Directed Translational Gain: Improving Locomotion in Large-Scale Virtual Environments

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Abstract
Locomotion in virtual reality is a topic that has undergone a great deal of research and has become increasingly relevant in recent years with the introduction of consumer level VR hardware. Tracked real walking, typically seen as the gold standard in VR locomotion regarding user immersion, is limited by the physical space available to a user. One solution to this is to extend the physical space by amplifying tracked user movement. Such translational gain is typically applied uniformly in the horizontal plane, leading to problematic amplification of lateral head motion during movement. Prior research has suggested directed gain as a solution to this, in which amplification is only applied to motion occurring parallel to a user's overall heading. Crucially however, previously proposed systems have all required a priori knowledge of user heading, preventing free exploration. Consequently, in this paper we present a novel approach to directed gain with support for unconstrained exploration and present the results of a study designed to test the relative strengths and weakness of this compared to uniform gain. Results of this study show that directed gain performed worse than uniform with regards to task performance, and better with regards to user sickness levels. Analysis of participant movement logs also revealed the existence of a previously undescribed phenomena in which the mapping between virtual and physical origins drifts over time under directed gain. This phenomenon is inherent to directed gain and has significant implications for directed gains feasibility as a widespread locomotion method.

CCS Concepts
• **Human-centered computing→Virtual reality**

Keywords
virtual reality; locomotion; translational gain; VR

1. Introduction
Recent years have seen the introduction and rise in popularity of consumer level VR hardware. As VR has continued to become more adopted there has been a steady push to provide users with VR experiences, and particularly games, that feature ever larger virtual environments with a strong focus on user locomotion. 2017 for example saw the release of the game Fallout 4 in VR [1], which features environments whose sizes are orders of magnitude greater than even the largest play spaces possible with current technology.

Contrasting this push for large environments, the size of an average users play space on the other hand has either remained the same or in fact reduced as is the case for the average UK living room [2]. This presents an obvious problem; how to enable immersive exploration of virtual environments larger than a user's play space. With exploration via 1:1 mapping of physical to virtual motions alone, this is simply not possible and as such severely limits the range of possible virtual environments. The typical approach taken by developers so far to get around this limitation, has been to use teleportation-based locomotion.

Teleportation is typically used as a hybrid method, allowing users to explore an area around them (of size equal to their play space) using real walking, with traversal to positions outside of this area being done via teleportation with a controller [3]. Despite being one of the most commonly used locomotion techniques in current commercial VR experiences, teleportation has seen relatively little research when compared with other locomotion techniques [3]. What research has been done has pointed towards teleportation performing as well as or better than (but still worse than real walking [6]) joysticks and walking in place when it comes to user effort levels, movement accuracy and sickness rates [6]. However, in terms of user presence and disorientation levels it has been found to perform worse than both real walking and walking in place [14].

A number of VR locomotion techniques have been put forward over the years, all of which can be roughly placed into one of two categories; real walking based, and non-real walking based. With methods such as teleportation lying somewhere between the two. However, research has shown that a user's sense of presence and spatial awareness within a virtual environment is strongest when they are able to move through that environment using real walking based techniques [4], [5], thus it is these techniques that stand to have the biggest impact on consumer virtual experiences. With regards to real walking-based locomotion techniques, there are three main approaches that have been proposed, namely; redirected walking, walking in place and translational gain. The latter of which, is the focus of this paper, and gain involves the amplification of the mapping between physical and virtual user movements [6], allowing users to traverse virtual environments larger than their physical play space.

The majority of research in the field VR locomotion has focused on redirected walking and walking in place methods over translational gain [6]. This is likely due the potential of both methods to enable the ability to explore arbitrarily large virtual environments. At present however, both methods suffer from severe limitations which stand as roadblocks to them seeing wide spread adoption in a consumer setting, with redirected walking having high space requirements, and walking in place methods requiring the use of additional hardware and user training [6].

Translational gain is somewhat unique, in that it does not seek to (and indeed cannot) enable exploration of arbitrarily large virtual environments. Instead it simply increases the size of the area explorable by real walking to be some multiplier of the size of the physical play space [6]. Whilst less capable at expanding locomotion capabilities, translational gain has none of the requirements and limitations inherent to walking in place and redirected walking [6]. Translational gain is also comparatively easier to implement into both new and existing VR experiences, and provided gain is not set too high, has been found to have little effect on object interaction [6], a key activity in the context of most VR games.

In addition, translational gain, unlike both redirected walking and walking in place, is not necessarily a replacement for existing teleportation-based locomotion. Instead it would likely see usage as part of a hybrid system that allows users to explore an area around them larger than their play space (by some factor) using real walking, whilst retaining the ability to traverse arbitrary distances using teleportation.

It is for these reasons that translational gain stands to make the greatest impact to consumer level VR games and experiences, its lack of space and hardware requirements, and its ease of implementation make it a strong candidate for use in existing and new VR titles. However, translational gain is not without its own issues. Traditional, or "Uniform" translational gain typically applies amplification to all user motions occurring the in the horizontal plane, leading to the amplification of lateral motion occurring during user locomotion [8]. In order to counter this, a form of directed translational gain can be used, in which only components of motion parallel to a user's direction of regard are amplified. All previously proposed directed gain systems however have had a severe flaw in that they cannot support free user exploration, as a result of requiring a priori knowledge of user heading [9]. Additionally, no research to date has directly examined the relative performance of directed and uniform gain in regard to task performance, perceptibility, sickness levels and workload.

In this paper we propose a robust translational gain system suitable for both uniform and directed amplification of user movements and examine the performance of it in both modes in the context a VR experience representative of a typical VR game. Before moving on to discuss the proposed gain system and its motivations, we will first briefly examine prior work that has been done in the field of VR locomotion and how it relates to this research.

2. Related Research

2.1 Redirected Walking

Redirected walking utilizes the fact that humans have greater difficulty perceiving their overall path of travel than they do perceiving their direction of travel at any given moment [9]. As a result of this, it is possible to apply small imperceptible shifts to a virtual scene in the form of rotations of the users view, which a user will not consciously perceive and will unconsciously compensate for whilst walking [5], [6]. Through the application of these rotations, a user can be made to walk along a circular arc in the real world which they perceive as being straight. Such rotations are commonly talked about in terms of curvature gains, defined by the radius of the circular arcs which users' paths are redirected on [5].

