Gain Compensation in Redirected Walking

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ABSTRACT

Redirected Walking Techniques (RWTs) enable a user to immersively explore a virtual environment larger than the available physical space by real walking. RWTs are based on the use of gains (translational, rotational and curvature), which introduce a mismatch between the virtual and physical trajectories. When these gains are applied within certain thresholds, the "manipulation" is unnoticeable and immersion is maintained. Numerous research has been carried out to identify these thresholds and factors that affect them such as walking speed, environment structure or tasks involved. However, it has not been known whether users change their walking behavior when RWTs are applied and if this in turn influences ftheir perception thresholds.

In this paper, we investigate the change in users' walking behavior, particularly their walking speed, when translational gains are applied. We call this behavior **gain compensation**. 17 subjects were invited to play a shopping game where they had to walk 50 straight segments to fetch the ingredients. During each segment, one of the five different translational gains (0.7, 0.9, 1.0, 1.2, 1.4) was randomly applied and users' walking speeds were measured. Results show that there is a negative correlation between walking speed and translational gain.

CCS CONCEPTS

• **Human-centered computing** → *Virtual reality*; • **Applied computing** → *Psychology*;

KEYWORDS

redirected walking, gain compensation

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1 INTRODUCTION

Virtual reality has been gaining importance in daily life and in many research fields such as medicine, cognitive sciences, architecture, manufacturing. Thanks to the development of tracking technologies, it is now possible to perform real walking in virtual environments (VEs). Compared to other locomotion devices such as treadmills [Banton et al. 2005], walking-in-place [Usoh et al. 1999], or navigation devices such as game controllers, real walking shows better performance regarding fidelity [Nabiyouni et al. 2015] and immersion [Usoh et al. 1999]. However, if large VEs should be navigated by real walking, they need to be compressed in order to fit into a physically constrained space. In order to solve this problem, [Razzaque et al. 2001] introduced the concept of redirected walking, where a mismatch between the user's movement in the real and virtual world is applied. This mismatch, quantified as gains, could be applied on different aspects of the waking trajectory such as: translation, rotation, and curvature. To prevent users from noticing the "manipulation" and maintain immersion, these gains have to remain within certain thresholds.

Several studies were conducted to identify the thresholds for different types of gain in [Engel et al. 2008], [Interrante et al. 2007] and [Nitzsche et al. 2004]. However, [Steinicke et al. 2008] provided a precise taxonomy of the three main types of gain and performed a thorough study on human sensitivity to redirected walking. Here, the maximum values for each gain that one can apply without being noticed by the users were defined. Later, refined results on the maximum applicable gains were published [Steinicke et al. 2010], where both point of subjective equality and detection thresholds for the three types of gain were evaluated. Research effort was also spent on investigating factors that affect these thresholds. [Neth et al. 2011] reported that lower walking speed decreases sensitivity for curvature gain. More specifically, at the speed of 0.75 m/s, the curvature gain allows for a radius of 10 m, while for a higher walking speed of 1.25 m/s the radius is 27 m. [Grechkin et al. 2016] investigated how the combination with translational gain could affect the detection thresholds for curvature gain, but found no significant effects. The combined results of [Neth et al. 2011] and [Grechkin et al. 2016] could potentially imply that the application of translational gain does not change users' walking speed, or if it does, not significant enough to affect the curvature gain thresholds. Nevertheless, only a few studies were formally conducted on how the application of RWTs influences users' walking behavior. [Bruder et al. 2015] investigated the effects of cognitive load and curvature gain on walking behavior. The results showed that both cognitive demanding tasks and high curvature gain significantly increase lateral sway, and high curvature gain also lowers the performance in visual/spatial memory tasks. However, they did not show whether this change in behavior affects detection thresholds. [Zhang et al. 2014] investigated how fast translational gain can be changed without affecting detection thresholds and incidentally measured the walking speed. They observed that users reacted to the gain differently, some walked slower when the gain is increased while others behaved the opposite. The lack of formal studies and concrete results on how the application of translational gain affects users' walking behavior, particularly their speed, has therefore motivated us to perform this study.

2 METHODOLOGY

2.1 Hypotheses

Firstly, the translational gain g_T in our study is defined as

$$g_T = \frac{v_{virtual}}{v_{real}} \quad (1)$$

where $v_{virtual}$ is the perceived speed in the VE and v_{real} is the physical walking speed . A translation gain less than 1 means the user moves slower in the VE than in real life, and vice versa. To investigate the possible existence of a gain compensation behavior under the application of translational gain g_T, the study should confirm or reject the following two hypotheses:

- **H1**: The applied translational gain g_T has an effect on physical speed v_{real}.
- **H2**: The applied translational gain g_T linearly correlate with physical speed v_{real}.

