Detached Walk-in-Place

MARTIN HEDLUND
Title: Detached Walk-in-Place
Author: Martin Hedlund
Email: marthed@kth.se
Supervisor: Anders Lundström
Degree: Master of Science in Computer Science and Communication
Examiner: Ann Lantz
Date: 2017-06-18
Detached Walk-in-Place

Martin Hedlund
Royal Institute of Technology
Stockholm, Sweden
marthed@kth.se

ABSTRACT
Locomotion, the ability to walk freely in virtual environments, is a problem with no standardized solution. Walk-in-Place is one strand of solutions in which the user’s physical movement creates forward movement in the virtual environment. This technique is particularly useful for navigation in smartphone-based virtual reality without location detection. However, current mobile implementations use gaze-directed steering which limits the user’s ability to simultaneously scan the environment, which can reduce maneuverability. Additionally, step detection is triggered by head movement which shakes the head-mounted display and can therefore create discomfort and motion sickness. Detached Walk-in-place (dWIP) uses an external gyroscope attached to the body, or held in the hand, to track the user’s body rotation. This detaches the walking direction from gaze direction and removes step detection from the head-mounted display. In this paper, I present a study of two different dWIP solutions (Torso- and Hand-directed). Both solutions are tested and compared with an existing mobile walk-in-place solution. Performance, user preference and simulator sickness were measured as the participants had to navigate a curved track using each method. The result shows that both dWIP methods required less steps compared with the current WIP, but the torso-directed dWIP is slower compared to the other two. There was no significant difference in user preference or simulator sickness. Overall, dWIP was well received and shows great potential as a mobile VR locomotion method.

Author Keywords
Virtual Reality; Walk-in-Place; Locomotion

ACM Classification Keywords
I.3.7 Graphics: 3D Graphics and Realism - Virtual Reality

INTRODUCTION
Virtual reality (VR) is increasing in popularity, and with the rise of smartphone head-mounted displays (HMD) (e.g. Google Cardboard, Samsung GearVR) the price of VR is conceivable for broader segments of people. However, many VR interaction practices are far from settled [33].

Locomotion, defined as the self-propelled movement in virtual environments (VE) [22], is considered one of the most important interaction components in VR since moving freely through virtual spaces have been a fundamental appeal of many applications, such as video-games, for decades [5, 15, 32]. Unfortunately, locomotion in VR can easily induce motion-sickness to the user [6, 23, 36, 44] and many VR applications are therefore designed to minimize, or completely remove, the locomotive element [5].

“Walk-in-Place” (WIP,) is a locomotion technique that incorporates body motion similar to regular walking [39]. As the name entails, the technique requires the user to walk (or jog) in place and typically uses that body movement as input for step detection (i.e. produce movement). This technique is similar to normal bipedal walking but doesn’t require much space and have been found to reduce motion sickness [36].

Most WIP implementations are currently designed so that the user moves forward in the gaze direction (i.e. where they are looking) [31, 34, 37, 43, 50], which have the advantage of not requiring external sensors. Mobile VR (e.g. Google cardboard) uses only a smartphone’s internal gyroscope to track a user’s orientation. Therefore, gaze-directed WIP can be implemented for Mobile VR without additional devices. Additionally, step detection (i.e. input for moving forward) can also be triggered without external sensors by using a smartphone’s internal accelerometer. Steps are in this setup triggered by a user’s head moving up and down [43, 51]. In combination, this allows a user to walk around in mobile VR without the need for additional devices. On the downside, gaze-directed steering limits the users to only move in the VE in the direction where they are looking, thus they cannot move and look around without changing their path [41]. Also, head step detection can be uncomfortable and distracting [13, 51], and could potentially increase motion sickness [36].

Two alternatives to gaze-directed steering are torso-directed steering and hand-directed steering (“pointing”) [14]. These methods allow the user to move forward and look around in the environment at the same time. This could contribute to a more realistic experience since our head and body directions are detached in real life. The methods could also give maneuverability advantages. Having the ability to look around can give the user cues about the environment which can be helpful for efficient navigation. For example, estimating when to turn, dodge an incoming object or aim at an enemy in a video game. The disadvantage of these steering techniques is that one or more external devices need to track the user’s torso or hand orientation. However, if the advantages described are achieved using external but inexpensive devices, an alternative method for locomotion in mobile VR would be justified.
Results from previous studies that directly compares these steering techniques have been mixed. Learnability (i.e. how quickly users learn a technique) [13, 45] and spatial orientation (i.e. ability to maintain body orientation and posture in relation to the environment) [49], have been enhanced in gaze-directed steering over torso- or hand-directed. Hand-directed have outperformed gaze-directed in relative motion tasks (e.g. walk three meters to the right of the building) [13] and torso-directed compared equally to gaze-directed in terms of cognitive load (i.e. mental effort) and information search (e.g. how many items a user can find and remember) [14].

