Breaking the Tracking: Enabling Weight Perception using Perceivable Tracking Offsets

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Figure 1. We propose a solely software based approach of simulating weight in VR by deliberately using perceivable tracking offsets. These tracking offsets nudge users to lift their arm higher and result in a visual and haptic perception of weight.

ABSTRACT
Virtual reality (VR) technology strives to enable a highly immersive experience for the user by including a wide variety of modalities (e.g. visuals, haptics). Current VR hardware however lacks a sufficient way of communicating the perception of weight of an object, resulting in scenarios where users can not distinguish between lifting a bowling ball or a feather. We propose a solely software based approach of simulating weight in VR by deliberately using perceivable tracking offsets. These tracking offsets nudge users to lift their arm higher and result in a visual and haptic perception of weight. We conducted two user studies showing that participants intuitively associated them with the sensation of weight and accept them as part of the virtual world. We further show that compared to no weight simulation, our approach led to significantly higher levels of presence, immersion and enjoyment. Finally, we report perceptional thresholds and offset boundaries as design guidelines for practitioners.

ACM Classification Keywords
H.5.2. User Interfaces: Interaction styles; H.5.2. User Interfaces: Haptic I/O

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Author Keywords
Weight perception; virtual reality; pseudo haptics.

INTRODUCTION
Virtual reality (VR) Head-Mounted Displays (HMDs) are recently being released as consumer products (e.g. Playstation VR, Oculus VR, HTC VIVE) and are currently strongly promoted by the entertainment industry. One of the big advantages of VR HMDs is the level of presence and immersion they are capable of creating. While prior research on VR has traditionally focused on technical or visual aspects to increase the immersion, haptics has recently been identified as one of the missing aspects which has also a significant impact on immersion and presence. In this paper we focus on one specific aspect of haptics, namely *weight*.

Currently, there are two approaches to simulate weight in VR, either using a physical actuator [21, 2, 31] or through visual indicators [15, 16, 22, 23]. A drawback of physical actuators is that they require a modification of the used controllers, and that there is currently no technology or mechanism which is capable of fully and realistically simulating the sensation of weight. Software modifications share the advantage that they can be applied in most of the currently available VR devices, but are limited in their expressiveness in creating a perception of weight, since visual cues are used as subtle as possible to let users be unaware of any manipulation. In this paper, we present a software based approach capable of simulating a visual and a haptic perception of weight for tracking-based VR devices (e.g. Oculus Rift, HTC VIVE).

Our solution consists of intentional and controlled offsets in the positional tracking of the hands or controllers. This creates the visual sensation of weight by nudging the user to lift the arm higher to perceive some form of additional exertion. This exertion can further be associated with holding an object having a certain weight (fig. 1). We present a spring-like model and its implementation in Unity3D capable of generating the sensation of weight using a simple software modification. We further conducted an initial user study, showing the success of our approach in simulating weight and fathoming the acceptance threshold of users in terms of shifting offsets. In a second user study, we quantified the impact of our weight simulation on immersion, engagement and enjoyment, showing significant improvement over the current state of the art (no weight simulation). In a final step, we quantified the granularity of the detection thresholds of offsets using a *two-alternative forced choice* study and provide those as guidelines of how to deploy our approach in current applications.

The main contributions of this work are:

- A solely software based approach (perceivable tracking offsets) for simulating weight sensations (visual and haptic) for tracking based VR applications.
- A study showing the increase of enjoyment, engagement and presence using the proposed weight approach compared to no weight simulation.
- Quantifying the perceptional threshold and weight boundaries, as design guidelines for practitioners.

While prior research that used tracking offsets to simulate haptics mainly focused on concealing them from the user, our approach embraces them. To the best of our knowledge, we are the first to deliberately use perceived tracking offsets as a form of communicating haptics. This allows a far larger design space. We argue that our approach can easily be implemented inside all current tracking based VR interactions and results in a significant better (immersion, enjoyment and presence) experiences than the currently non-existent simulation of weight.

