concerned about going through this area in real life versus virtual was the weight distribution of the power on the back, you know, if you make a turn to shore, even though the fork truck doesn't have a problem, you know that weight on the back could carry your boxes off to the side. I guess that's one of the differences between the VR and the real life. So you inherited the weight of the boxes, I don't think it has an effect on that physics movement.
		PE10: I didn't pull up at the right angles. Because the pallet didn't enter the forks fully, so there is the length in the back is a little bit extended. So it makes you worried while making these turns that you are going to hitting up the cones or something like that. That type of situation doesn't happen and the forks are not fully inside.
		PE11: Looking at the back to line up the forks with the pallet.
	What were you doing while driving with the pallet?	PE3: So now I think I've got an extra long load on it. So I'm watching everything in the corners and the spins to try not to hit the cones. Because it looks like I've got an extra two feet out the back end. If you watch our plants back, excuse me, oh, plants back going into a turn. Right. And it's just to make sure I'm still pulling it, which is weird. But I'm not swinging. So why did I not moving down. Slow to this turn, just because of the extra leg. And I'm just again, my eyes are going where the turn is compared to where I want to put the machine. So mostly it's going to be straight ahead. They're just bright and paying attention to the corners. Because again, I think I've got another two feet behind me.
		PE4: I feel pretty comfortable that I know where the pallet and its forks are. And I was taught to use the squaring method for your shoulder. And I think that's what I'm doing. I'm squaring the path up on my shoulder. So I can see that out of my peripheral vision. So I don't need to be really looking over there too much. I did check it out a couple of times. But again, I'm comfortable where the pallet is. I didn't realize I looked from side to side. That's that's kind of interesting. I used to drive a bus years ago and I was one of the commercial drivers and they were always honest to be constantly checking your complete path right there. So pretty much focused forward. getting set up, we're gonna have to look back now to bring it in to the

		designated square. Got it pretty good. I'm really looking to my left. I don't think I ever checked my right side. But I felt pretty comfortable.
		PE10: Because the pallet didn't enter the forks folding, so there is the length in the back is a little bit extended. So the way you like worried while making these trends that you are going to eating up the cones or something like that
		PE11: I am looking straight. While turning I am looking to know where I am going.
	What were you doing in the drop zone?	PE3: So if I turn it sharp, cut it, and we'll be tapered off. Although this is the one where it wouldn't let me go off either. So I've lined up everything. I'm looking good. I'm planting down to make sure that I can put it where it tells me to put it since I've got the extra space coming back. And just watching watching. And I should have it right about here. And it will let me lower. Right. This is where you told me to pull it up just a hair. This one on the other hand was just strange. There was a glitch, but you get to see my right hand and wait for it. Oh and this is where you told me that we'll call this complete disregard the great would not let me do anything.
		PE4: The box was in the center because I was in the center of the yellow. And I think we got it on hope no problem.
		PE7: Alright, so now you are on the drop zone. See, I pulled out before I released my palette. So usually you release the palette clumps first, Daniel, I mean, I guess in the real truck, if you don't release the pellet plant, you cannot move the pellet will just come radius again. So that's another difference.
	Do you think it will be helpful if you can see the alignment of the fork	PE3: It might help to take care of the glitch in the VR simulator. The only things in real life that would be in an off here would be the weight of the pallet. So if you've got something that weighs several 100 pounds, it may move because of the engine. Which means the back end of this thing would have slid around, this would have this fork, which is the bottom for running alongside would it just run along the side? So the fork have been? It would have been possible before the forks, but over to the right.
	Do you usually load pallets from an open area like in the VR?	PE3: There could be two or three pallets located together with two facing like the one here and one happened to be facing different odd direction. All up against the wall. So then you got to put a fork in all the one that's facing in either direction out so that you can get both forks.
	Please explain the shouldering/squaring method that you use.	PE4: Okay, when I was, I've worked. I've done a lot of things in the past and I've, I've worked in commercial driving. And when I was first taught to drive the bus, I was taught a technique called squaring. And that's when your square and that's when your turn is lined up with your shoulder then you can make a same turn and I know that I've followed this technique for running the lifts and when I train people to operate the left so I talked about squaring and I know that I tend to look ahead more because I'm focused on what's in front of me because I feel comfortable that my turn will come out.
	What are your thoughts on the height limiter for the forks and the	PE7: Due to sprinklers and things like that in the legs, those will have a height limiter, and then your lower limiter, your saw, it's almost like a two stage you'll lower down. And it gives you a comfortable riding height. But if you're going to pick a pallet, you would hit so we're picking up the pellet,