These studies do not suggest any major benefit of using torso- or hand-directed steering over gaze-directed. However, the implementations and equipment used in previous studies have varied greatly. For example, when implementing torso-directed steering, Nilsson et al [33] suggested that positioning the rotation tracker closer to the hip could make a better placement than the torso. Users tend to slightly turn their upper body while looking around and thereby veer off track [33]. Hand-directional steering have been precise and appreciated in other locomotion methods [17], and may have similar benefits if incorporated in a WIP method. Furthermore, if an external device is used for steering, the same device could be used for step detection. This setup could potentially be less distracting and reduce motion-sickness for users, compared with a setup that uses head movement for step detection.

In order achieve a walk-in-place method for mobile VR that both separates the gaze and movement direction, and removes step detection from the user’s head, a new method called “Detached Walk-in-Place (dWIP)” was developed. It uses an external gyroscope and accelerometer that is either attached to the user’s back (close to the hips), or held in the user’s hand. In other words, two dWIP versions was created, one torso-directed dWIP and one hand-directed dWIP.

The purpose of this paper is to evaluate the potential of these two dWIP methods. This is done by comparing the dWIP methods to each other and to an existing mobile walk-in-place solution created by Tregillus & Folmer [43]. Their method uses gaze-directional steering and head step detection, but have been found to be an easy to use, immersive and intuitive locomotion technique [43], thus a good benchmark for mobile walk-in-place. All three methods are compared on performance, user preference and simulator sickness in a study were participants are tasked with navigating a curved track from start to finish. By measuring the three methods on these three metrics, this paper aims to answer the following research question:

*How does the torso-directed and hand-directed detached walk-in-place compare, in performance, user preference and simulator sickness, to each other and to the walk-in-place solution presented by Tregillus & Folmer [40]?*

**BACKGROUND**

There are many approaches for allowing people to navigate and move around (locomotion) in VEs. First follows a recap of the most prominent locomotion methods for VR, followed by an overview of the walk-in-place method. Then follows an overview of steering methods and step detection studies.

A straightforward method for locomotion in VR is to use a regular gamepad with joystick, as seen in video-game consoles. Riecke et al [37] found that gaze-directed steering in combination with a joystick gave better control over locomotion speed compared with only using a joystick. A problem with using a regular gamepad with joystick is that it reduces immersion, occupies the hands, and motion-sickness is usually increased with joystick locomotion [17, 29, 38].

A method for locomotion in VR more similar to normal walking is using an Omni-directional treadmill, a treadmill that can move in 360 degrees. They have been demonstrated to provide an intuitive and immersive locomotion experience [18, 46]. Commercial devices are in development but will likely be costly, and will therefore probably not be an affordable alternative for the majority of the smartphone VR consumers. The omni-directional treadmills also require learning, good balancing and can restrain the user in unnatural ways [16].

Bipedal walking, to walk normally, is the most natural form of locomotion for humans [24] and previous studies have found that physical walking results in the most realistic experience [38, 45]. The disadvantage of physical walking is of course that the VE must map the physical environment. On devices such as the HTC Vive, this can typically be achieved within an enclosure of a few square meters. Since the Vive uses positional tracking, the locomotion can be achieved with normal walking within the enclosure.

**Walk-in-place**

The main advantage of walk-in-place methods are the similarities with normal walking, but without much need for physical space. As normal walking, walk-in-place methods have been found to increase spatial awareness compared to joysticks, and scoring comparatively or below normal walking [31, 51]. Syed et al [40] found that walk-in-place reduced motion sickness and increased users perceived presence (i.e. feeling of being present inside the VE). Similarly, Usoh et al [45] replicated the first walk-in-place study [39] and shared the conclusion that walk-in-place gives users more subjective presence over a joystick alternative. The same conclusion was drawn by Terziman et al [42] in a similar study.

**Steering**

Steering is the continuous manipulation of the direction of heading [15]. In other words, how the user controls his or her walking direction. The direction of heading is obtained
from tracking the direction of selected body parts of the user. Two body parts have commonly been used for steering in walk-in-place VR; the head (gaze-directed) and the torso (torso-directed) [33, 41]. In VR, the HMD already tracks the user’s head direction and gaze-directional steering can therefore be implemented without the need for additional equipment. In torso-directional steering, the user’s torso direction is tracked and used as forward direction in VR. When comparing torso-directed to gaze-directed steering, one study found the torso-directed to decrease spatial awareness compared with gaze-directed [48]. Razzaque et al [35] used torso-directed steering when implementing their RWP (Redirected walk-in-place). Their torso-tracker was attached to the back instead of the torso, which Nilsson et al [33] suggests could be more akin to normal walking. They found that users perceived presence to increase compared with the joystick method. A recent study by Kitson et al [27] compared torso- and gaze-directed methods but found no significant differences.