Redirected walking algorithms function by using these curvature gains in order to steer the path of a user away from the boundaries of the play space [5]. Such algorithms require that a user's path through the virtual environment be relatively straight and require some a priori knowledge of a user's intended destination in order to prevent any boundary collisions [6]. As a result of this, it is not yet possible for redirected walking to support completely free user exploration involving sudden or unpredictable movement [6], without having to resort to immersion breaking re-orientation events when a user inevitably hits a boundary of the play area [6].

In order for the redirection of a user's movement to remain unnoticeable, the amount of curvature gain which can be applied must be kept below a certain threshold. The exact value of which depends upon the nature of a user's activity within the virtual environment. For exploration, prior research has found that users could be redirected by around 18 degrees over a 5m path, resulting in an effective walking arc of 32m, without being aware of the redirection [6]. When users are engaged in secondary tasks, this value can be reduced to an effective arc of approximately 15m without being detectable [6]. For more constrained exploration of fully predetermined paths, this can once again be reduced to an effective arc of around 7m [6], however even this still easily exceeds the size of a typical VR play space.

Whilst a very powerful technique, redirected directed walking is at present not even close to being suitable for use in an average consumer setting, the largest hurdle faced is the need for a play area larger than what is available to a typical user, in order to avoid frequent re-orientation events. In addition to these size limitations, most existing redirected walking algorithms only support limited exploration with predetermined waypoints, and there exists no algorithm to date that supports completely free exploration of the type commonly found in commercial VR games.

2.2 Walking in Place

Walking in place is a general term for a set of locomotion techniques in which a user navigates a virtual environment by standing in place, either on the ground or on a treadmill device, and performing walking motions. As the user does not physically move anywhere, these methods are able to allow free exploration of infinitely large virtual environments with minimal play space requirements [10]. Research has shown walking in place methods to perform much better than using joysticks or hand gestures for locomotion when considering immersion, simulator sickness and spatial awareness [6], [11]. However, walking in place is not able to match the spatial awareness of real walking, and still suffers from the sensory mismatch in movement that is experienced in joystick powered locomotion (although to a lesser extent) [6]. Such mismatches are theorized to be one of the main causes of motion sickness [12]. Walking in place also suffers from the fact that it requires specialized hardware in order to function, this can range from motion sensors attached to the user's body [11], to omnidirectional treadmill devices [13]. Which in the case of the latter, are likely to place significant restrictions on user interaction in VR by limiting their possible movements. In addition, the need for extra, (and in the case of a treadmill device, expensive, both spatially and financial) hardware places a barrier to entry to using walking in place methods in typical consumer settings. Limiting their usefulness to only a small subset of users willing to invest in additional hardware.

2.3 Translational Gain

Translational gain involves the amplification of user movements through the application of a multiplier to a user's real walking translation through the play space. For example, with a gain multiplier of 2x, a user who walks 1m in the real world will traverse 2m in the virtual environment [6]. At its most simple, this amplification is applied to movement on all axis, although gain is often limited only to the horizontal plane to prevent nausea caused by amplified vertical head-bob motion occurring when walking [6].

For low enough levels of gain, prior research has shown that users are unlikely to consciously perceive the application of gain and will without realizing correct for the gain by adjusting their walking speed [6]. The level at which gain becomes detectable has been found to lie around a multiplier of 1.6x [7]. Higher levels of gain, even up to around 50x, whilst noticeable, have been found to have no negative impact on spatial awareness or sickness when a user is engaged in a secondary task [7]. Traditional translational gain is applied uniformly in the horizontal plane; however, such uniform applications of gain have the unwanted effect of amplifying the lateral motion of a user's head whilst walking, which is known to cause discomfort [8]. In addition, this application of gain to lateral motion has been found to interfere with object interaction [9]. Effects on object interaction can be somewhat mitigated through the use of a gain ramping function, which attempts to keep the level of gain essentially non-existent when a user is stationary or only moving very slowly, but constant once they are walking [8].

Directed translational gain seeks to prevent amplification of lateral motion by constraining gain to only be applied to components of motion parallel to the user's direction of travel [8]. Prior attempts at creating directed gain systems have involved having a priori knowledge of user heading either via guided walking tasks [9], or by defining heading to simply equal the user's gaze direction at any given moment [8].

Interrante et al [8] describe a directed translational gain system they dubbed "Seven League Boots", in which gain could be toggled on and off by the user, being applied only to components of motion lying parallel to a user's view direction. Pilot testing of this system showed promising results, with users preferring the system over uniform gain [8]. In a typical virtual environment, a user's heading cannot always be known ahead of time and using gaze direction alone is not suitable for free exploration in interactive experiences where a user may not always be looking in the direction they are moving [6]. It also worth noting that no research to date has examined the relative performance of directed and uniform gain regarding perceptibility, sickness level and workload.

A more generalized approach to determining user heading is needed for the creation of a robust translational gain system, in order to enable directed gain to be suitable for the types of free-form VR games and experiences typically seen in a consumer setting. As such this research seeks to propose a system which addresses these needs, and to investigate how it performs compared to uniform gain in a VR game representative of a typical VR experience.

3. Ideal Translational Gain System Requirements

To design a robust directed translational gain system, one question that must be answered is exactly which types of movement should be subject to amplification.

3.1 Movement Schema

For brevities sake, it is more apt to consider movements that should not be subject to amplification than those that should. Consequently, we propose the following enumeration of user motions which should not be subject to amplification in an ideal translational gain system, where any movement type not listed below should be subject to amplification.

1) **Lateral motion of the user's head whilst walking**. Research has shown amplification of this to cause discomfort [8]
2) **Small idle motions occurring when a user is stationary.** Initial testing found the amplifications of such movements to be considerably more noticeable than others.
3) **Motion occurring whilst a user is stationary but interacting with objects.** Amplification of these movements has been found to have a negative impact on object interaction [9].
4) **Very slow motion**. Initial testing found amplifications of very slow movement to be more noticeable than others, and to reduce the feeling of fine control over movement.
5) **Any motion occurring in the vertical axis.** Amplification of this leads to discomfort from exaggerated head-bob [6].
6) **Motion along a tight circular arc.** Initial testing found any amplification of circular movement to be considerably noticeable and disorienting.
7) **Any movement of tracked handheld controllers independent of user movement**. Initial testing found the proprioceptive mismatch of a user's hands appearing in a different place relative to the user's body in the real world to be incredibly disorienting and noticeable.
8) **Any motion (in all axes) occurring as a result of a user crouching down or standing up.** Initial testing found amplification occurring during these actions to cause intense discomfort.