	platform?	you would still need to go beyond the learning correct.
Load Pickup (M2)	What were you doing before the driving started?	PE3: I'm getting oriented with the physical and the virtual. That way I know when I reached out where I left the knob on the wheel, and where everything is, then you're telling me to push about parents. Okay, so, start the lesson, self explanatory. How many times? I hate it once. Uh huh. No, I'm just, again, making sure I got what I got. Right? orienting the physical to the virtual, I'm not even moving it.
		PE4: I guess I was looking for the controls again. No Why delay, watch there. I'm checking my palette type. Again, that's just the force of habit. And I wasn't used to not having the limiter. But we have to go through this override switch to get ours to sit down on the bottom.
	Please describe your strategy to enter the aisle.	PE3: I'm looking over there because I know that I'm gonna make the move and go over there. So Okay. Moving, moving, moving. This thing I really wished that it would do with 360.
		PE4: After trying this three times, I realized I didn't have to get quite as close to the yellow lines. The first two times I was getting right up on him. And you know, when I looked down, he couldn't even see him because I was riding on. So I felt more comfortable.
	What were you doing while picking up the boxes?	PE3: I'm now looking where? Where it is. I've got to drive to be able to get close enough without hitting shows. To pick the box. My clients down. No, touch it. Touch it left handed. It's invisible. Right. So nothing right. And yeah, finger wave. Come on. I always tried to left first if it's on the left. And if it's on the right, I'll always go to the right. Okay, so now I'm not sure what it is. I got stuck for a few seconds and that's true. I forgot that have now almost broke the system. So we're going to back out and just kind of go a little closer. It could have been that I was so far out that it just didn't want to have fun. Tried to close the gap between me and the show. So this is where I know I lifted the physical arm and leaned out with my right hand and now we're just getting oriented before we take off reading what we need to do and now we got another I've got the curls go over. Eventually, I'll start looking to my right on this aspect and down because I want to make sure the gap is not there. And I know where the boxes now I'm just looking at big Bootstrap. There we go. Checking the yellow stripe down, and we're gonna raise up now, this is one nope, yep, gotta go a little bit higher and got it now one of the things I did earlier was travel with this in the air. I was told I was not allowed to do that. So now I'm following following the route it's laid out. Following around making sure not there we go. How close do we have to get? Let's find out. So on one hand at this point in time, left, left or right but one finger. So following it following it watching it watching it side watching I don't want to knock down shelves shelves are expensive. They get unhappy if you do that. So we pull up with this box well, it should be a one handed, right hand touch and failed will try to be tall enough not magic but now again I'm looking, looking around, looking around what's going on? Make sure that I lift the pallet off the floor and we're going to try to go over and then I know what's going to happen. I've got to pull further up and back it in because it's not close enough and for some reason they won't let me get off the ground level to get it which I think is fine I'm on ground level freedoms happen often but that's fine. No, go forward. You turned it wrong