Another steering technique that could be implemented to walk-in-place is hand-directional steering. This method tracks the user’s hand orientation to determine forward direction in VR. Usoh et al [45] found that users found it easier to navigate a VE using gaze-direction over hand-direction. However, hand-directed steering has outperformed gaze-directed steering in a relative motion task. That is, users could move more easily in relation to an object when they could look at the object and move in another direction (e.g. a user can move to get a better view of a painting on the wall) [13]. Teleportation is one means of locomotion [16] that utilizes a form of hand-directed steering in which the user points in the desired direction and gets teleported there instantaneously. Although commonly used in many VR applications [1], few studies have evaluated the teleportation method [16]. What have been found is that teleportation can drastically reduce motion-sickness and enhance the users sense of control [16]. The limitations are that one hand usually needs to be occupied while moving and applications can feel less realistic [16].

**Step detection**

Walk-in-place also varies in step detection methods. In general, these methods can be split into two categories; systems that detect foot-ground contact, and systems that track continuous movement [33]. Examples of foot-ground systems are physical walking platforms or Wii Balance Boards. They track the user’s stepping speed based on load sensors embedded in the platform [9, 10, 34, 48]. Step detection based on movement have been implemented using camera tracking of shadows or head movement [42, 53], magnetic tracking of the user’s heel velocity [19, 47], and skeletal tracking using Kinect [28]. One implementation used two smartphone-accelerometers attaches to the user’s ankles [26]. All of these methods do not require the users head to move up and down, but they do require extensive use of extra equipment.

The implementation of dWIP is largely based upon the work of Tregillus & Folmer [43]. They developed a walk-in-place method for Google Cardboard based upon Zhao’s algorithm for step detection [52]. The algorithm has a low over-head, which is extra important for mobile VR since smartphone’s processing power is rather limited compared to PCs, but it have been found to give solid results [40]. In short, the algorithm interpolates between a minimum and maximum speed based upon the time since the last step was detected. Thus, shorter time interval between steps increases the walking speed. dWIP uses the same algorithm, with the difference instead being that body or hand movement triggers a step to be detected, instead of head movement.

**EXPERIMENTAL EVALUATION**

The goal of this study was to compare the performance and simulator sickness of the two dWIP prototypes with each other, and the gaze-directed WIP-method made by Tregillus & Folmer [43]. More importantly, the goal was also to evaluate if users had any preferences for either method. Preferences may vary greatly with context, so the study was narrowed to the task walking a curved track. The reasoning was that the utility of detaching gaze-direction from navigational direction may become more apparent in this context. However, the task would still confine the user to perform a very specific task (complete the track), thereby making performance comparisons more reliable. The participants goal was to get to the other side of the track as fast as possible while avoiding bumping into the walls.

In this section, the three methods are referred to by different names. The current gaze-directional WIP-method is referred to as “Head” since the movement direction tracker and the step detection trigger are both located in the smartphone in the HMD. The dWIP-methods are referred to as “Back” (Torso-directional steering) and “Hand” (Hand-directional steering) for similar reasons.

**Participants**

A total of 12 participants were recruited (Nine males, three females). All students of KTH with an average age of 23.75 (range 20 to 29). 8 had never, or only once, experienced VR before. Two participants had tried VR approximately 2-5 times and two participants had tried VR more than five times before. Only one participant had tried a walk-in-place application before. The participants also filled in information about their exercise amount and video-game experience.

**Study Design**

The study used repeated measures in which all participant tested all methods in a total of three trials per method. The independent methods were thereby the Head, Hand, and Back WIP-methods. Since three methods were tested, there was six combinations of testing order. To control for learning effects, every combination of the testing order was
performed as much as all the others. In this case two times, since the total number of participants was 12.

**Performance**

To evaluate performance differences, a curved track was designed (Figure 2) where the participant had to navigate around seven walls, three times for every method. The track was designed curved to be more challenging compared to tracks with straight trajectories. I assumed a more challenging track to revile performance differences between the methods more clearly if there are any. Furthermore, I assumed that dWIP would make it easier for participants to turn around obstacles. A curved track (i.e. track obstacle path) is therefore a logical first task to evaluate potential performance gains in either dWIP method.