Note that the only rule that is specific to directed translational gain is the first, all other rules can be (and indeed in this research were) followed for a robust uniform gain system.

3.2 Heading Detection Requirements

For any directed gain system to support completely free user movement, we also require an algorithm for detecting user heading that meets the following specifications

1) It should be able to detect the direction of a user's motion independently of the user's gaze direction.
2) It should be responsive to sudden changes in heading.
3) The determined heading should be stable for stable paths.

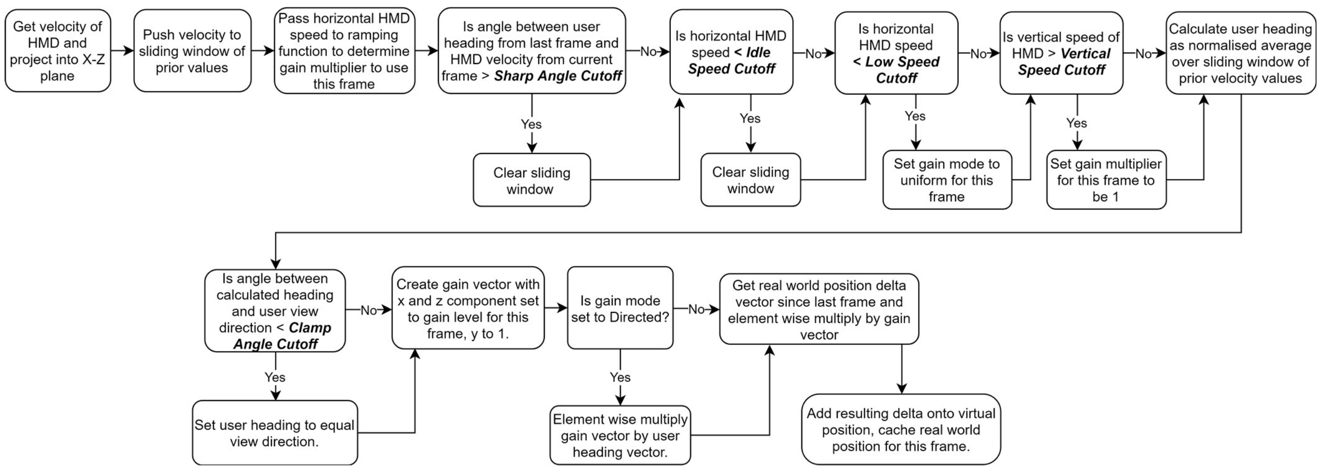

Figure 1. Flow chart for translational gain system indicating the steps taken by the system every frame of the simulation.

4. Gain System Implementation

With consideration to the movement schema and heading detection requirements presented in, a robust, flexible translational gain system with support for both directed and uniform gain is proposed. Rather than provide an overly verbose description of fine details of the system implemented for the purposes of this research, we refer the reader to the flow chart in Figure 1, indicating the main steps taken by the system at the start of each frame of the simulation. We will however briefly consider the key features of the system and how they relate to the aforementioned requirements.

4.1 Heading Detection

For detection of user heading, we propose a hybrid method which considers both a user's velocity over time and their view direction at any given instant. Every frame of the simulation the x-z components of the user's real-world velocity are captured and cached in a sliding window of some size. The system then takes all values stored in the window and uses them to calculate an average normalized heading vector. At this point the system compares this heading vector to the users current view direction projected into the x-z plane and if the angular delta between the two is below some value (*Clamp Angle Cutoff)*, sets the users determined heading for this frame to simply be the users view direction. As we wish to support free exploration, we cannot rely on the users view direction alone as it may not always align with their heading.

But for paths where the determined heading is sufficiently close to the users view direction, we can safely approximate the users actual heading with their view direction, leading to less frame by frame noise variation in heading whilst still meeting requirement 1 from section 3.2.

An important factor to consider in addition to value of the *Clamp Angle Cutoff*, is the size of the sliding window to use for getting an average velocity direction over. A larger window will result in a more stable heading over time, as lateral motion between steps will largely even out. This is desirable for meeting requirement 3, however, such a large window is problematic in that it can cause the heading detection to be slow to respond to changes in a user's path, stopping the system from meeting requirement 2. Simply discarding the concept of the window and using the user's instantaneous velocity direction at any given time would allow the system to be fully responsive but would open it up to significant noise issues and highly unstable heading detection between frames.

Fully meeting all three of the requirements laid in 3.2, and doing so for all simultaneously, is incredibly difficult, and for a non-AI based approach such as the one proposed in this research, likely not possible. Instead we must seek to obtain a balance between all three requirements, leading to a system that is responsive and flexible enough to not cause discomfort, without causing highly unstable heading values.

4.2 Slow and idle motion

In order to adhere to items 2, 3 and 4 of the movement schema, we require that the level of amplification applied to a user's motion be kept as close as possible to zero when the users speed is low. To achieve this a ramping function was implemented which gives the gain multiplier, G, to be applied at any given time as:

$$G = ramp(V)$$

Where V is the magnitude of the user's current velocity projected onto the X-Z plane, and $ramp()$ is a function defined by:

$$ramp(V) = \begin{cases} \exp(V) & if\ V \leq V_{Cut} \\ G_{Max} & if\ V > V_{Cut} \end{cases}$$

Where G_{Max} is the maximum gain multiplier that should be applied to the user's motion, V_{Cut} is the cut-off velocity above which gain is constant, and exp() is an exponential function of the form:

$$y = a(e^{bx}) + 1$$

Where the constants a and b are determined by setting up simultaneous equations using the following reference points:

$$Point\ 1 = \left(\frac{V_{Cut}}{2}, G_{Min}\right)$$

$$Point\ 2 = (V_{Cut}, G_{Max})$$

Where G_{Min} is some value close to 1 (for the purposes of this research, a value of 1.0016 was used). The choice of $\frac{V_{Cut}}{2}$ for the first reference point was made as this was found in initial testing to provide ramping functions that gave a good balance between keeping gain low at low speeds and a smooth increase up to the maximum level as users began to move. Higher values led to a sense of unresponsiveness, with the sudden kicking in of gain as speed increased being very noticeable. Lower values do not have this issue but result in higher gain at lower speeds.