RELATED WORK

Multi-sensory feedback plays a significant role for presence in VR applications [6, 10], with haptics being one of the most important senses. There are different features of an object that can be explored based on haptics, like texture, hardness, temperature and weight [19]. All aspects are part of current VR research, while we focus on the latter one - the simulation of weight. For this, currently two main approaches are being researched. First, the simulation of real weight of a grabbed virtual object by exerting actual forces in the real world, and second, the use of visual features called pseudo-haptics.

Real Weight Simulation

Current controllers, like the ones of the Oculus Rift or HTC Vive, as well as tracking devices (e.g. Leap Motion), ignore kinesthetic feedback. It is difficult to physically represent different weights, since a controller has only one specific mass. Nevertheless, several research projects were published that try to overcome these limitations.

Ryuma Niiyama et al. [21] propose a weight-changing system using liquid metal that is pumped into the grabbed object. They were able to dynamically control the weight between 0.5 g/cm^3 to 3.2 g/cm^3. Another approach is the elastic arm [2, 1] which is based on an elastic armature mounted between the user's hand and shoulder. When extending the arm, users feel the resistance of the stretched bound.

Shifty [31] is a prototype which consists of a rod where a movable weight is mounted. The center of mass is shifted when this weight moves between the grip and top end of the rod. The user is then able to feel the change of rotational inertia. Yamamoto et al. propose shaking interaction [30], a system that simulates inertial forces while shaking. The forces are generated by accelerating a weight and apply in the axis of motion. The object's weight cannot be perceived while resting, though.

A work that is not about weight simulation, but about haptics regarding touch combines cognitive features of multi-sensory integration and visual dominance with real haptic feedback is presented by Kohli et al. [12]. They propose redirected haptics, warping the virtual space to match real geometries. Using their approach, a variety of virtual objects can be mapped onto a single real object to provide a feeling of touch. A similar approach was proposed by Azmandian et al. [3].

Physical weight representations allow the perception of weight over multiple senses and most likely provide the most realistic feedback in VR. Though such devices have their limitations regarding weight or comfort and most important require additional hardware which may not be available.

Integration of Haptic and Visual Sensations

Besides the attempt of generating real weights and forces, research suggests that our perception of weight – or haptic in general – is a multi-sensory process, which most of all depends on the integration of visual and haptic cues.

Our general perception is based on a variety of different senses that have to be merged [28, 9]. This is similar to the perception of object properties, which depends on different senses (particularly haptics, proprioceptive and visual ones). Rock and Victor [26] for example investigated the influence of visual information on the perceived size of an object. They found that vision had a larger effect on the size perception than haptics. Ernst and Banks [8] proposed a statistical model of visio-haptic integration, stating that the influence of each sense is dependent on the actual performance of the single sense. As visual stimulus, they used a dot stereogram as background plane, while displacing the dots to add noise to the visual sense. The influence of visual information on the perceived size depended on the applied noise.

Manipulating virtual objects requires a spatial mental model of the virtual environment, but in VR there is often only a single channel providing the necessary information. Biocca et al. [5] therefore hypothesized that participants would experience a form of visio-haptic cross modal transfers when interacting with virtual objects. They conducted an experiment in which participants manipulated objects in VR without haptic feedback and reported on haptic sensations. They could show that haptic sensations correlated with sensations of spatial and sensory presence.

The presented works show the importance of visual cues on haptic perception and are the fundamentals of pseudo-haptic feedback approaches. Since our approach is only based on visual features we build on the presented insights. While real weight perception should not include sensory mismatches (e.g. between the proprioceptive and visual one), we deliberately include such mismatches without the restriction that the manipulation of visual features should not be perceived. Redirecting motions in VR was e.g. done to enhance the perception of slow motion [25], where participants did not report on a loss of control. We found that participants liked obvious offsets as a weight representation and accepted them as part of the virtual world. We also implemented such an approach for general kinesthetic feedback and coupled the pseudo-haptic effect with vibration [24].