The dependent variables were time to complete the task (Time), number of steps it took to complete the task (Steps), and number of times a participant hit a wall (Collisions). The variables were chosen since they are commonly used in other studies [13, 26, 42, 43] and are basic variables for comparing how efficient a task can be completed with a certain technique. All variables indicate how good a method respond to the user’s intentions since the user’s intention was to get to the other side of the track as fast as possible without bumping into the walls. The time it takes to complete the task indicates, obviously, how quickly a user can move around obstacles with the method. The number of steps can however indicate one of four explanations: 1) The user took a longer route through the track which requires more steps. 2) The user was walking slowly. The algorithm for step detection [55] outputs a slower speed if there is more time in between steps. Slow speed does not propel the user forward in the VE as much as faster speed, and he or she would then need to take more steps to complete the task. 3) Opposite to the previous explanation, if the time in between two steps are below a minimum threshold, the user may trigger a step “unnecessarily” since he or she is already moving forward at maximum speed. This could contribute to the user taking more steps to complete the track. 4) Lastly, if a user for some reason walks in circles or in the wrong direction, the number of steps would increase. It would have been ideal to also track the participants route in this experiment, since this indicates how efficient a user could navigate the track with a method. To optimize rendering performance (i.e. frame rate), which is important for the experience of VR, tracking route length was removed and replaced with step detection instead.

A one-way repeated measures ANOVA was used to test for differences in the mean values between the three methods [4]. If the data would not meet the ANOVA assumptions of normal distribution, no outliers and sphericity, the data would be transformed and tested again [4]. The Shapiro-Wilk method was used to test for normality, and sphericity was tested using Mauchly’s test [4]. The assumptions were violated if p < 0.05. If the data still did not fulfill the assumptions, a Friedman’s test [3] would also be used to verify the results. Statistical significance was accepted at p < 0.05 for both the ANOVA and Friedman’s test, and if true, a Bonferatti correction [3, 4] for pairwise comparison was performed to verify which methods had differences between them. All nine trails per participant were included in the analysis.

**User preference**

Preference was measured using a questionnaire, and a System Usability Scale (SUS) [8, 11, 12]. The questionnaire consisted of these seven questions: 1) Which method do you prefer the most? 2) Which method do you prefer the least? 3) Which method do you think you would prefer if improvements were made? 4) Which method do you feel was most realistic? 5) Which method do you feel was least realistic? 6) Which method was easiest to learn? 7) The answer options were the three methods. Question 3-7 had a fourth “Don’t know” option since they were vaguer in nature. The questionnaire answers were tested using a chi-squared goodness of fit test [5], which compares expected frequency distribution with outcome (e.g. flip a coin a 100 times and expected distribution frequency should be close to 50-50). For the test to be reliable, the expected frequency of each option (Head, Back, Hand) had to be at least five [2]. In other word, the test should assume that five participants preferred Head, five preferred Back and five preferred Hand. Since the participant sample size was 12, the questionnaire data was merged into categories with expected frequency of six outcomes each. Each question was thereby analyzed three times, comparing each answer with the other two or three answers (three if “Don’t know” was included). For example, the question “Which method do you prefer most?” was analyzed comparing the answer frequency of “Head” to the answer frequency of “Back” and “Hand”. If the test was significant, a majority of participants either preferred Head, or did not prefer Head, over the other two methods. If the test was not significant, the participants preferred Head equally to any of the other two methods. The preference questionnaire also included a last voluntary comment option. The SUS scores was analyzed using the Friedman’s test [3].

**Simulator Sickness**

Simulator sickness was measured using a Simulator Sickness Questionnaire (SSQ) [25]. The SSQ is made up of three sub-categories; nausea, oculomotor, and disorientating sickness. The SSQ score ranged between zero (no symptoms) and 21 (Maximum symptoms). Since the design of the study included repeated measures, it was impossible to distinguish the sickness impact of previous trails on the next. For example, how much does a SSQ score depend on the previous method trail (e.g. the Hand-method), and how much did the current method trail (e.g. the Back-method) contribute. This study uses the previous SSQ score as a base for measuring the change in SSQ. I therefore assumed that for two equivalent SSQ scores, the score from the first method trails fully contributed to the score from the second method trails. Since the SSQ data is ordinal (categories are
“None”, “Slightly”, “Moderate” and “Severe”), a Friedman’s test was used to analyze the results [3].

Figure 1: Left) User using dWIP-Hand. Right) User using dWIP-Back

Implementation
The implementation of dWIP is based largely on the work of Tregillius & Folmer [43]. This allows for a comparison between dWIP and a proven mobile walk-in-place method, changing only the steering method, the device for step detection and threshold for step detection (the threshold was decided to be slightly lower in the Back-method).

A Nexus 5 was used as the external gyroscope (for body rotation) and as the external accelerometer (for step detection). Gyroscope data was sent every frame. The HMD used was GearVR with Samsung Galaxy S6. The application was created with Unity and used Bluetooth communication between the HMD and Nexus.