From this, we obtain a ramping function of the form shown in Figure 2.

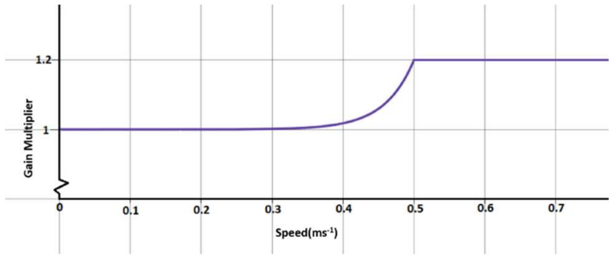

Figure 2. Example gain ramping function. In this example G_{Max} is set to 1.2 and V_{Cut} is set to 0.5ms^{-1}.

The choice to use an exponential ramping function is based on prior research pointing to this type of function resulting in the greatest sense of user control [15].

In addition to the use a gain ramping function, we can also in figure 1 that the system includes two checks related to a user's speed. The first checks to see if the users overall speed in the x-z plane is above some value denoted by *Idle Speed Cutoff.* If this is the case, then we consider the user to be idle, with any motion being the result of small idle noise movements. Therefore, any data that has been cached relating to the users heading up to this point is no longer valid, as the user now has no heading, and so it is discarded. This enables heading detection to remain responsive and quickly pick up on a user's heading once they do start to move again.

After checking if the user is idle, a second check is made on the user's speed to see if it is low but non-negligible, being below a cutoff denoted by *Low Speed Cutoff.* In this case, whilst we now assume the user has begun to move, we can't be sure that they have been moving long enough for us to accurately determine their heading., The system therefore temporarily forces the gain mode to be uniform until the user reaches a higher speed. This helps to reduce the effect of noise causing initial heading estimations to be incorrect, whilst still retaining a sense of responsiveness by ensuring that gain is still applied.

4.3 Circular Motion & Sharp Changes

Item 6 of the movement schema requires that motion occurring upon a tight circular arc not be subject to gain. Determining exactly what constitutes a 'tight' circular arc is beyond the scope of this research, but initial testing found that amplification of circular motion was much more problematic in more open environments which were better able to support sustained circular movement by a user. In smaller enclosed environments amplification of circular motion is far less noticeable, and is, to an extent, desirable, as a user's path will naturally tend to have some tortuosity when exploring a more constrained environment.

In order to detect the occurrence of circular motion, the system examines the angle between a user's physical velocity vector projected into the x-z plane in the current frame, and the heading vector determined in the previous frame. If this is angle is found to be above the *Sharp Angle Cutoff*, then the system considers circular motion to be occurring. The system then discards all currently stored information relating to a user's heading, as in the instance that circular motion is now happening none of this information is valid anymore. Note that the system implemented does not in fact disable gain at this point, despite the rule 6 of the motion schema, as due to time constraints this behavior had to be removed after initial testing with it found it to cause considerable user discomfort.

This angular delta detection logic also plays into item 2 of the heading detection requirements, that is, the ability of the system to respond to rapid changes in user heading. As well as detecting the occurrence of circular motion, this behavior also detects sudden large changes in user heading which indicate all currently stored information on user heading is likely no longer valid and should be discarded, allowing the heading of the user to immediately snap to the user's new velocity.

4.4 Hand Motion

Not shown in Figure 1 is the way in which the system ensures gain is applied only to hand tracked controller motion inherited from the user by any tracked handheld controllers. In order to this, the system tracks all such controllers in the real world by their relative position to the HMD instead of measuring their absolute world position. The virtual avatars for the controllers can then simply be positioned to always have the same relative position to the camera as they do to the HMD in the real world.

4.5 Crouch detection

In order to prevent any gain being applied when a user is crouching the system checks to see if the users vertical speed is greater than the *Vertical Speed Cutoff.* If this is true, we consider the user to be crouching and disable gain this frame by setting the multiplier to 1.

5. Experimental Setup

A study was conducted to examine the performance of the proposed gain system in both uniform and directed gain modes. Prior research has investigated the impacts of directed and uniform translational gains on measures such as user comfort and workload. Crucially however no prior research has looked at the performance of a directed gain system generalizable to free exploration, and none have attempted to perform a comparative analysis of uniform and directed gain in the context of the same task. With an interest in translational gains applicability to real world consumer level VR experiences and games, we thus set out to test the proposed system in a controlled manner featuring an environment and tasks representative of those found in a typical VR game.

5.1 Physical Environment

A 6x6m empty lab space was used to conduct the experiment, with an HTC Vive Pro [16] being used for the HMD and handheld controller. Tracking of HMD and controller position was done using the HTC Vive trackers, resulting in an effective area of 4x4m of space being used in the center of the room. The cable for the HMD was attached to a desktop running the simulation on the edge of the room by a cable. Participants were instructed to hold a controller in their dominant hand, with the cable in their free hand in order to reduce the risk of tripping. Participants were also monitored by a researcher at all times to ensure they didn't trip.

5.2 Virtual Environment

The virtual environment (Figure 3) consisted of a kitchen featuring various tables and counters around the perimeter of the environment as well as various visual props as decoration. Placed the tables were randomly selected food items. Players were tasked with collecting ingredients to bring to a preparation "machine" situated on the table at the front of the room beneath a chalkboard, upon which a list of ingredients and the users remaining time were displayed. The scale of the environment was kept static throughout.

Figure 3. The virtual environment

5.3 Experimental Task

The experimental task took the form of a short item collection style game, in which participants were tasked with collecting ingredients from the room in order to complete as many recipes as possible in three minutes. A recipe consisted of 7 randomly selected ingredients, placed at randomly selected spawn points around the edges of the room. At any given moment, a participant was required to walk to the current ingredient (denoted in text on the chalkboard a pulsing highlight shader on the object),and pick it up using a tracked Vive handheld controller. When no ingredient was held, a tracked model of the controller was rendered in the virtual environment, being replaced by a model of an ingredient when one was picked up.

After picking up an ingredient, the user was then required to bring it to the ingredient preparation machine at the front of the room and insert it by moving the ingredient object into bounds of the machine, causing it to disappear. Once all 7 ingredients had been delivered to the machine, a new recipe would begin, with its associated ingredients being spawned throughout the room. Participants began the task standing in the center of the room, facing the ingredient preparation machine. Once three minutes of

Table 1. Parameter values used for gain system during study.