Pseudo-Haptics

Pseudo-haptic feedback is to provide haptic sensations without the actual matching haptic stimulus, but instead by inducing those sensations using vision [13]. Visual feedback is provided synchronized to motions or actions of users. Due to the sensory integration while generating haptic perceptions, it is possible to create such haptic illusions based on visual features.

Several experiments were conducted that show how pseudo-haptic feedback can be used to create several haptic illusions. For example, friction was implemented by manipulating speed and size of a mouse cursor [15, 16], stiffness was simulated by visually offsetting the hand position on a computer screen [27] or a multi-modal combination of force and displacement using a 3D mouse [17, 14]. Different object shapes were visualized by displacing the visual representation of the user's hand to match the object's surface [4]. Lécuyer et al. contributed that participants perceive friction, gravity or viscosity, when a virtual object was slowed down using a 2D and a 3D mouse [18]. Pusch et al. [22, 23] used visual hand displacements to create the illusion of resistance of wind in VR. In their results, 9 out of 13 participants stated that they could actually feel some kind of force that was pushing their hands.

J'auregui et al. [11] used different animations of lifting objects of different weights recorded by a motion capturing system. When applied on a virtual avatar they could show that these animations of a virtual avatar influence the perception of weight.

Dominjon et al. [7] used a pseudo-haptic approach to simulate weight. Participants compared the weight of virtual balls, seen on a computer screen, while lifting a real ball. When the visually sensed virtual motion of the object was amplified, they could observe, that the weight was perceived as less.

The approach of Dominjon et al. [7] to visually amplify motions in VR to simulate different weights shows promising results regarding weight perception simulation. As Biocca et al. [5] stated, haptic illusions even increase with the perceived spatial and sensory presence. We assume, that such effects even apply stronger in immersive VR scenarios, so that visual induced haptic perception increases with technical advancement. Though the presented results can not be applied directly to the context of VR, since they were exploring indirect manipulation (not 3D interaction) using a hidden static controller and a 2D representation on a screen. The sense of proprioception to locate the arm and hands in 3D space and the stronger sense of virtual body ownership are unique to VR and both potentially breaking with the use of offsets in tracking. In addition, there are no results beyond investigating the general idea of pseudo-haptics. Such effects were never applied to actual applications diminishing the value for practitioners, nor is there any guidance on how to apply such effects in VR applications. In addition, the current suggested pseudo-haptic implementation is not suitable for VR applications. When constantly amplifying motions, the offset will also constantly increase to the actual tracking, since lighter objects would constantly move faster than the actual hand. Though short interactions with lighter or heavier objects could be displayed, this approach is most probably not suitable beyond the short time of lifting an object.

We therefore developed an own model, based on prior works and not only tested perceptual thresholds, but also explored the design space as well as effects on weight perception in a VR gaming application.

WEIGHT MODELING APPROACH

The presented prior work showed the influence of visual feedback on haptic perception and that visual feedback can be modified to generate pseudo-haptic effects. Pseudo-haptics mainly focus on presenting subtle effects that are barely perceivable by the user and therefore only allow for small deviations of the perceived weight. Our idea is to take this approach one step further by including obvious offsets between the tracked and the visual position of the hands to generate a wider range of perceivable weights. Our approach uses two forms to convey the perception of weight: (a) obvious visual offsets for the visual sense (b) nudging the user to lift the arm higher for the haptic sensation.

Idea

We designed a weight metaphor based on a force model, without increasing the tracking offset, even during longer interactions. When considering the physics behind lifting an object in a simplified way, there are two forces that work against each other. The first one is the gravity, pulling the object towards the ground. The second one is the force which a person applies to lift the object. When lifting a heavier object, one has to increase the force and to strain one's muscles to a greater degree. This also makes up for the difference between lifting a virtual object, and a real one – the required force remains the same with virtual objects, as the controller weight never changes.