		now yeah, that's what you need. Not too much. It's got to go back Come on. Don't be afraid to say I'm watching that you have a line watching aborting and one oh so close. Okay one more time Come on. And that's probably where I was lifting up the physical arm that it didn't show and the magic again. Ticked all the boxes now we gotta go park we got to make sure that we don't hit the back end are the same.
		PE4: That was actually a lousy turn and I went way over, but I'm mostly looking up front, looking for my box, but we're trying to stay right outside of the ride outside of the Gallo. Here, I always drive with those handlebars or the safety. I don't remember the proper word that safety arms. So I'm always to reach over I was lifting the safety arms and putting them down. I think I backed up a little here or on one of these because my since my swivel wheel is in the front, I can back up to get out of those tight spots, you know the one time I pulled forward and hit the shelf and started backing up because I can make a tighter turn instead of that big pallet swinging out when to the end. That's a technique I would I always use out of the building to bring it back in the eye on just focused on the blue arrow words telling me to telling me to go up and nothing something like box probably got a little high on now. I wish they dropped in container. That would be awesome. Some of ours are so darn heavy, and again gotten used to the machine dropping all the way to the bottom and I'm correcting for that ours would never do that you'd have to hit a bunch more buttons to get the pallet to set. And that's where I'm truly instead of turning to go forward, I'm backing up. And I'm using my front wheel to swivel away and I've created some more rooms I'm nowhere close to getting bagging onto the uprights again. Just focused on forward looking for looking for my next pickup location. Here I was looking at the tag it's not in the simulator but the unit that picture of boxes and as you said I'm dropping down if we were doing this in the building real time we're locked on the wire and I'm moving forward before I'm dropping so these were kind of new skills for me to bring it bring it down. So we're going to go pick up our next box and keep looking down to line up with the line. As you can see I'm not as close as I got on the first two I don't know I don't need quite as much rarely kind of pick up pick up a box now when I dropped down on this one I think this is one where I really backup because the next pickup location is so close. I'm just going to first I'm going to check my mind for crying I've given it a little and I'm pretty sure I really back up a lot on this one yeah I'm moving back I'm going to use my swivel wheels to be able to make a sharp turn and get that pallet away from uprights and now we're swinging forward got plenty of room and we're going to pick up that last box off the floor and I don't think I even got very close at all on this one I was getting more comfortable with how much room maybe simulator I'm not sure what the delay what I was doing here with the inlay approach the box.
		PE11: Making sure I go all the way down, then not touching the floor before I start to drive again. Looking up for it so I can make sure I'm slightly above it. And then I'm backing out here just because I know that the other location is a little bit closer to automatically line up with. Did not want to turn too much and hit the rack, so I backed up a little bit.
	What were you doing during changing	PE3: I'm looking down but we need to make sure that remember when I looked that up, I must have did it. Honk Honk Honk up stop and home you

	aisles?	never know what's coming. I'm surprised I didn't glance back to make sure I lifted both ways. Like crossing the street. Did I invert the palette? I don't I wouldn't change the y turn following the path on the path it's all fun and games to your Poklonnaya now there we go. Here's the path now I'm gonna figure out how close I need to get.
		PE4: I'm checking my left and right I am going to look back to my right here big time and make sure I'm not going to swing that pallet out and and hit the upright because when you do it rarely turn around. We've got some safety guards in front of our end units to help protect against that. Probably squaring up my turn number one where I kept I guess same thing I'm looking to make sure I'm not going to swing out into I didn't I was so focused on the other I made a horrible turn and had to correct I had to weigh oversteer on I would have just driven right into the shelves right there.
		PE11: In my head I'm just kind of imagining I think where are the forks when I'm not looking to kind of know where they are.
	What were you doing when you were near the drop zone?	PE3: Again start off just want to get busted that is it. This will always want to account wandering the other one. So I didn't stop by stop. Anyway, look both ways before you cross the street. There we go. There's one. There's two now. Now we're looking up in the parking lot. Trying to get it one phone call on the phone with one. Now we're looking to make sure that we had it. And we did.
		PE4: I'm probably gonna do the same thing back up a little but this one was not near as sharp you know I got a little close there but not I didn't back up on that one again. I guess it was getting more comfortable with our simulator. simulator work oh ya checking normal end of aisle routine be checking my last right.
	What are your thoughts on leaning over to the side to align the truck with the yellow lines?	PE7: That's what I had learned by looking out to the side if you're driving a Fork truck and you're in a row even some of them where the width of the aisle is only big enough for the Fork truck. Maybe this much room is two inches on each side. If you make sure you get one side in correctly the other side takes care of itself so you don't need to go with this just watch that side and go.
	What are your strategies for driving with a pallet?	PE7: Once you're handling a specific material specific size of something, you get the muscle memory, you know how far the forks are behind you, you know how the loads are going to react to you making a turn this fast or making them turn this slow. So that has a big part to do until you are comfortable with the material that you're moving and handling. I feel like you should always take extra precautions in the beginning, making sure how the loads are reacting behind you. If you take off too fast or slow down and how I wasn't going to be affected, then as you go through and you're handling that same product or palette or whatever, you just become faster. You get confident if you think you know you've got to be under control. And that's what happens. You know, I go in, raise, lift up something and then go return and I would have to build trust or something small you know that way.
	What are your strategies for aligning the truck with the	PE11: I am usually looking at the yellow line to match up the truck. Because of the experience, I have an intuitive sense of where it is. So sometimes, I might look to check if it seems like it might be a little bit too close, like I

