A User Experience Study of Locomotion Design in Virtual Reality Between Adult and Minor Users

Zhijiong Huang* Yu Zhang† Kathryn C. Quigley‡ Ramya Sankar§ Allen Y. Yang¶

University of California, Berkeley

Abstract

Virtual reality (VR) is an important new technology that is fundamentally changing the way people experience entertainment and education content. Due to the fact that most currently available VR products are one-size-fits-all, the user experience of the content interface and user interaction for children is not well understood compared to that for adults. In this study, we seek to explore user experience of locomotion in VR between healthy adults and healthy minors along both objective and subjective dimensions. We design the experiment where subjects complete a task of moving the body and touching underwater animals using VR controllers. The locomotion in VR is implemented using one of four different modalities, as well as using real-world walking without wearing the VR headset as the baseline. Our results show that physical body movement that mirrors real-world movement exclusively is the least preferred by both adults and minors. However, within the different modalities of controller assisted locomotion, there are variations between adults and minors for preference and challenge levels.

Index Terms: Human-centered computing—Visualization—Visualization techniques—Treemaps; Human-centered computing—Visualization—Visualization design and evaluation methods

1 Introduction

Recent advancements in Virtual Reality (VR) have demonstrated great potentials of changing both business practices and people's daily lives. However, currently almost all the VR hardware products (such as Google Daydream, Oculus Rift, and HTC Vive) are designed around the archetype of a typical adult user. Furthermore, for minor users, the physical requirements of full body movements combined with typical short duration of attention in VR also exacerbate the challenges for minors to have equal or similar user experience as adults. In fact, several commercial VR systems specifically advise against usage by minors younger than 13 years old. When the software design does not feel the need to consider the physical and cognitive variations from the younger population, their user experience may suffer. Specifically, this creates a barrier for adopting VR technology for minors in the education and gaming sectors. To this end, we believe the fundamental principles of how user experience from minors differs from adults are still less understood.

In this paper, we propose to study an important category of user interaction modalities when they are being experienced by both adults and minors in VR, namely, the body locomotion. This problem is critical in pursuit of the fundamental principles of VR user experience for minors because VR interactions in immersive 3D space typically require users to provide 6 degree-of-freedom (DOF) input of their head motions and hand motions, and to perceive the 3D environment from their egocentric perspective. All of these inputs would be limited by minors' upper limb motions and lower limb motions together with their comfortable levels, all of which need to be understood through carefully designed user experience experiments.

To achieve this goal, we first summarize five main modalities of locomotion in VR with wearable VR head-mounted display (HMD) and hand-held controller(s):

1. Mapping human lower body movement to the movement of the egocentric perspective in VR, typically involving the walking motion.
2. Mapping human upper body movement to the movement of the egocentric perspective in VR, typically involving the flying and swimming motion.
3. Using buttons on the controller to provide direction and velocity commands, which resembles driving a vehicle in racing games.
4. Teleportation, which refers to transporting the user's egocentric perspective instantaneously to a 3D location selected by the controller.
5. Any combination of the above modalities.

Our target subject population includes adults (age older than 17 years) and minors (age older than or equal to 7 and younger than or equal to 17 years) who do not have known physical and cognitive impairments. In this setting, we want to understand whether the different physical and cognitive capabilities between healthy adults and minors would lead to different user experience when the goal is to move their virtual egocentric perspective to complete certain per-programmed tasks in VR environment.

To address these issues, we set up an experiment in VR to investigate the validity of the following two hypotheses:

1. In VR, using controller assisted movement modalities can improve the user experience compared to that using only physical body movements.
2. There exist variations in the challenge level and preference using these locomotion modalities between adults and minors.

In order to test our hypotheses, we choose to design a simulated VR experience in an underwater environment. In an underwater environment, the human avatar has true 6 DOF in body movement, and the real-world motion would involve both the upper body and the lower body. Therefore, it is more challenging and complex to control underwater body movement than moving on the ground in a stand-up posture.[1] We believe this experimental setup enables

*e-mail: zhijiong@berkeley.edu, equal contribution
†e-mail: yu_zhang@berkeley.edu, equal contribution
‡e-mail: kquigley@berkeley.edu
§e-mail: rsankar@berkeley.edu
¶e-mail: yang@eecs.berkeley.edu

[1] In fact, one of the very first modern VR experience is the Blue Whale Encounter published on Vive Steam platform. Nevertheless, the users there can only walk around a virtual ship deck with no simulation of swimming motions under the water. Therefore, its user experience is limited compared to the scenarios we investigate in this paper.

us to thoroughly investigate the user experience of the locomotion modalities, and will shed light on the fundamental principles of designing good user experience for both adults and minors.