If different weights shall be presented, the forces that pull objects down also have to differ. The same amount of force needs to be applied in the opposite direction to keep it in the same height. Since there is no such force in VR, we define an offset vector between real tracking position and visually displayed position as a force vector. This offset force increases with the tracking offset until both, the weight and the offset force are equal. Therefore the lifting of heavier objects results in a larger offset. This indirectly results in a stronger perceived force a user has to apply to lift a heavier object compared to a lighter one.

Instead of a constant spatial offset between tracked and visual position the described mechanism acts like a spring between the tracked position and the actual visible one, while the visual hand is pulled down by the object's virtual weight. Furthermore, our approach considers inertial properties of the virtual object. We design heavier objects in a way they need more time to accelerate and to slow down. By applying these features we aim to create a visual perception of object's weights close to real physics behaviour.

However, we also had to implement a solution for the moment of grabbing. Using the previously described mechanisms a grabbed object (including the virtual hand) would fall down after the object was grabbed due to the applied weight force. We therefore decided, to increase the presented offset while lifting the object. As the virtual object falls down in the moment of grabbing, the visual position remains the same until the hand starts moving. The visual position then adjusts towards the virtual object's one while lifting. An object therefore moves slower during the first lifting. The heavier the object, the slower it starts moving.

Implementation

Basic Approach

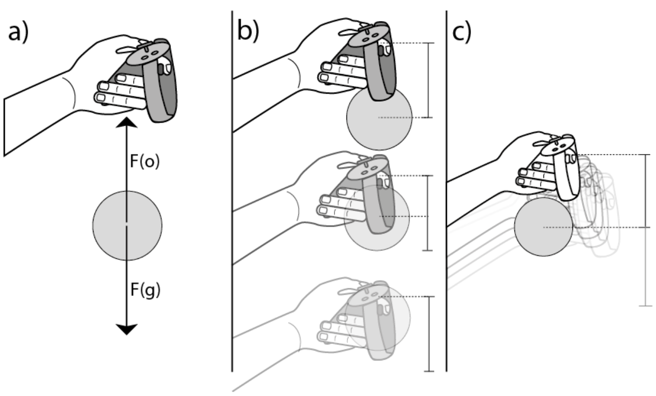

Figure 2. a) When an object is grabbed it is pulled down by the weight force (F(g)). The imaginary force (F(o)) is working against the weight force and increases with the offset between visual and tracked position. b) When an object is grabbed, the visual position first remains on the tracked position. While lifting, the visual position is shifted towards the object one's. c) The faster an object is moved, the more the visual position is shifted towards the tracked one.

To implement our approach, we divided the process of positioning the virtual hand and the object in two parts. The first one is the real hand's position as tracked by the sensor. The second one is an imaginary object (that is not necessarily displayed) which is described by its position, current velocity and a weight value. The movement of the object is influenced by two forces. The first one is the weight force, which is $F(g) = m \cdot g$, where g is the gravitational acceleration (around $9.81 m/s^2$ at sea level). The second one is an imaginary force that acts in the opposing direction which we further on call offset force ($F(o)$). The offset force is calculated by a function that multiplies a constant value (c in m/s^2) to the actual offset in meters. The offset force is a metaphor for the higher effort we have to expend when holding a heavier object. It can be compared to a spring applied between the tracked hand and the object with the constant c being the stiffness of the spring. Both forces are added to the object's velocity. The velocity is then applied to the current position of the object. The updated position of the object is therefore dependent on its last velocity (v_{t-1}), its last position (P_{t-1}) as well as the forces $F(g)$ and $F(o)$ and is calculated as follows.

$$P = P_{t-1} + v_{t-1} + \Delta t \cdot (F(g) + F(o)) \tag{1}$$

with

$$F(g) = m \cdot g \tag{2}$$

with m being the object's mass and g being the gravitational acceleration

and

$$F(o) = c \cdot o \tag{3}$$

with c being an imaginary constant and o being the offset between the object's position and the tracker's one

An equilibrium of both forces ($F(o) = F(g)$) defines the actual position where the object comes to rest (see figure 2). If the imaginary constant c is defined the same value as g, the final offset therefore would be equal to the object's mass.