Parameter	Sharp Angle Cutoff(°)	Idle Speed Cutoff(ms^{-1})	Low Speed Cutoff(ms^{-1})	Vertical Speed Cutoff(ms^{-1})	Clamp Angle Cutoff(°)	V_{Cut} (ms^{-1})	G_{Min}	G_{Max}	Sliding Window Size (s)
Value	0.5	0.15	0.45	0.5	15	0.4	1.0016	1.5	1

gameplay had passed, the participants view was faded to black, and an audio queue instructing them to remove the HMD was played.

5.4 Experimental Design

The experiment conducted was a single factor within-subjects design, with gain mode (uniform, directed or none) being the independent variable. All participants completed a run of the game under each gain mode, with the maximum level of gain being identical between the uniform and directed runs. The order of runs was randomized for each participant. After each run of the game, participants were asked to sit down to fill in a short questionnaire. This served to ensure all responses were as fresh in a participant's mind as possible, as well as helping to negate any possible cumulative effects of nausea and fatigue. At the end of each experiment participants were invited to take part in a short loosely guided interview. 8 participants (7 male, 1 female) were recruited to take part in the study and were not offered any financial incentive for their participation. Participants primarily consisted of students from the University, and all but one participant had no knowledge of the specifics of what was being tested in the prior to taking part. Throughout all experiments, parameters for the gain system were kept at the values shown in Table 1.

5.4.1 Measures

In addition to capturing detailed logs of participant movement characteristics, a variety of objective task performance measures as well as subjective user responses were also collected for each run of the game.

5.4.1.1 Performance Measures

- **Time:** The mean time taken to for to complete a recipe from the time at which it began, in addition to the mean time taken to bring an ingredient to the preparation machine from the time the ingredient became activated.
- **Grabbing Accuracy:** The mean geometric distance between the centers of the tracked controller avatar and ingredients when a user pulled the trigger to pick them up.

5.4.1.2 Subjective Measures

- **5 point Likert scales, from 'Strongly Disagree (1)' to 'Strongly agree (5)':** "My movement felt unusual", "I felt unstable while walking", "I felt unstable while reaching".
- **Simulation Sickness:** Measured using the Simulator Sickness Questionnaire [17]
- **Workload**: Measured using the NASA TLX test [18]

5.4.1.3 Movement Data

The following movement characteristics were logged for each run of the game:

- **Mean path tortuosity:** Where a path was defined as both the route taken by a user from picking up an ingredient and ending when the ingredient to placing it in the preparation machine. Or the route taken by from placing an ingredient in the preparation machine to picking up the next ingredient. Tortuosity was calculated as the arc-chord ratio of each path.
- **Virtual artefact collisions:** Collisions with virtual scene geometry were logged.
- **Mean physical speed in the horizontal plane:** Read from sensors
- **Mean physical acceleration in the horizontal plane:** Calculated from velocity
- **User position logs:** Logs of physical position of HMD each frame.

6. Results

6.1 Performance Measures

6.1.1 Time

Examining the mean time taken to for each participant to complete a recipe, we find that participants performed best under uniform gain, with a mean time of 38.3s ± 6.4s Followed closely by no gain with a mean time of 39.7s ± 10.2. Participants by far performed worst with respect to time under directed gain, with mean recipe a time of 42.3s ±10.8s. The exact same pattern is found when once considers the mean time taken to deliver an ingredient, with uniform, no gain and directed gain having mean times of 6.4s ± 1.1s, 6.6s ± 1.7s and 7.1s ± 1.8s respectively.

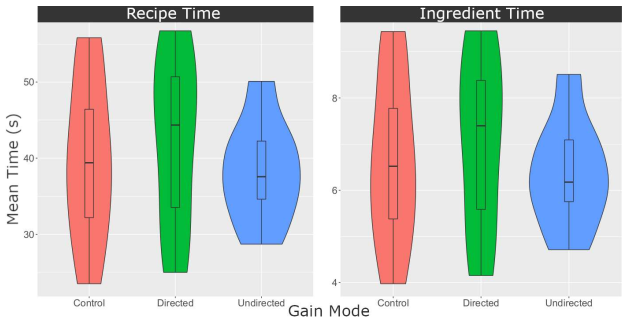

Figure 4. Mean recipe completion and ingredient delivery times for each gain mode.

6.1.2 Grabbing Accuracy

Mean grab offset was found to be largely equivalent across all gain modes; with directed, uniform and no gain resulting in mean offsets of 0.136m ± 0.004m, 0.130m ± 0.017m and 0.135m ± 0.018m respectively. When we consider the distribution of results for each mode, as shown in Figure 5, we find a notably greater spread of values for both uniform and no gain modes, with a far more compact distribution seen for directed gain.

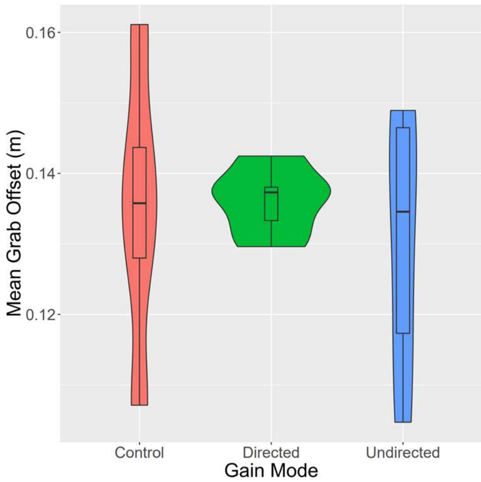

Figure 5. Violin plots of mean grab offset for each gain mode.

6.2 User Movement

6.2.1 Artefact Collisions

Artefact collisions were observed at similar rates for both directed and no gain modes, with mean collision counts of 0.4 ± 0.5 and 1 ± 1.3 respectively. Uniform gain was found to perform considerably worse, with a mean collision rate of 2.2 ± 2.5.