2 RELATED WORK

Previous academic works relevant to this study are divided into two categories. The first category is the research illustrating principles, benefits, and drawbacks of different locomotion techniques. The second is to understand challenge and preference variations between different age groups' for locomotion systems in VR.

According to [2], which provides a comprehensive overview of VR locomotion techniques, the locomotion techniques are classified into steering travel, selection-based travel, manipulation-based travel, and walking locomotion. For example, steering techniques include gaze-directed steering with which the user is moving in their gaze direction or optionally in lateral directions [5]. Selection-based travel requires the user to perform a selection task, e.g., by pointing to a destination in the virtual world, which will teleport the user's viewpoint to the target location [1, 3, 13]. Manipulation-based locomotion is motivated by user's body motion [2]. For example, drawing a circle in the air makes the user move forward. Walking locomotion could be taken as a natural travel technique when the VR settings are based on the ground, which is implemented by mapping users' motion information in the virtual world with that in the real world [11].

Additionally, some previous works compare user outcomes for VR locomotion techniques. The joystick technique, which is an instance of steering travel, has been reported to lead to a significant increase in motion sickness compared to the other locomotion techniques [9]. Teleportation, which is an example in the selection-based travel category, requires some time for users to understand their new surroundings after teleporting. This potentially leads to disorientation and can break immersed feeling for users [6, 10, 12]. Finally, natural locomotion techniques like walking have been reported to be slightly more advantageous than semi- or non-natural techniques when it comes to a sense of presence or user preference [3, 12].

Another group of research focuses on comparing how different age groups walk in VR compared to walking in the real world. In one research study conducted by Omar et.al. [7, 8], the spatiotemporal parameters for young adults (age 18-34 years) and older adults (age 45-83 years) in both reality and VR are measured. The results indicate that older adults have similar walking biomechanics in both conditions. On the other hand, for young adults the gait speed is slower and steps are shorter in VR compared to the real world [7]. This result is also supported by [8], which had 19 participants with ages between 18-38.

With respect to the research in this paper, the natural locomotion implementation is defined as swimming motion instead of walking, because it is more natural for users to swim rather than walk in an underwater world. A group in the NHTV University of Applied Sciences Breda conducted research related to the swimming locomotion. They created a diving game, in which players swim with a virtual Diver Propulsion Vehicle. The paper demonstrated that minors have more consistency between the real world and VR than the adults [4], which could imply that people of different ages may have their own preference for swimming locomotion.

3 METHODOLOGY

In order to study the accessibility of different locomotion methodologies for healthy adults and minors with respect to the two hypotheses in Section 1, we have chosen to implement four modalities in a simulated underwater VR environment developed through Unity, and designed an experiment to investigate the performance and preference for these modalities. The VR device used in this experiment is HTC Vive.

3.1 Four Locomotion Modalities

The four locomotion modalities and one baseline modality are described in Table 1, one type Swimming is considered a natural locomotion based on physical movements, while the other three are controller assisted locomotion. The first technique *Swimming* mirrors body movement when swimming in real life. On the user side, the player has to do a swimming motion and needs to pull the triggers at the beginning and release them after each stroke. On the programming side, the game calculates the difference in position of the controller between each script iteration (one per frame) and moves the player directly accordingly. The faster the user moves the controllers the faster they moves in the VR, mirroring the natural swimming process. Steering is controlled by the starting and ending point of the controllers for each stroke.

Second, we use controllers to allow subjects to teleport. A user can hold the trigger, which creates an arc, at the end of which is a sphere. The user can change the direction and position of the sphere by moving the controller and touching a forward or backward panel. When the trigger is released, the avatar moves to where the sphere was. In this study, we classify this as a controller assisted locomotion technique.