Adding Inertia

Only applying these two forces would result in a maximum of inertia. When again considering the example of a spring, the object would take a longer time until being in rest, resulting in wobbly movements. We therefore apply a third force that slows down the object and is defined as a vector equal to the inverse direction of the object's current velocity. Depending on the object's weight, this force is scaled. Lighter objects follow the tracked movements very closely, while heavier objects accelerate and also slow down at a lower rate to enhance the feeling of the actual weight of the object. The heavier the object, the larger the magnitude of the inverse velocity vector during movements, while resulting in a smaller magnitude while resting.

The Grabbing Process

To prevent the object including the virtual hand from falling down directly after grabbing, we shift the actually displayed position according to the distance the hand was moved since grabbing started in relation to the offset. As soon as the hand moved as far as the magnitude of the tracking offset, the offset is continuously displayed. We illustrate this feature in figure 2. Until the offset is reached, the position of the virtual hand and object are calculated by:

$$P = P_H + \frac{\|(P_G - P_H)\|}{\|Offset\|} \cdot (P_O - P_H) \tag{4}$$

with P_H being the tracked hand's position, P_G the position where the object was grabbed, and P_O the object's position

The Influence of velocity

The last property we included for the simulation is another shifting between the tracked hand's and the object's position depending on the current velocity of the hand. While moving the hand, the visually displayed position of hand and object therefore get closer to the tracked position. We designed this feature to have only little influence. Though it is designed to support the metaphor of putting more effort into moving an object with a higher velocity of the hands, which in our case leads to less tracking offset. This feature is illustrated in figure 2 c).

FIRST STUDY

After implementing the system, we conducted a first study, with the goal of investigating how participants would perceive and interpret the described effects. Another goal was to find out how far we could go – how much offset between the actual and the visually sensed position could be applied until a user is no longer willing to accept the presented weight metaphor.

Procedure

The participants were welcomed and thanked for their interest. They were told that they could abort or pause at any time, signed a consent form and filled in a demographic questionnaire. In order to get answers that are not biased in any way, we first only introduced them to the used hardware (Oculus Rift CV1 with Touch controller), and instructed the participants to grab objects by pressing a trigger on the controller. None of the participants were informed about the topic of weight simulation. The presented scene was minimalist – only including a skybox and two equally sized spheres with the same neutral white texture on it. Then the participants were instructed to grab and lift the first sphere (which was the *lighter* one) with a resulting tracking offset of around 2 cm. When the object was released, it was reset to the initial position immediately without any animation. This was a measure to prevent communication of any other information regarding the object properties but the ones created by our algorithm. Afterwards, the participants grabbed the second and *heavier* object which resulted in a tracking offset of 8 cm. While doing so, the participants were allowed to lift both objects as often as they desired. We then asked the participants to think aloud about differences between both objects.

In the second task, the participants were instructed to lift several virtual objects onto a displayed box, while after each task, the virtual weight varied. We deactivated the initial lifting process, so that the sphere including the visual hand fell down as soon as the object was grabbed. This was done, because we wanted to know how much offset the participants would accept in VR, which would have been biased due to the slow offset increase during the lifting process. We asked the participants to state whether they would like to have the presented weight metaphor in a VR application, if they would accept it or if it would not be suitable. We presented 14 different weight offsets ranging from 10 cm to 64 cm. The weights were presented in a random order. After each weight was presented we repeated the procedure for another three times – again in a different random order.

Participants

We recruited ten participants (7 male, 3 female) with a mean age of 28 (standard deviation 1.5). We also asked them to state for how long they have been using VR systems in months before. The range was between 3 and 48 months and a mean of 19 months (standard deviation 14.6).