Table 2. Log Data

Measure	Mean Ingredient Time	Mean Recipe Time	Mean Tortuosity	Mean Velocity	Mean Acceleration	Artefact Collisions	Mean Grab Offset
Mean (No Gain)	6.6s ± 1.7s	39.6s ± 10.2s	1.25 ± 0.06	0.66 ms^{-1} ± 0.15 ms^{-1}	2.19ms^{-2} ± 0.6 ms^{-2}	1 ± 1.3	0.135m ± 0.018m
Mean (Directed)	7.1s ± 1.8s	42.3s ± 10.8s	1.34 ± 0.05	0.54ms^{-1} ± 0.13 ms^{-1}	1.91ms^{-2} ± 0.61ms^{-2}	0.4 ± 0.5	0.136m ± 0.004m
Mean (Uniform)	6.4s ± 1.1s	38.3s ± 6.4s	1.32 ± 0.05	0.51ms^{-1} ± 0.07 ms^{-1}	1.81ms^{-2} ± 0.44ms^{-2}	2.2 ± 2.5	0.130 ± 0.017m

Although as can be inferred the plots shown in Figure 6, this can in part be explained by the presence of a single outlier value of 7. Looking instead at the median collision counts as shown in Figure 6, we see that uniform still underperforms compared to directed and no gain modes.

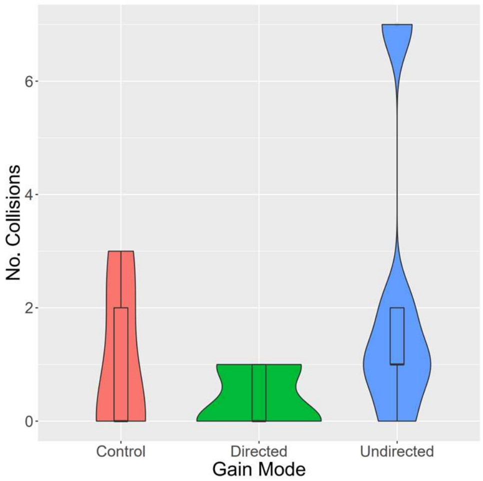

Figure 6. Violin plots of artefact collision count for each mode.

6.2.2 Position Logs

For a perfectly uniform application of gain, we would expect to see the mean interquartile range in the x and z directions of all participants paths under no gain, to be reduced by a factor proportional to the gain multiplier, given that the size of the virtual environment remained constant. Looking at the position logs for no gain obtained, we find mean interquartile ranges of 0.58m and 0.64m in the X and Z axis accordingly, and so would therefore expect to see corresponding values of ~0.4m in both directions given the gain multiplier of 1.5. For uniform gain, we find the IQR in the X axis approximately matches this expected value, at 0.41m, in the Z axis however we find a value of 0.57, which would correspond to a gain multiplier of only ~1.1. For directed gain this disparity was even more pronounced, with an IQR value of 0.60m in both axes.

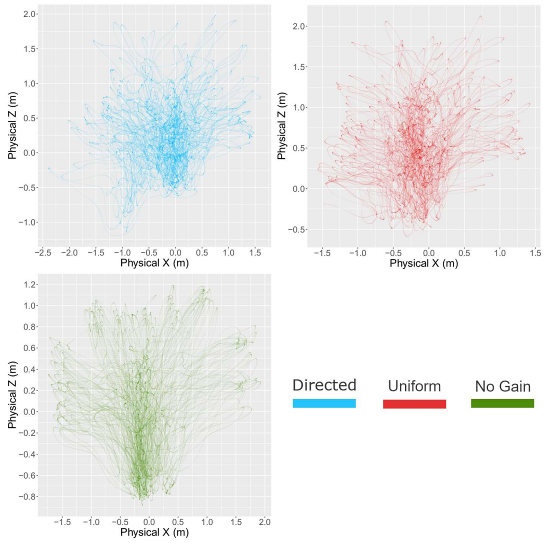

Figure 7. Position data for all participants in each mode.

6.2.3 Velocity and Acceleration

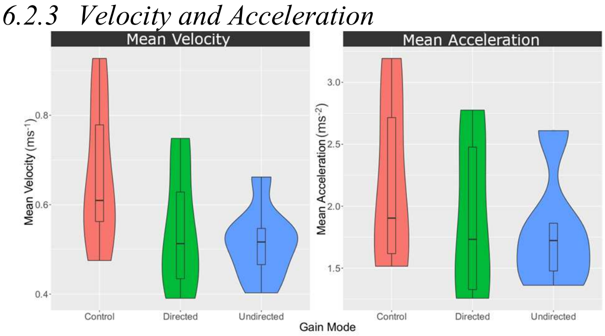

Figure 8. Violin plots of mean velocity and acceleration for each mode.

Both mean velocity and acceleration were found to decrease under directed and uniform gain as compared to no gain, with uniform gain seeing the largest reductions down to mean values of 0.51ms^{-1} ± 0.07 ms^{-1} and 1.8 ms^{-2} ± 0.44 ms^{-2}. Looking at Figure 8 we see

Table 3. Workload and sickness results

Measure	TLX mental demand	TLX physical demand	TLX temporal demand	TLX performance	TLX effort	TLX Frustration	TLX Total Workload	SSQ Score
Mean (None)	14.4 ± 9.5	20.0 ± 17.7	20.0 ± 22.2	18.8 ± 23.9	16.9 ± 16.8	6.3 ± 7.4	16.0 ± 13.5	13.1 ± 22.6
Mean (Directed)	21.3 ± 15.2	24.4 ± 16.7	24.4 ± 24.0	24.4 ± 19.3	20.6 ± 19.9	10.6 ± 9.2	20.9 ± 13	17.8 ± 25.2
Mean (Uniform)	18.8 ± 11.1	21.3 ± 18.3	24.4 ± 26.7	20.6 ± 31.0	16.9 ± 16.8	7.5 ± 8.7	18.2 ± 13.3	18.2 ± 23.2

that the median mean acceleration and velocity for both uniform and directed modes were very similar. The greater spread of values we see for directed gain explaining the disparity in mean values.

6.2.4 Tortuosity

Tortuosity as measured by the arc-chord ratio gives a value ≥ 1, where a value of 1 indicates a perfectly straight path and a value of infinity indicates a perfect circle [20]. No significant difference was found between the uniform and directed with both values being within a standard deviation of one another at 1.34±0.05 and 1.32±0.05 for directed and uniform modes respectively.