Third, we define another controller assisted modality called *Look & Follow*. The modality is implemented by defining the direction of the user movement through the orientation of the user's head pose, which is typically tracked in real time by sensors in the HMD. The avatar will start to move when a user pulls a trigger on the controller.

Finally, we create an *Assisted Swimming* modality as a combination of *Swimming* and *Look & Follow*, where subjects would move the controller as in a swimming method, but pull the trigger to move with the same steering motion as the *Look & Follow* modality. We will not tell the users that moving the arms in swimming motion actually had no effect to the actual movement in VR. Instead, the actual movement is determined exactly as the *Look & Follow* modality. The purpose of adding a "fake" swimming motion is to enhance the immersiveness of the locomotion for the underwater environment. We also classify this as a controller assisted locomotion technique.

In order to compare the challenge level and preference of the four locomotion modalities, we have also created a baseline where the subjects are asked to walk naturally to complete similar tasks in a room without wearing VR devices. In our study the baseline serves as a point of comparison to see how challenge level and preference compare to the neutral, everyday experience of walking.

Table 1: Four Locomotion Modalities in VR and a Baseline

Modalities	Descriptions
Swimming	The subjects hold two controllers and mimic the motion of swimming in the real world.
Look & Follow	Subjects will move in the direction they are facing when pulling the trigger on controller.
Teleportation	Subjects will see a target ball when pulling the trigger. They will teleport to the position of the targeted ball instantaneously after releasing the trigger.
Assisted Swimming	Subjects follow a natural swimming motion with controllers, but use the trigger to move with the *Look & Follow* locomotion technique. This mode is a combination of the first two modalities.
Baseline	Subjects walk around a room naturally to complete a simple task without wearing VR devices.

3.2 Tasks

In order to compare the challenge level and preference of the four modalities, we set up a simple task. The requirement for the task is that subjects need to move towards three different groups of fish and touch them in the VR space as three sub-tasks. At the beginning, the subject will always be placed in the same location relative to the three groups of marine animals, i.e., the origin of the world coordinate system. The average distance between the subject to each group of the animal is five meters. As the subject approaches any one group of the animals, if they can use one of the controllers to touch one of the animals within their arm's reach, the sub-task is deemed complete. Subsequently the subject can proceed to move towards the rest animal groups if those sub-tasks have not been completed.

To experience each locomotion modality, a subject would need to finish the above task (that contains three separate sub-tasks) for one of the locomotion types. In our experiment, on average, it would take about 15 minutes for an adult or a minor to complete one task in VR, except in baseline where the duration is quite fast since it is natural to walk in the real world.

This situation presents a problem when we enroll subjects who are minors, some of whom were as young as 7 years old. We have found that very few minors can complete more than one task in VR without feeling tired or distracted. Therefore very early on we can conclude that each subject, especially as a minor, can only be interviewed to experience one locomotion in VR.

Under this limitation, we still need to frame a fair comparison to compare the performance and preference of the all four locomotion types. To achieve that, we rely on the use of the baseline as described in Table 1. In particular, in each of the interview session, a subject regardless being an adult or a minor will be asked to complete one session of the baseline and one session of the one of the VR locomotion types. Then, quantitative and qualitative metrics that aim to measure the user experience will be collected, which we will describe next.

3.3 Metrics

We collected objective data for objective performance analysis, and collected subjective data for both challenge level and preference analysis. The objective metric for challenge level analysis was done by recording the completion time for each subjects experimental task in one of the four VR locomotion modalities.

Table 2: Questionnaire

Questions	Ranking
Q1. How would you rate the challenge level moving in real life on a scale of 0-10 (10 means most difficult)?	0-10
Q2. How would you rate the challenge level moving in virtual reality on a scale of 0-10 (10 means most difficult)?	0-10
Q3. Comparing real movement with the virtual movement, which one do you find easier?	Real or Virtual
Q4. How would you rate your preference level moving in real life on a scale of 0-10 (10 means most preferred)?	0-10
Q5. How would you rate your preference level moving in virtual reality on a scale of 0-10 (10 means most preferred)?	0-10
Q6. Comparing real movement with virtual movement, which one did you prefer?	Real or Virtual

For the collection of subjective data for both challenge level and preference analysis, we conducted short interviews with subjects, which is shown in Table 2. For subjective challenge level evaluation we asked subjects to rate the difficulty level of the real-world baseline and locomotion modalities for a range between 0 and 10, see Q1 and Q2 in Table 2. For the preference side, we asked subjects to rate their preference for both the baseline and one of the locomotion modalities for a range between 0 and 10, see Q4 and Q5 in Table 2. Finally, in the interview with subjects Q3 and Q6 in Table 2 were set up as sanity checks for the subjects to make sure that they were answering consistently. For instance, we compared answers of Q3 to those of Q1 and Q2 and would discard this record if the answers showed conflict.