	yellow lines in front of the racks?	went too far. So I don't hit the rack. So I'll usually slow down if I got a little bit too close.

A.2: Feedback preference questionnaire

Please select the feedback condition (No feedback, Visual only, Haptic only, Combined Visual and Haptic) that matches the best with the below description:

Q1. Which of the four feedback conditions was the most effective?
Q2. Which of the four feedback conditions was the most distracting?
Q3. Which of the four feedback conditions was the most time-efficient?
Q4. Which of the four feedback conditions informed you the most about the impending collision?
Q5. Which of the four feedback conditions was the most comfortable to you?
Q6. With which feedback condition you were the most confident in performing the task or the objective?
Q7. Which of the four feedback conditions you would like to have as a permanent feature (Consider it for an actual forklift truck)?
Q8. Which of the four feedback conditions would you be willing to use in a real forklift truck with an augmented reality environment?

A.3: Semi-structured interview questions

Questions after each feedback condition and each module:

1. What do you think about the utility of these visual features that you experienced?
2. How do these features help with the task you were supposed to execute?
3. How do these features hinder the task you were supposed to execute?
4. What changes do you recommend to improve this design?

Table A.2: Descriptive statistics for the objective measures of completion time (sec), Task, and Penalty scores.

Module	Feedback Type	Completion Time Mean (SD)	Penalty Score Mean (SD)
M1	NF	159.8 (45.2)	14.7 (34.8)
	V	176.7 (71.6)	2 (4.1)
	H	140.9 (41.8)	0.7 (2.6)
	VH	177.4 (55.8)	2 (5.6)
M2	NF	241.6 (38.6)	28.9 (51.8)
	V	291.4 (80.8)	23 (36.7)
	H	278.7 (72.2)	38.6 (60.7)
	VH	293.9 (96.7)	40.3 (69.3)

Table A.3: Summary of NASA-TLX (Mental Workload and Frustration), and overall SUS score.

Module	Feedback Modality	NASA-TLX Mean (SD)						SUS Score: Mean (SD)
		Mental Demand	Physical Demand	Temporal Demand	Performance	Effort	Frustration	
M1	NF	30.6 (16.6)	13.3 (7.5)	19.4 (15.1)	28.6 (30.1)	24.9 (13.4)	20.1 (17.8)	74.3 (20.1)
	V	29.4 (20.0)	15.8 (14.6)	13.4 (7.3)	30.8 (32.2)	31.4 (21.4)	21.7 (24.8)	74.8 (13.6)
	H	20.5 (14.7)	13.7 (14.5)	15.2 (13.4)	32.8 (37.0)	24.9 (18.1)	14.1 (18.6)	76.2 (12.8)
	VH	28.1 (18.8)	14.4 (15.8)	19.9 (16.8)	28.0 (28.8)	28.5 (21.1)	22.6 (23.9)	71.8 (14.5)
M2	NF	27.7 (24.1)	16.5 (24.3)	16.4 (21.0)	23.2 (28.5)	26.8 (25.2)	15 (26.3)	73.2 (22.9)
	V	27.7 (12.2)	12.7 (10.2)	12.1 (8.7)	24.1 (25.5)	30.9 (20.4)	15.7 (11.6)	74.8 (14.7)
	H	28.2 (12.2)	14.0 (13.0)	16.3 (10.2)	26.0 (31.0)	27.8 (16.4)	16.1 (10.9)	77.8 (10.7)
	VH	27.9 (14.1)	14.2 (12.2)	15.9 (12.1)	25.8 (30.8)	30.0 (17.8)	17.7 (15.7)	72.2 (15.9)