6.3 Subjective Measures

6.3.1 Workload and Sickness

The NASA TLX test scores overall task workload on a scale from 0 to 600, where lower values indicate a lower workload. Total workload scores for all gain modes were found to be low, never exceeding a score of ~40, with directed and uniform modes laying within a standard deviation of one another with workload scores of 20.9±13.0 and 18.3±13.3 respectively.

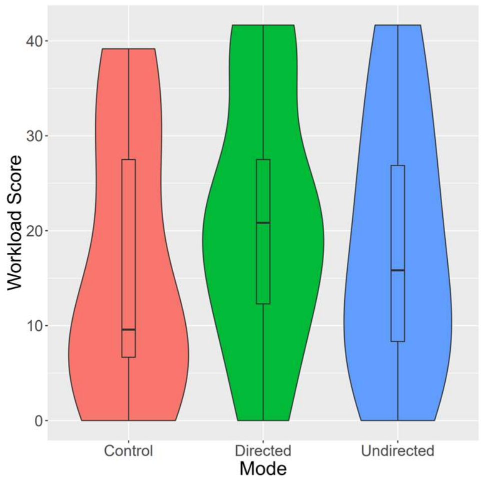

Figure 9. Overall NASA TLX workload scores for each mode.

Looking at the mean SSQ scores for each mode shown in Table 3, all gain modes have mean sickness scores below the threshold of 18.8 at which simulator sickness is suggested to become problematic [6]. Both uniform and directed gain modes produced mean scores higher than no gain, with directed gain having a slightly lower mean score. Of note is the fact that one participant in particular noted abnormally high sickness levels for all modes, resulting in a very pronounced standard deviation for all modes.

6.3.2 Likert Scales

Table 4. Likert Scale Results

Likert Measure	Unusual Movement	Unstable Walking	Unstable Reaching
Mean (None)	1.5 ± 0.7	1.4 ± 0.5	1.4 ± 0.5
Mean (Directed)	3.3 ± 1.3	2.8 ± 1.6	2.6 ± 1.4
Mean (Uniform)	2.3 ± 1.4	2.4 ± 1.4	2.0 ± 1.5

Across all questions posed to participants on a Likert scale, scores for both directed and uniform gain were significantly higher than for no gain. For all questions, the mean score for directed and uniform mode lay within one standard deviation.

6.3.3 Interview Responses

Utilizing a thematic approach, common themes were identified.

Inconsistent perception of scale

Several participants noted that the scale of the virtual environment did not feel natural when gain was applied.

P7: "*It felt like the whole world was a little off…It didn't quite feel real…. It was almost like an uncanny valley effect but of scale if that makes sense. Like it wasn't quite real in some way*".

Interestingly, multiple participants reported feeling a sense of unnatural scale when no gain was applied, and conversely felt that the scale with gain was natural.

P2: "*In the last one (no gain) it felt like the room was bigger, because I didn't move as much as I expected to when walking.*"

Responsiveness and overshooting

Multiple participants described a sense of over responsiveness, in which the gain would be applied to quickly to a user's motion making them move more than they had intended..

P5: "*Yeah particularly in the first one (directed). I'd take a step forward and go further than I thought I would, then step back to correct and again go too far, making it hard to balance.*"

P3: "*In the second one (directed) I'd say it felt too responsive. I'd walk and it would shoot forward a bit too much, when I leaned it felt like it leant too much, almost like I was going to topple over...*"

As well as causing participants to overshoot their intended position, this also led to a feeling of 'jerkiness'.

P3: "*The second one (directed) was not good, I felt really unsteady and my movement felt really jerky.*"

P0: "*I think it depends on how your gait is when you're walking. If it's more linear it's not so bad….*"

Issues with reaching

Participants highlighted this overshooting behavior as being particularly troublesome when reaching to grab ingredients.

P6: "*Biggest issue was reaching. Especially in the second one (directed). If I reached and missed, and then went to reach a little further, there were times where I would then overreach. That was when I felt I was losing my footing, going more than I intended.*"

One participant, who was observed to approach the game in a somewhat unique manner by choosing to lean as much as possible and avoid walking when possible, found directed gain to be particularly problematic.

P3: "*The second run (directed) was really awkward…My movements felt less in sync which what I thought I was doing.*"

Lateral Motion

One participant (who it should be noted, was intimately familiar with the topic and purpose of this research prior to testing) reported high salience of amplification of their motion, and in particular, their lateral motion, during the directed gain test only.

P8: "*It was noticeable that when I took a step I felt a lot of lateral motion. It was really noticeable that my movement was very exaggerated when I was moving. To the extent that I felt much more considered about my movement and walked a lot more gingerly and carefully, trying to avoid walking when I could by just reaching.*"

7. Discussion

Before we consider the results presented in more detail, it is prudent that we first address the limitations inherent to this study. For many of the results presented, whilst differences were observed between different gain modes, for the most part these were not statistically significant. Given the overall trends observed in these over several measures, it is our belief that significant differences do actually exist, but that limited sample size used in this study has resulted in outliers adversely effecting the significance of results.

7.1 Task Performance

Our findings on task performance show that with regards to time taken to complete tasks, directed gain appears to perform slightly worse than both uniform and no gain modes. Referring to table 3, we see that regarding user perception of task performance, directed gain performed considerably worse than uniform. In the context of VR gaming, this is particularly troublesome. If a player feels that they are performing poorly, this will have negative impacts on their sense of flow within the game [19]. This suggests that for task oriented virtual experiences such as games, uniform gain may be a better fit. Future research should seek to further investigate the impact of directed gain on task performance, particularly at higher levels of gain for which previous research has pointed to a multiplier of 3 being the point at which uniform gains effect on becomes problematic [6].

7.2 Simulator Sickness

The results on sickness levels align with prior work suggesting that amplification of lateral motion in uniform gain causes higher sickness levels [8]. Whilst the differences observed in this study are slight, it is possible that as the amount of gain increases, the difference may become more pronounced. Further study into sickness levels with directed gain at higher gain levels is needed.

7.3 User Movement

We saw that participants experienced significantly less collision events with virtual scene geometry under directed gain than both uniform gain and no gain. This would seem to speak in favor of directed gain increasing a user's fine motion control in VR, suggesting that directed gain may be better suited to virtual experiences which require fine grained locomotion. However, it is unclear as to whether this decrease in collisions is simply a result of users taking a more cautious approach to their movement in response to the higher sense of instability whilst walking. Indeed, referring to participant 8, we saw that they made a conscious effort to walk "*…a lot more gingerly and carefully…".* Additionally, as collisions were detected with scene geometry around the edges of the environment, it is possible that most collisions occurred during reaching. As multiple participants expressed a sense of instability when reaching, this could have led to a more careful and considered approach to reaching resulting in reduced probability for collisions.