Once we collected the data, our first step was to calculate a baseline for each dimension. Since the baseline was designed as a real-world experience, as shown in the Table 1, we calculated mean values of all 40 children subjects' assessment for the real-world experience for each dimension. In next step we obtained two mean values for each locomotion modality among the 10 subjects who tried and gave evaluation to this that specific modality. The final step was the most important procedure, in which we compare the differences between the mean value of the locomotion modality and that of the baseline. The differences were regarded as relatively unbiased evaluation for each locomotion modality and the same process was applied on the data obtained from the adult group.

3.4 Experiment Process Summary

The flowchart in Figure 1 illustrates the experiment process. Before the experiment, subjects were asked to read and sign consent forms and a screening form. In the first step of the experiment, subjects were asked to complete a real-world task of walking in the room. Next, the subjects begin the VR portion of the experiment.

In the experiment, each subject only tries one locomotion modality. First they do a short tutorial, which teaches the subject how to navigate in VR with the specific locomotion modality they are assigned with. The tutorial lasts until the subjects reach the target position in the tutorial or reach 80 seconds, whichever is shorter.

Once subjects are trained on how to move, they begin their the task mentioned above in VR with their assigned locomotion modality. The time limitation for the task is 300 seconds. We assigned the order for testing the four locomotion methods in advance to guarantee each modality would have metrics data from 10 adults and 10 minors. After the subjects completed both the real-world and VR tasks, they were invited to complete a short interview to assess their experience of the baseline and locomotion modalities in VR.

3.5 Selection of Participants

A total of 100 subjects were recruited randomly from people on campus and visitors to museum, comprising of 43 adults aged between $19-65$ and 57 minors aged between $7-17$. Each subject spent around 15 minutes in the experiment and interview. The minors and adults were tested separately but following the exact same protocol. The Institutional Review Board (IRB) approval was obtained ahead of this experiment.

At the end of the experiment, 40 sets of adult data and 40 sets of minor data were considered valid. We rejected three sets of adult data and 17 sets of minor data. There are two criteria that lead to the rejection of subject data. First, four minors who reported discomfort in VR and declined to complete the experiment. Second, 16 sets of data were rejected due to subjects' inconsistent answers to the questions on the questionnaire (Table 2). Q3 and Q6 were designed to be sanity checks and if subjects were inconsistent in an answer to Q3 or Q6, their data set was rejected. For instance, when asked about which experience they preferred (Q6 on the questionnaire) and to rate their preference (Q4 and Q5 on the questionnaire), some participants said they preferred the virtual experience to the baseline but gave a lower rate to the virtual experience.

3.6 Limitations

We imposed a time limit of 300 seconds for the virtual reality section because we found minors can only do the whole experiment for 15

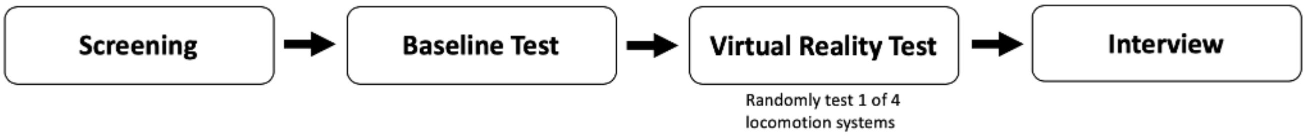

Figure 1: Flowchart for the Experiment Process

minutes or less due to attention span and limitations of our IRB. Additionally, having minors spend too long in the virtual environment could make them feel uncomfortable. This time limit may potentially influence the results of average completion time.

4 Results

In the study we used box plot to show the result of challenge and preference level for each type of locomotion. In addition we also analyzed the average completion time for each type of locomotion for adults and minors.