Results

When the participants were asked to think aloud about the two differences of both spheres, the first assumptions varied. Three stated that there would be no difference, while four instantly stated that the two spheres differed in weight. One participant first stated that lifting the *lighter* sphere felt like holding a Christmas ball while the other one felt more like a bowling ball. One participant stated to perceive the tracking offset. Other associations were about different inertia, or that one sphere would pull the hand downwards. Each participant except one came to the point of associating the different offsets with a different weight within 30 seconds of thinking aloud. One participant even stated to actually feel the weight while holding the heavier object.

In the next step, the participants had to lift spheres of different *weights* which resulted in an offset between 10 and 64 cm and were asked whether they would like to have such a weight representation, or would accept it or if it would not be suitable. There was one participant stating to fully accept the metaphor of weight resulting in offsets. If the offset was too high to lift the object, he compared it to an object that would be too heavy for him to lift in reality. Since this opinion was unique regarding the other participants, we excluded this participant from the following results. The participants repeated each weight four times and we compared the acceptance between the first and last iteration to see whether participants would get used to the metaphor. All participants rated the weight representation as *good* until an offset of 20 cm in the first iteration and accepted an offset of around 35 cm. These values increased in the last iteration to 24 cm (good) and 42 cm (accept).

SECOND STUDY

The first study provided the information that participants interpret the presented tracking offsets as weight and also about how far such an approach could go. The aim of the second study was to gather insights on how such a metaphor would influence presence, enjoyment and the perception of weight and consisted of three tasks. For the first one, we designed a bowling game, where the participants could either lift the balls with or without our metaphor. After the ball was thrown, the weight was equally treated by the physics engine in both conditions. The second task was designed to find out more about detection thresholds – how much offset is required to enable people to distinguish virtual weights. The third task was quite short and only had the goal of getting real, absolute weight associations using our virtual representation.

Procedure

The participants were first welcomed and thanked for their participation. They were then told that the study was about weight representation in virtual reality and that there were

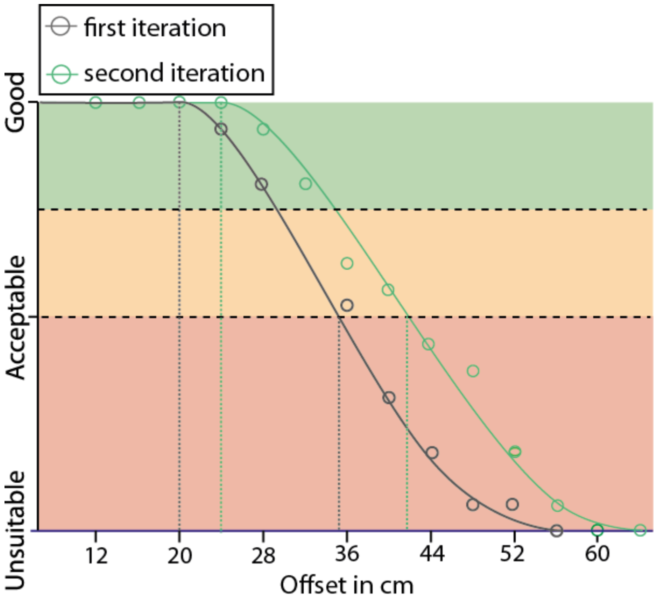

Figure 3. Plot of the participant ratings of different presented offsets as well as the trend line. The green area includes ratings where at least 50% of the participants rated the offsets as a *good* metaphor, the yellow area includes offsets which were accepted by all participants. The red area includes values which were not accepted by all participants.

three tasks, including two games of bowling. Each participant was also told that he or she could abort or pause at any time if they did not feel well. The mechanisms (e.g. offsets) that were used to represent weight were not explained to the participants. After this introduction, each participant signed a consent form and filled in a demographic questionnaire. In the next step, the participants were introduced to the VR glasses and the used controller, as well as its functionality. If there were no more questions, they started to play the first game of bowling, either with or without our weight metaphor. The order was counter balanced over the number of participants to overcome any biases that could arise by having each participant starting with the same condition. After the first game, which took about four minutes, the participants were instructed to fill out three questionnaires, including the Witmer-Singer presence questionnaire[29], the E^2I [20] questionnaire as well as our own questionnaire. The participants then played a second game of bowling, either with or without the presented weight metaphor (depending on the condition they started with). After the second game, the participants again filled out the mentioned questionnaires. Then a last questionnaire was presented including free textual feedback, as well as some comparative questions.