2.2 Gain Selection

Since it is unknown if users compensate for the applied gain, and if they do, whether it is conscious or not, we investigate both cases of perceptible and non-perceptible gains. These gains are chosen based on the psychometric curve obtained in [Steinicke et al. 2010].

- $g_T = 1$: no redirection is applied, users' walking speed in this case is used as the base line.
- $g_T = 0.9$; $g_T = 1.2$: these gains lie within the detection thresholds, both corresponding to 70% detection rate and are considered non-perceptible.
- $g_T = 0.7$; $g_T = 1.4$: these gains lie outside the detection thresholds, both corresponding to 90% detection rate and are considered perceptible.

Due to the anterior-posterior and medial-lateral body sway during human walking, the application of these translational gains on all motion directions would result in unnatural diminished/amplified body sway and potentially cause a break in immersion. Therefore, the gains are only applied to the predicted forward direction based on users' past trajectory.

2.3 Experiment Design and Procedure

Since the aim of this study is to investigate the users' behavior under the application of translational gain, it is necessary that the study should guide the users to walk naturally on a straight path a significant number of times, during which their speed could be measured. The task should not be too repetitive to keep the users engaged, but also not too demanding, which may cause increased lateral sway [Bruder et al. 2015]. The design of this experiment therefore revolves around these requirements.

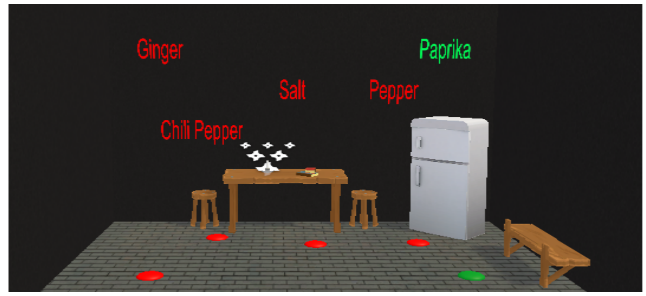

Figure 1: A scene in the study

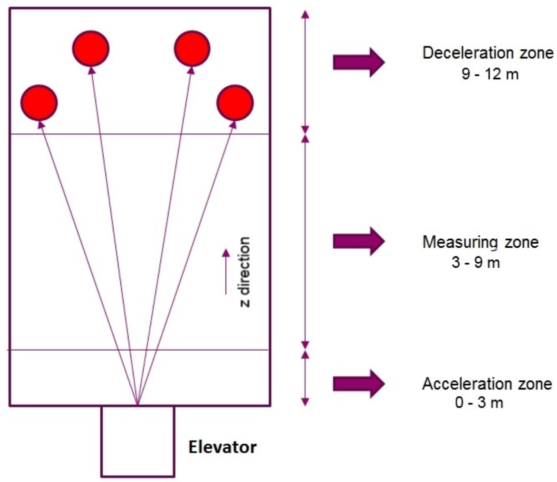

Figure 2: Basic layout of the rooms and the measuring zone.

The VE is modeled as a multi-story grocery store, where ingredients can be found on different floors. In the study, the users are required to choose 5 different recipes and find their way around the store to fetch the ingredients. After selecting a recipe, a specific ingredient is shown to the users and they proceed to a particular floor using the elevator to fetch it. To pick up the ingredient, users naturally walk on a straight path from the elevator to a location on this floor which is highlighted by a green circle and the corresponding green text (Figure 1). Once the ingredient is picked up, the users walk straight back to the elevator to proceed to the next floor. During these back and forth walks, one gain from Section 2.2 is randomly selected and applied while users' positions are recorded. Recording is activated only in the measurement zone (Figure 2), where a constant walking speed is assumed. Walking speed was not measured directly, but was calculated based on the distance the users walk and the amount of time it takes them to travel this distance.