Figure 2 is the box plot, which contains the average completion time, standard deviation (std) and data distribution among both adult and minor subjects with respect to each locomotion modality. It shows that minors completed the task quickest with *Assisted Swimming* modality ($avg. = 117.84s$) and slowest with the *Swimming* modality ($avg. = 286.60s$), while adults spent longest time completing the task with *Swimming* modality ($avg. = 276.00s$), and adults completed tasks most quickly with *Look & Follow* ($avg. = 80.50s$).

Figure 2: Time for adults and minors to finish a task in different modalities (mean values are shown as X sign).

Results of subjective assessment are presented in Figure 3. The values are presented in box plot and the baseline. The graph indicates that adults rated *Swimming* with the worst average score (6.10) and gave *Look & Follow* the best score (2.60). At the meantime, minors rated *Assisted Swimming* with best average score (2.10) and rated *Swimming* with worst average score (6.70).

Figure 4 illustrates the preference level of each modality, which is represented through the box diagrams of each locomotion modality and the baseline. The plot indicates that adults liked *Look & Follow* the most with an average score of 8.10, and they least preferred *Swimming* with an average score of 4.90. It also shows that the *Assisted Swimming* is minors' favorite locomotion modality ($avg. = 8.20$), and they rated the *Swimming* with the lowest average score (6.40).

5 Discussion

In our study we found similarities and differences between adults and minors for both challenge level and preference across the four locomotion modalities.

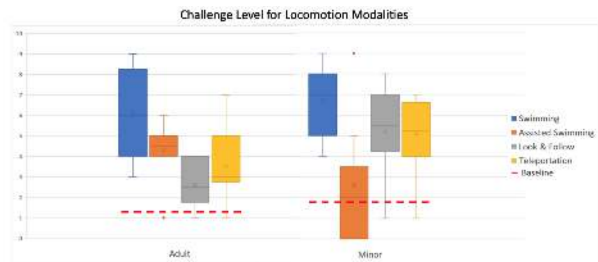

Figure 3: The challenge level ranged between 0 to 10 from questionnaire (mean values are shown as X sign). The baseline number for adults is average 1.15 and for minors is average 1.68 (shown as the red dash line).

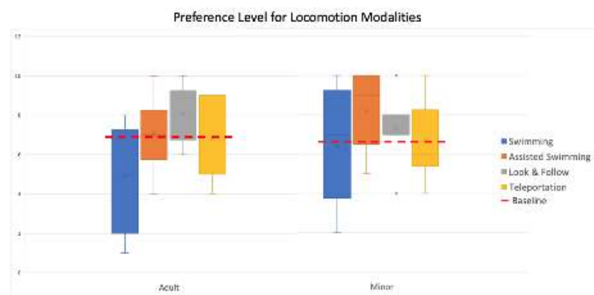

Figure 4: The Preference level ranged between 0 to 10 from the questionnaire (mean values are shown as X sign). The baseline number for adult is average 6.93 and for minors is average 6.63 (shown as the red dash line) and standard deviation 2.29.

5.1 Accessibility Comparison Between Adults and Minors

For the average time to finish the task, as presented in Figure 2, we found that minors spent least time completing the task with *Assisted Swimming* modality ($avg. = 117.84s$) and *Swimming* modality took them most time ($avg. = 286.60s$), indicating that the former being the easiest and the later being the most difficult for minors. Similarly, among adult group, the average completion time was highest for *Swimming* modality ($avg. = 276.00s$), meaning that *Swimming* modality is also the most difficult for adults. However, adults finished the task most quickly in the *Look & Follow* modality ($avg. = 80.50s$), which is different from that of minors, meaning that *Look & Follow* could be the easiest modality for adults.