In the dWIP Back-method, an ad-hoc prototype was created using a belt, clamps, elastic bands, a Sport-Fit armband and duct tape (see figure 1). The z-axis of the gyroscope turned out to be more reliable, therefore the prototype was designed to have the Nexus positioned horizontally. The prototype was positioned on the back of the user, close to the hips, as suggested by Nilsson et al [33] (figure 1). In the dWIP Hand-method the user simply held the Nexus in one hand.

Procedure
Each of the 12 participants started out by filling out the SSQ. Next, they were given instructions of the task. Before the task started they adjusted the focus and fit of the GearVR. To minimize the risk of participants physically drifting or falling over, a square shaped carpet was placed underneath for orientational support (figure 1). For the Hand- and Back-method, the participants learned how to calibrate the Nexus and testing to walk inside a tutorial area. For the Head-method, participants also tested to walk around inside the tutorial area before the task started. The task consisted of a curved track (figure 2) that the participants completed three times per method. The goal was to get to the other side as fast as possible while avoiding bumping into the walls.

Figure 2: Overview of the curved track. The red line represents the path through the track.

When all three method trails were completed, the participant was teleported to an open space “end-area”. The purpose was to let the participant get some more feel for the method without having any concrete objective. This scenario only lasted for about 10 seconds extra. Immediately after the participant removed the HMD, they filled in the SSQ and SUS again for the given method. After all methods had been tested, the participant filled in the preference questionnaire. Finally, they were asked to give qualitative feedback in a short open-ended interview.

RESULTS
Following is the results of the study comparing the dWIP-Back method, the dWIP-Hand method, and the WIP-Head method. The outcome of the performance, preference and simulator sickness data is presented accordingly. Lastly, qualitative feedback in the form of written comments and interview answers are presented.

Performance results
Time
Significant results from the ANOVA indicate that participants were slower (took long time to complete the track) when using the Back-method. Mean time completion was 22.3s (Head), 26.4s (Back) and 20.7s (Hand). However, the ANOVA assumption of normally distributed data was violated for the Head-method time data (p < 0.01) and Back-method time data (p = 0.029). The time data for the Back-method trails had an outlier, and the time data for the Head-method trails had 5 outliers, including one extreme value. The test was performed a second time with transformed data. Results from the second ANOVA test also indicated significant results, however, the assumption of normality was still violated in terms of the Hand-method time data (p = 0.048). The Friedman’s test was therefore also carried out with significant values for the time data. Median time completion was 19.3s (Head), 26s (Back) and 20.5s (Hand). P-values for the Friedmans’s test pairwise
comparison were \( p < 0.001 \) (Head vs Back), \( p = 1 \) (Head vs Hand) and \( p = 0.03 \) (Back vs Hand).

**Number of steps**

Regarding the number of steps for task completion, the ANOVA indicated significant results for participants taking more steps with the Head-method compared to the other methods. Mean number of steps for the Head-method was 89.5, 61.7 for the Back-method and 60.3 for the Hand-method. As with the time data, the normality and outlier assumptions was violated for the Back-method (\( p < 0.01 \), 1 outlier) and Hand-method (\( p < 0.01 \), 2 outliers). In this test, the data too skewed from normal distribution that it became impossible to transform the data to fulfill the assumptions. The Friedman’s test also indicated a significant result however. Median number of steps for the Head-method was 89, 59 for the Back-method and 56 for the Hand-method. P-values for the Friedmans’s test pairwise comparison was \( p < 0.001 \) (Head vs Back), \( p < 0.001 \) (Head vs Hand) and \( p = 1 \) (Back vs Hand).

**Number of collisions**

There was no significant difference from the ANOVA between the three methods in the number of wall collisions participants did with each method. Mean number of collisions were 4.9 (Head-method), 4.6 (Back-method) and 4.6 (Hand-method). All the ANOVA assumptions were met and therefore the Friedman’s test was not carried out.

**Preference results**

The chi-squared tests indicated significant results for five answer outcomes: “Do you prefer Hand the least” (Yes: 2, No: 10, \( p = 0.021 \)), “Do you think Head was least realistic?” (Yes: 2, No: 10, \( p = 0.021 \)), “Do you think Back was easiest to learn?” (Yes: 0, No: 12, \( p < 0.01 \)), “Do you think Hand was hardest to learn?” (Yes: 2, No: 10, \( p = 0.021 \)). “Do you think Head was hardest to learn?” (Yes: 2, No: 10, \( p = 0.021 \)).

**System Usability Score**

No significant difference was found in the Friedman’s test for SUS scores. Median scores were 82.5 (Head), 82.5 (Back) and 85 (Hand). One participant failed to complete a SUS questionnaire due to technical problems, which unfortunately was noticed long after the experiment was over. Hence the total sample size was 11 participants for this test.