2.4 Experiment Setup

The setup consists of an Oculus DK2 head mounted display (HMD). The optical tracking system Intersense IS-1200 is attached to the HMD and provides 6 DOF position tracking at a rate of 180 Hz. The system is powered by a backpack-mounted laptop. Models are free assets from Unity, and the game play was also made with Unity. The environment was optimized to run constantly at the HMD's maximum frame rate of 75 Hz. A wireless mouse is utilized for

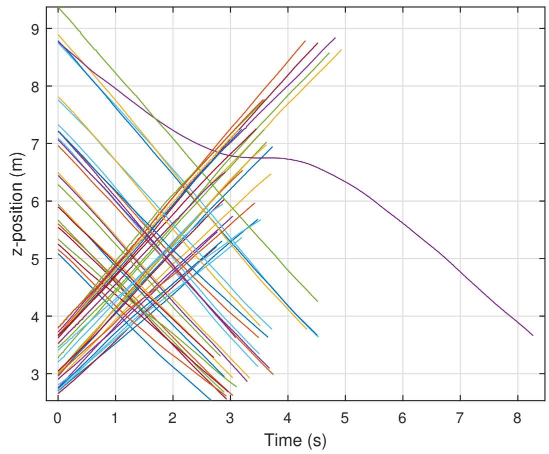

Figure 3: Example plot of all the measured paths of a subject.

Table 1: Average walking speed per gain

Gain	0.7	0.9	1.0	1.2	1.4
Speed (m/s)	1.2375	1.1914	1.1726	1.1110	1.0629

users' interaction with the environment such as selecting a floor in the elevator or fetching the selected ingredients. The available tracking space is 12m x 6m.

2.5 Participants

17 subjects, aged from 20 to 56 ($\mu = 27 \pm 5.2$), 14 male and 3 female, were students and staff of the department. 8 subjects had no experience with virtual reality, while 9 had some or a lot of experience. All have normal or corrected vision. The subjects were not informed about the purpose of the experiment. Prior to the experiment, the task is explained to the subjects and then they have the opportunity to walk around for a few minutes to get familiar with the VE. Over the course of the experiment, each subject was exposed to all five different gains and each gain was evaluated 10 times per subject, yielding 17 x 5 x 10 = 850 measurements.

3 RESULTS AND DISCUSSION

During the experiment, subjects did not always behave as expected. In a few cases, they suddenly stopped walking and looked around before proceeding further. The speed from these cases is not what we want to measure. These cases are visually detected and removed by plotting each user's position over time (Figure 3). After this step, 17 measurements out of 850 were discarded. For each of the 17 subjects, 5 averaged walking speeds are calculated for the 5 corresponding gains, resulting in 17 data points per gain which compose our data set. The speeds corresponding to the same gain across all subjects are then averaged and the summary can be found in Table 1.

3.1 H1: Applied translational gains have effect on physical walking speed

Firstly, the assumptions of normality and homogeneity of variances are verified using Shapiro Wilk tests of normality ($p > 0.05$) and

Table 2: p-values of the pairwise comparison (with Bonferroni correction) paired sample t-test for the null hypothesis H$_0$: $\overline{\mathbf{x}}_{g_1} = \overline{\mathbf{x}}_{g_2}$ (where $\overline{x}$ is the mean speed and g_1, g_2 are gains)

g2 \ g1	0.7	0.9	1.0	1.2	1.4
0.7					
0.9	0.066				
1.0	$9.6e-04$	0.801			
1.2	$2.8e-06$	$1.3e-07$	$1.6e-05$		
1.4	$8.1e-08$	$8.7e-11$	$8.7e-07$	$2.5e-04$	

multi-sample tests for equal variance ($p = 0.9939$). A one-way between subjects ANOVA then was conducted to compare the effect of applied translational gain on walking speed in five gain conditions: 0.7, 0.9, 1.0, 1.2, 1.4. There was a significant effect of applied translational gain on walking speed at the $p < 0.05$ level for the five conditions [$F(4, 80) = 5.73, p = 0.0004$]. Post hoc comparison using multiple comparison paired sample t-test together with the Bonferroni correction indicated that the mean speed for the no gain condition ($g_T = 1$) was significantly different than the $g_T = 0.7$, 1.2 and 1.4 conditions ($p < 0.05$), but not significantly different from the $g_T = 0.9$ condition ($p = 0.8$). A summary of the results can be found in Table 2. The $g_T = 0.9$ condition, despite having the same detection rate as $g_T = 1.2$, does not significantly affect the walking speed, suggesting that perception of gains is not the cause for this compensation behavior. Instead, these results suggest that gains (perceptible or not) that are different enough from 1 do have an effect on walking speed. [Neth et al. 2011] found that lower walking speeds result in higher curvature detection threshold in the case of no translational gain ($v_{virtual} = v_{real}$). However, when combined with translational gain where $v_{virtual} \neq v_{real}$, it is unclear which speed ($v_{virtual}$ or v_{real}) is the factor that affects curvature gain thresholds. Let the baseline virtual and real speeds of a user under no gain condition be $v_{virtual_0} = v_{real_0}$. Due to the gain compensation behavior, the subjects do not maintain a constant real speed (blue line in Figure 4) nor a constant virtual speed (black line in Figure 4) but adapt their virtual and real speeds to be $v_{virtual_1}$ and v_{real_1} such that they satisfy Equation 1 but $v_{virtual_1} > v_{virtual_0}$ while $v_{real_1} < v_{real_0}$ in the case $g_T > 1$. If virtual speed is the only significant factor, then with $g_T > 1$ a lower curvature gain should be used. However, if real speed is the only significant factor, a higher curvature gain could be used. Nevertheless, we have observed in our other curvature gain threshold studies that both visual flow (related to virtual speed) and body awareness (related to real speed) seem to affect detection thresholds. Since virtual speed and real speed have opposite effects on curvature detection threshold, it is unclear what the effect of their combination is. [Bruder et al. 2015] presented findings that a combination with translational gain does not affect curvature gain thresholds. This could mean that the effects of virtual speed and real speed may have canceled each other out. However, it has been mentioned in [Bruder et al. 2015] that the number of participants was relatively low for a threshold detection test. Additionally, the pseudo-2AFC method is biased and the constant stimuli method requires significant number of repetitions to be accurate, which was limited in [Bruder et al. 2015]. These factors could be "noisy" enough to have overwritten the potential effect.