For the challenge level illustrated in Figure 3, we compared the results. The evaluation given by minors for *Assisted Swimming* ($avg. = 2.1$) was quite close to their evaluation for the baseline ($avg. = 1.68$), while the other three modalities were significantly more challenging than the baseline. This means that minors regard *Assisted Swimming* to be almost as easy as walking and the others much harder. Even considering the standard deviation for *Swimming* ($std. = 1.60$) , *Look & Follow* ($std. = 1.63$), and *Tele-*

portation ($std. = 1.74$), they are still higher than the baseline for walking ($std. = 1.59$), with *Swimming* ranking as the most difficult at ($avg. = 6.70$). Adults assigned the lowest challenge level to the *Look & Follow* modality ($avg. = 2.6$), but still found it to be more difficult than the baseline for walking of ($avg. = 1.15$) even considering the standard deviation. The other three were much higher than the baseline, with *Swimming* at ($avg. = 6.1$) ranked the most challenging modality. Additionally, compared to minors' group, results from adult group show relatively lower standard deviation in the evaluation, which may indicate more reliability in adults' data or possibly more variation in motor-skill abilities in minors.

The preference level between adults Figure 4 showed some similarities and differences. We found that the adult preference higher than the baseline of ($avg. = 6.93$, $std. = 2.59$) was for *Look & Follow* at ($avg. = 8.1$, $std. = 1.37$), meaning that adults found the other three forms of locomotion either worse or the same as walking in the real-world. Although the adult preference for *Assisted Swimming* at ($avg. = 7.1$, $std. = 1.7$) and *Teleportation* ($avg. = 6.8$, $std. = 1.78$) are close to the adult preference baseline, the standard deviation makes those results uncertain. On the other hand, minors preferred both *Assisted Swimming* at ($avg. = 8.2$, $std. = 2.00$) and *Look & Follow* at ($avg. = 7.3$, $std. = 1.50$) over the baseline of ($avg. = 6.63$, $std. = 2.29$), meaning they preferred these two movements over walking in the real-world, and the remaining two less than walking. Although minors' had a slight preference for *Teleportation* of ($avg. = 6.75$, $std. = 1.81$) and *Swimming* of ($avg. = 6.4$, $std. = 2.80$) near the baseline, due to the standard deviation these results were not certain.

5.2 Hypotheses Verification

Based on the discussion above-mentioned, we can verify the two hypotheses we have proposed.

First, both adult and minor groups show significantly more difficulty with *Swimming* motion than the other three assisted motions, and subjects from both groups reflected obvious preference to the controller assisted locomotion over the natural *Swimming* modality. Additionally, both adults and minors took much longer to complete the task using the natural swimming modality, which further indicates that it is more difficult to use. The finding confirms our first hypothesis, which states that using controller assisted movement modalities in VR can improve the user experience compared to locomotion which only uses physical body movements in VR.

Secondly, although both groups found controller assisted locomotion more accessible, there is still variation for preference and challenge level within different types of assisted movement. For example, minors preferred *Assisted Swimming* over walking and also found it easier than walking. This also correlates with *Assisted Swimming* having the shortest average completion time for minors. Minors also had a preference for *Look & Follow* over walking, but found it more difficult than walking. On the other hand, adults found *Look & Follow* easiest and preferred it over walking, while finding all the others harder and less preferable to walking. Adults also had the shortest completion time for *Look & Follow*, supporting the result that it was top rated. These findings aligns well with our second hypothesis predicting the existence of variations between minors and adults.

6 Conclusion

In this paper, we conducted an experiment to evaluate the accessibility of virtual reality locomotion modalities to healthy adults and minors. We found that in virtual reality, assisted movement modalities could provide better experience to users than natural movement modality. On top of that, there are variations between adults and minors in the evaluation for each modality.

In the following, we conjecture some reasons for the conclusions obtained above, which could be potential directions of future research on this topic.

The *Assisted Swimming* modality turned out to be the most popular among minors, probably because it is less tiring than the *Swimming* modality but at the same time is more immersive and more fun to do than *Look & Follow* and *Teleportation*.

Finally, if we look at the top two most preferred types of locomotion, they are between *Assisted Swimming* and *Look & Follow*. If one would further consider the situation when subjects would have motor impairment to the upper or lower limps, which we did not consider in this paper, *Look & Follow* would be the most preferred modality and *Assisted Swimming* would be less desirable.

Acknowledgments

This work was supported in part by ONR Grant N00014-19-1-2066, FHL Vive Center for Enhanced Reality Seed Grant, and a Siemens Corporation research grant. We also thank Clemence Wormser and Xinxin Mo for their contributions in coding the VR program that was used in the development of the experiment computer program.

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