**Simulator sickness results**

No significant difference was found between the methods using the Friedman’s test. Median change in Nausea were 1 for the Head-method, 0 for the Back-method, and -1 for the Hand-method. Median change in Oculomotor symptoms were 0.5 (Head), 1 (Back) and -1 (Hand). All methods had a median of zero disorientation change.

**Qualitative feedback**

Following is all the feedback from the preference questionnaire and the open-ended interview, split up per method.

**Head-method feedback**

Two participants said that bobbing his/her head contributed to feeling nauseous. Another said that “It is easier to just nod your head instead of jogging”. The Head-method had the best potential according to one participant. Two participants said it was the easiest method to use, and according to one of them, it was because “…it was less ‘Gizmos’ to think about”. The first of those two also said he/she felt a bit locked when using the Head-method.

**Back-method feedback**

One participant said that the Back-method drifted too much and “Doesn’t run where you’ll think you’ll run”. In the preference questionnaire, another participant also commented on the drift. He/she wrote that “The head and hand methods are probably best used as a compliment to the back method. The back method would be great if the delay was smaller”. Two participants commented that the Back-method was harder to learn. From the preference questionnaire, one participant gave the feedback “Back takes a few seconds longer to learn than just the head but is preferred since it’s more realistic. It was really nice to be able to run one way and look the other (I tried it in the end in the open field)”. The other participant only said that the Back-method was the hardest. One said that he/she had “No real need to look around since it wasn’t that much to see, but I would have benefited from it more in a game like Amnesia (First-person horror game)”. A forth participant
said, “I liked back the most, it’s best for games like shoot’em ups (subgenre of shooting games)”. Lastly, one participant said that the Back-method is most worthy to continue working on.

**Hand-method feedback**

The Hand-method was the hardest method and took the longest time to learn according to the one participant, and the easiest method to learn according to another. Another participant said that “The Hand-method can be the easiest because it’s user friendly”. One participant said he/she did not jog with the Hand-method, but instead only moved the smartphone. The same participant made a similar comment in the preference questionnaire. A fifth participant said that “The Hand was the best. Worked d*mn good”.

**General feedback**

Two participants said they had problems with the movement speed in the application. One of them said “Jogging faster worked better because the step detection was better, but that got you more nauseous” and also that “The movement for walking speed doesn’t feel natural, it works better when jogging”. The other participants said he/she would like it to be easier to control the speed in the application. Two other participants gave feedback on simulator sickness. One said he/she got nauseous from all the methods and another said he/she does not think it would be possible to use an application with either of the methods for 2-3 hours without feeling sick. Five participants gave positive feedback to all the methods, saying “Everything worked surprisingly well”, “Very fun application”, “Nice stuff”, “No one (method) was more difficult to use, all were about equally easy” and “Very interesting technique in general”.

**DISCUSSION**

How does the torso-directed and hand-directed detached walk-in-place compare, in performance, user preference and simulator sickness, to each other and to the walk-in-place solution presented by Tregillus & Folmer [43]? First, I will discuss the performance results, followed by the preference results and simulator sickness results. Lastly, I will discuss the study design and potential future improvement.

Participants using the dWIP Back-method were slower than when using the WIP Head (i.e. the method by Tregillus & Folmer [43]) or the dWIP Hand-method. This was a slight surprise, since I assumed turning around corners to be easier using a torso-directed steering method. There are many potential explanations to this. One potential explanation could be that many participants did not use their entire body while using the Head- and Hand-method, as two participants commented on. That is, they did not jog or walk in place as normally when using a walk-in-place method. Instead, to trigger the step detection, they stood still and only moved their head or hand. Using smaller motions could have made it easier to keep up the speed, since the step detection algorithm outputs higher speed if the time interval between steps are smaller. If more participants minimized their body motion, it could be a potential explanation for slower time performance for the Back-method, which required the participants to fully move their body, thus making it more cumbersome and slow. A second explanation could be that Back-method was more difficult to learn as it requires a whole new dimension of body coordination as both the body and head needed to be coordinated simultaneously to complete the tasks. This was also clearly visible from the data as none of the twelve participants thought that the Back-method was easiest to learn. Similar findings have also reported that non-gaze-directed steering could increase cognitive load, thereby making such a method more difficult to learn [14]. Eight participants indeed answered that the Head-method was easiest to learn. Interestingly, the time performance of the Hand-method was equal to that of the gaze-directed Head-method in the study. Therefore, it is reasonable to believe that is has more to do with the combination of torso-steering and full body movement, than with dWIP in general.