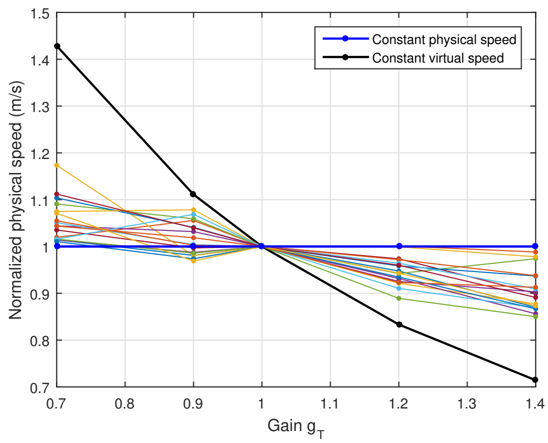

Figure 4: Normalized speed of all subjects

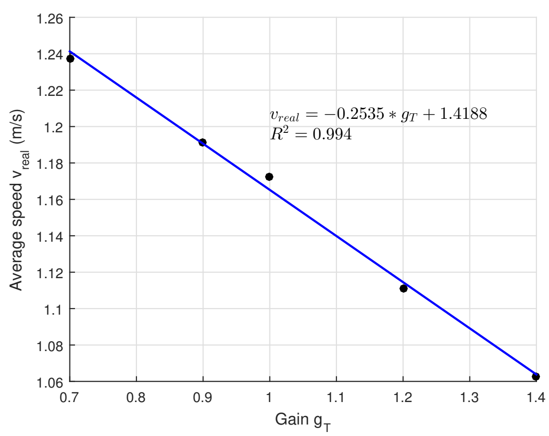

Figure 5: Fitted line obtained from linear regression

3.2 H2: Applied translational gains linearly correlate with physical walking speed

Linear regression coefficients were calculated from the average results in Table 1 to assess the relationship between translational gain and walking speed. The equation

$$v_{real} = -0.2535 * g_T + 1.4188 \quad (2)$$

was obtained with goodness of fit $R^2 = 0.994$. Figure 5 summarizes the results. Linear hypothesis test on the slope of the fitted line returns $p = 0.0001$. Therefore, the null hypothesis that the slope equals 0 is rejected. Taken together, our results suggest that there is a linear relationship between translational gain and walking speed, defined by Equation 2. The results obtained do not comply with the observations in [Zhang et al. 2014] that some subjects walk faster while others walk slower when gain is increased. This could be due to the fact that their study was not primarily designed to study this behavior, and therefore could have contained some factors that affect the result. Figure 4 clearly shows a common trend that almost all subjects walk faster when gain is decreased, and slower when gain is increased.

4 CONCLUSIONS AND FUTURE WORK

In this paper, we studied the influence of applied translational gain on users' walking speed in virtual environments. It was shown that there is a linear relationship between translational gain and walking speed described by Equation 2. We also found that users modify their speed when the gain significantly differs from 1, regardless of whether the gain is perceptible or not. A large-scale study is still needed to thoroughly investigate the effect of combining translational gain with curvature gain on curvature detection thresholds. The result from this would be useful for practical applications where translational gain and curvature gain could be optimally combined to maximize the efficiency of redirected walking.

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