Table A.4: Summary of Dwell time on Area of Interest (AOIs), and Gaze Entropy.

Module	Feedback Modality	Dwell Time on AOIs							Gaze Entropy
		Visual Overlay	Pillar/Rack	Wall	Floor	Main Console	Pallet	Traffic Cone	
M1	NF	N/A	0.05 (0.1)	2.1 (1.8)	10.1 (8.8)	6.4 (4.3)	5.1 (4.9)	0.1 (0.1)	8.4 (0.2)
	V	0.04 (0.1)	0.01 (0.01)	4.8 (13.4)	10.2 (11.0)	3.9 (2.7)	4.8 (3.9)	0.1 (0.1)	8.2 (0.6)
	H	N/A	0.1 (0.1)	0.7 (0.7)	7.2 (4.3)	4.3 (2.6)	5.4 (5.5)	0.1 (0.1)	8.2 (0.4)
	VH	0.04 (0.1)	0.6 (1.0)	7.0 (14.3)	7.4 (3.9)	4.1 (3.0)	6.3 (6.2)	0.1 (0.1)	8.3 (0.5)
M2	NF	N/A	0.02 (0.02)	3.5 (1.6)	3.6 (1.3)	7.8 (2.4)	6.3 (3.0)	N/A	8.5 (0.3)
	V	3.9 (0.9)	0.02 (0.02)	3.0 (1.7)	3.3 (1.1)	7.5 (2.4)	4.7 (2.0)	N/A	8.3 (0.4)
	H	N/A	2.4 (0.6)	0.3 (0.2)	3.4 (1.5)	7.7 (1.7)	6.3 (3.3)	N/A	8.4 (0.4)
	VH	3.8 (1.3)	2.5 (1.1)	0.6 (1.4)	3.4 (1.5)	7.4 (2.7)	5.6 (2.9)	N/A	8.4 (0.5)

Table A.5: Pairwise comparison of feedback condition on subjective and objective measure

Variable	Module	Effect	Pair 1	Pair 2	95% CI	*p-value*	% decrease
Completion Time	M1	*Feedback Condition*	VH	H	[11.1, 115.5]	.012	20.6%
Mental Demand	M1	*Feedback Condition*	V	H	[5.2, 26.4]	.002	30.3%
			NF	H	[2.7, 23.9]	.009	33.0%
			VH	H	[0, 21.2]	.049	27.0%
Frustration	M1	*Feedback Condition*	V	H	[4.3, 28.9]	.004	34.9%
			VH	H	[2.3, 26.9]	.015	37.8%
Dwell time: Pillar	M2	*Feedback Condition*	H	NF	[1.7, 3.4]	<.001	99.2%
			H	V	[1.7, 3.4]	<.001	99.1%
			VH	NF	[1.3, 3.0]	<.001	99.0%
			VH	V	[1.3, 3.0]	<.001	99.1%
Dwell time: Wall	M2	*Feedback Condition*	NF	H	[1.1, 4.8]	<.001	91.4%
			V	H	[0.9, 4.6]	.002	90.9%
			NF	VH	[0.1, 3.7]	.040	82.0%
Dwell time: Pallet	M2	*Feedback Condition*	NF	V	[0.2, 4.1]	.026	25.3%
			H	V	[0.2, 4.0]	.028	24.1%