The WIP Head-method made participants take more steps to complete the tasks. This was expected and one of the motivations behind this study and the development of dWIP. As previously described, there are four plausible explanations to this result. One plausible explanation could be that it was easier to trigger steps with the Head-method since one participant said that the Head-method did not require full body movement. It only required the user to move his or her head up and down slightly. This could potentially have led to steps being triggered more quickly and easy. But it could also have led to steps being triggered unnecessarily, thus counted more in the data than was actually taken advantage of in the test track. However, based another participants feedback, the Hand-method resembled the Head-method in the aspect of how easily step detection was triggered. In other words, it could have been equally easy for users to trigger steps by moving their hand up and down slightly, and to move their head up and down slightly. If unnecessary step-triggering was the only explanation, then the Head-method and Hand-method would show similar results regarding the number of steps taken. Another possible explanation could be that participants moved slower with the Head-method. If the time between steps are longer, the speed becomes slower and thus propels the user forward in shorter distances compared to faster speeds. This explanation is not likely since the Head-method was faster than the Back-method, and equally fast as the Hand-method. Because it was faster than the Back-method, the travel speed had to be faster and thus the time between steps had to be shorter. A third explanation could be that the participants walked in circles or in the wrong direction with the Head-method, thus triggering more steps. This is also unlikely, since the track design was straightforward without any possible detour options. That enough participant walked the wrong
direction with the Head-method, to significantly impact the result seems implausible. Therefore, it seems likely that both dWIP methods gave participants an advantage for moving in relation to another object (i.e. around the walls). The same conclusion has been drawn by Bowman et al [14], when comparing Hand-directional steering to Gaze-directional steering. In other words, participants may have moved more easily moved around the walls of the track with dWIP, thus using fewer steps compared with the WIP-method, and thereby traveling a shorter route. A possible explanation for how they moved more easily around the walls is that they could focus their gaze on the wall ending, while moving forward simultaneously, thereby optimizing their path around it. I illustrate my assumed explanation in figure 4 below. With the Head-method, a user cannot turn their head slightly to check when to turn. To avoid the risk of colliding into the wall, thus losing all speed, participants could have taken a couple of steps extra to “be on the safe side” before attempting to turn around the wall.

![Figure 4: Plausible walking path around walls with dWIP torso- and hand-directed steering (left) or WIP gaze-directed steering (right). The blue triangle represents field-of-view, the red arrow represents walking direction.]

Before the experiment, the Head-method was suspected of generating more wall collisions, since the gaze-direction would make it harder for the user to move and look at the wall simultaneously [14, 40]. The fact that there was no significant difference could be due to the fact that participants walked a longer route around the wall when using the head-method in order to avoid collisions. This explanation is supported by the fact that the head-method generated significantly more steps.

Before the experiment started, I expected the Back-method to be more popular, since I expected it to be experienced as the most realistic and most advantageous for navigating a curved track. However, there were no significant differences in preferred method or SUS scores. The only significant result regarding realism was that a majority did not think the Head-method was the least realistic. This is also surprising since gaze-directed steering is less similar to normal walking compared with the other methods [41]. As stated previously, this could partly be due to the fact that many participants did not jog or walk in place. Instead they only moved their hand or head enough to trigger the step detection. But this implies that participants should have picked the Back-method to be more realistic than the Head-method, since it did require users to jog or walk in place. This was not the case. If torso-directed steering is experienced as more realistic compared to gaze-directed steering, other factors than steering method affected participants perception of realism. Two potential explanations can be derived from the data. First, a majority of participants did not think that the Back-method was the easiest to learn. Secondly, two participants commented that the Back-method occasionally drifted slightly. If more participants experienced drifting problems, this could have affected the results. No participant commented that the Hand-method drifted, even though the method uses the same equipment and software implementation. This could potentially be because participants could correct for the drifting error by slightly altering their hand position. Correcting the drifting error with the Back-method would require the participant to slightly turn the entire body, and that may have made the drifting more apparent or annoying. It could also be that the drifting error only occurred randomly for two participants. The Hand-method did certainly not cause drifting problems since it does not include an external gyroscope. In combination, difficulty to learn and drifting problems could have been enough to reduce the Back-methods experienced realism.

Another significant finding from the preference questionnaire was that a majority of participants did not think the Hand-method was the worst method. This is interesting, since none of the participants thought that this method was the most realistic. However, a majority did not think that the Hand- or Head-method were the hardest methods to learn. This suggests that the participants valued learnability or ease of use over realism in this particular context. In general, it was interesting to note that some participants only moved their head or hand for step detection, despite full body walk-in-place movement being more akin to normal walking. This tendency towards minimizing movement can be observed within other application areas and platforms too, for instance, the Nintendo Wii was introduced to increase movement and more bodily engaging games but many users learn to play the games sitting in their couch with minimal movements. Perhaps this is a general human evolutionary tendency in which we strive to perform tasks in as energy efficient manners as possible.