7.4 Effective gain level and positional drift

Participant movement data revealed disparities in the expected range of motion for uniform and particularly directed gain. The cause of these disparities comes in the form of a previously undescribed phenomena we have dubbed 'positional drift', in which the mapping between the virtual and the real-world origins slowly changes over time. We believe that the source of this drift is twofold, arising partly from the gain ramping function discussed in section 4.2, and partly from an inherent, and to our knowledge previously unexplored issue, with directed translational gain. Let us consider a user, under uniform ramped gain, who slowly walks in the X direction from the center of the virtual room to a boundary. Due to their low speed, the gain multiplier remains at 1, meaning the user walked a distance, x, in both the virtual and real world. The user then walks back to the center of the room, only this time they walk at a speed above the cutoff velocity of the ramping function. Say that G_{Max} is set to a value of 2, meaning that as the user has walked a distance of -x in the virtual world, he has therefore walked -0.5x in the real world. Thus, the mapping of the of the virtual to the physical origin has been translated by (0.5, 0). This drift, combined with the limited sample size of this study, likely explains the slight disparity observed in the mean interquartile range of motion data for uniform gain. It does not however, answer the question of why the range disparity with directed gain is so much more pronounced.

Under directed gain, once the multiplier is applied to the users heading vector to obtain the gain multipliers for X and Z, the effective gain on a user's movement is reduced. Consider for example a user standing at (0, 0) in both the real and virtual world, walking to a virtual position of (1, 1), walking a distance of $\sqrt{2}$m in the virtual world. Say we have a gain multiplier of 2, one might therefore expect the user to have walked $(\sqrt{2}/2)$m in the real world. However, by applying our multiplier to the users normalized heading vector of $(\frac{1}{\sqrt{2}}, \frac{1}{\sqrt{2}})$, we can derive the following equations for the users change in physical position.

$$1 = \frac{2\Delta P_x^R}{\sqrt{2}}\ ,\ 1 = \frac{2\Delta P_y^R}{\sqrt{2}}$$

Where P^R is the users position in the real world. Solving these equations, we can thus find the users new physical position, $P^{R,}$ as $(\sqrt{2}/2, \sqrt{2}/2)$. From which we can calculate that the user has traversed a distance of 1m in the real world, larger than the expected distance of $(\sqrt{2}/2)$m, meaning the user has been subject to an effective gain multiplier of ~1.4 rather than 2. Such reductions in effective gain multiplier can cause positional drift. Consider again our hypothetical user, whose physical and virtual positions are now;

$$P^R = (\sqrt{2}/2, \sqrt{2}/2) \quad , \quad P^V = (1, 1)$$

Let us now imagine that the user walks to the virtual position (0, 1) along a heading (1, 0). Again, assuming a multiplier of two, this means that their real positional delta in the X axis can be given by:

$$-1 = 2\Delta P_x^R$$

Their new physical and virtual positions can thus be given as:

$$P^R = (\sqrt{2}/2 - 0.5\ ,\ \sqrt{2}/2) \quad , \quad P^V = (0\ , 1)$$

From this we can see that the mapping between x = 0 in the virtual world to the real world has been shifted by $(\sqrt{2}/2\ , -0.5\ )$meters. Unlike the drift seen with uniform gain due to ramping, this drift appears to be much more exaggerated, possibly leading catastrophic consequences. For several participants their directed runs came close to being prematurely halted, as they began to drift close to the bounds of the physical space as time went on. For uniform gain, the drift caused by gain ramping, whilst problematic, did not in this study reach unacceptable levels such that players would have soon hit the boundaries of the play space. However, it is not clear if this would be the case for more extended periods of use. It is not clear however if this was a result of the inherent drift in directed gain alone, or if it was instead a combination of this and the drift caused by ramping. The level of drift seen in this study could also be influenced by the choice of parameters for the gain system, and it is possible that with proper optimization of them drift could be substantially reduced.

The inconsistent effective gain multiplier inherent to directed gain, may also in and of itself be problematic. Prior research [6] has pointed to the possibility of user habituation to gain over time. An inconsistent level of gain may stand to limit a user's ability to become accustomed to the presence of it. It is also possible that this inconsistent gain is why directed gain and was singled out in interviews as having jerky movement. Users and changing their heading would be subject to a different level of gain than what they were previously. This could result in a feeling of overshooting if the user now moves with a higher level of gain than before. In room scale VR experiences, positional drift poses a significant issue to using the proposed system, particularly in directed mode. For larger games utilizing a hybrid locomotion with teleportation over larger distances, such drift is less problematic, as boundary collisions will inevitably occur. The question is would the presence of drift significantly increase the rate of these collisions over what would occur anyway. For uniform gain, the obvious solution is to remove gain ramping, although as discussed doing so is not without issues. Directional gain will inherently always have some positional drift, and as such it could be the case that it is simply not suitable for use in consumer VR experiences. Future research should seek to investigate two key questions; (1) Whether the drift introduced by gain ramping is problematic enough to cause boundary collisions over time with uniform gain, (2) Whether the problematic levels of drift observed with directed gain are inherent to directed gain as a concept, or an amalgamation of the inherent drift that does exist and the drift introduced by gain ramping.

8. Conclusions

The size of virtual environments explorable via real walking is limited by the size of a user's physical play space. Through the use of uniform translational gain, the size of explorable areas can be expanded, but this comes at the cost of amplified lateral motion and increased sickness levels. In this research, we proposed a novel approach to directed translational gain. Testing of this system found that directed gain performed slightly worse when considering task performance, suggesting that for task based virtual experiences, uniform gain may be more suitable. Analysis of motion logs revealed the presence of a previously undescribed phenomena we call 'positional drift', in which the mapping between the physical and virtual origin drifts over time, potentially resulting in boundary collisions for the user. This phenomenon is inherent to directed gain, and thus has dire implications for its feasibility as a locomotion technique moving forward. A second source of drift was also uncovered as a result of the gain ramping function that was used for both uniform and directed mode. The level of drift introduced by this is however substantially lower, although further research is needed into its effect over a longer span of time.

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