Finally, no significant difference in SSQ scores was found in this study. However, two participants said that they got dizzy and nauseous from too much head movement, which is in line with previous studies [35], and a reason for removing step detection from the head. Also, each participant only spent roughly a minute in the VE per method. Longer exposure time may have given a different outcome. The within-subject design study could have impacted the results of the simulator sickness scores more than expected. For example, if a participant scored 10 on nausea using the Back-method and 11 on nausea using the Hand-method, this study assumes that the participant would
only score one with the Hand-method if he or she had no symptoms beforehand. Since the SSQ scale is ordinal, participants may hypothetically be more prone experience sickness increases between SSQ scores of 0-10, compared to increases between 11-21. In other words, the increase from “None” to “Slightly” may be more apparent than the increase from “Slightly” to “Moderate”. It could also be that the second or third method trails always increased the SSQ score since the exposure time in VR increased regardless of the method. However, if one method was significantly different from the other, it is reasonable to assume that this method would cause higher SSQ scores compared to the other methods, regardless of total exposure time in VR. In either case, future studies should test the methods between subjects, or use breaks between the trails, to make sure participants experience no sickness symptoms before they started testing a method.

Continuing the discussion of the study design, another limitation is that recruited participants were all student between the ages of 20 and 29. It is reasonable to assume that stamina decreases with age, and thus the dWIP Back-method would be more tiring for many potential users. Easier step detection, perhaps possible with the new GearVR controller [7], could minimize the body movement for using the method. Furthermore, this study only tested the methods within the task scenario of navigating a curved track, and evaluated metrics were confined to task completion time, number of steps and number of collisions. Free exploration tasks could also be beneficial for users to fully experience the methods. Also, information gathering, the practice of absorbing information from the environment, is one performance metric were torso- and hand-directed steering are expected to outperform gaze-directed steering [14, 41]. This would be an interesting metric to evaluate in future studies.

Certain limitations still exist in both the current WIP and dWIP. For instance, neither support strafing (walking sideways) or walking backwards. These are common maneuvering capabilities in many first-person games [15, 33] and a logical expansion for a future dWIP implementation is to incorporate these options. Two participants commented that the movement speed felt too slow in all methods. Finding the most preferable speed is important for future implementation. Also, the rapid advancement of eye tracking technology [21] could be an interesting expansion of dWIP. For example, users normally use their eye gaze when navigating [20], which could potentially be used to slightly rotate the rendered screen image, instead of slightly rotating the head. Detaching step detection from the head would probably be necessary in eye-gaze steering in order to minimize the HMD from bumping distractively. The dWIP implementation used in this study had some drifting problems which a more stable gyroscope may counter. The new GearVR controller [7] have a better gyroscope sampling rate than the Nexus 5 [30], and should be tested as a dWIP controller.

Overall, the two dWIP methods compared well against the existing mobile walk-in-place method and can definitely be considered as feasible alternatives. They were more efficient in terms of the amount of step a user needs to take to reach a goal and received mostly positive feedback from the study participants, including comments on the advantages of using dWIP in various game scenarios. If more training time was given and the drifting problem solved, task completion time may have been lower for the dWIP Back-method.

FUTURE WORK
To further expand the dWIP-method, I suggest looking into these two potential improvements. First, drifting problems should be mediated with another device as gyroscope input. Second, evaluate how to implement strafing, backwards walking, speed control and eye tracking capabilities.

New studies should give participants more training with the methods before they perform a task, and if possible let more time pass between tasks to more reliably separate simulator sickness per method. Also, different task scenarios, such as information gathering and free exploration should be evaluated with dWIP.

CONCLUSION
In this study, a new mobile walk-in-place method, dWIP, was prototyped and tested against a current walk-in-place method. Two different navigation modes were created for dWIP, one torso-directed and one hand-directed and compared to a WIP solution controlled by the head. Surprisingly, participants in the study performed the experiment task slower with the torso-directed dWIP, which might be explained by the increased demand on a new form of head and torso coordination and a need for more practice to master. However, although they performed the task slower, participants still took fewer steps with both dWIP methods to complete the task, which indicates significant efficiency benefits. In addition to these quantitative metrics, a majority of participants also preferred one of the dWIP methods in favor of the head, although none of them stood out as more favorable. In total, the results show some promise for dWIP solutions. However, more experiments are needed with more types of task scenarios.

ACKNOWLEDGMENTS
I would like to thank my supervisor Anders Lundström for all feedback and support given during this study. I would also like to thank Robin Grönholm and the company Knowit for providing support and a work environment. Lastly, I would like to thank all participants who volunteered in the experiment and all those who provided helpful comments on previous versions of this document.
REFERENCES


52. Zhao, Neil. "Full-featured pedometer design realized with 3-axis digital accelerometer." Analog