The next task was a two alternative forced choice (2AFC) task in which the participants should lift two equally looking, same sized spheres and should tell which one was the *heavier* one. Since such a method requires many iterations, the participants had to compare the two presented spheres for 120 times. This includes five weight steps applied on two different origin weights. Each comparison was repeated 12 times. The order was fully randomized. The study took on average one hour and participants received 10 Euro.

Figure 4. A screenshot of the bowling scene.

Part I: Bowling

During one game of bowling, each participants threw 10 balls in total. Every time a ball disappeared in the bowling gutter, its position was reset to the original position so that the participants did not have to, but could use different balls. Overall, six different balls were present, each having a different size (which was related to its actual weight) and were ordered with increasing weight from left to right. To give the participants an initial guess about the balls' weight in each condition, they were informed about this order. The pins were reset after two balls. After a strike, they were reset immediately. Therefore the participants could score up to 100 points (10 balls times 10 pins). The current score, as well as the remaining ball count was shown to the participants in a screen placed on the ceiling of the bowling alley (see figure 4).

The balls were set to be kinematic, which means they were not influenced by the physics engine as long as the objects were grabbed. As soon as they were released by the participant, the physics engine came into effect and controlled the balls physics. We also transferred an initial force to the engine, which was equal to the current velocity and strength of the virtual object to allow users to throw them despite the handover between our algorithm and the physics engine.

Part II: Detection Thresholds and Weight Estimation

Both the detection threshold and weight estimation task were kept quite simple. The scene was empty, only including a skybox of a sunset. Since the participants had to compare the *weights* of two spheres in the detection threshold task, two spheres were displayed, while only one was displayed during the weight estimation task. A screenshot of the detection threshold task is shown in figure 5.

In the threshold estimation task, the participants had to compare two identical looking spheres regarding their *weight*. One of the spheres had a weight resulting in a offset of either 8 cm or 20 cm, the other one had an additional offset ranging from 0.8 cm and 4 cm (in 0.8mm steps). The order as well as if the left or right sphere was heavier was randomized. The task was designed as a *two-alternative forced-choice* (2AFC) task. The idea behind such a task is to get the probability of correct estimates by repeating each comparison multiple times. If participants can not distinguish between both weights,

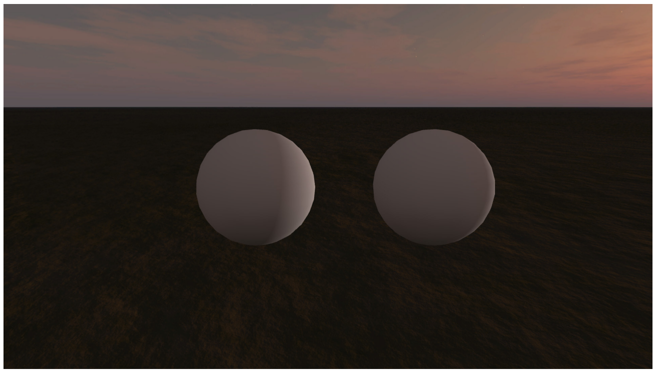

Figure 5. A screenshot of the detection threshold task scene.

they will answer randomly, resulting in a probability of 0.5. The more reliably they can distinguish them, the higher the number of correct estimates and therefore the probability of detection. In our case, each comparison was done 12 times. The participants had therefore 120 comparisons to do in total (5 additional offsets applied to 2 different weights times 12 repetitions).

The last task was used to gather an absolute weight estimation in kg being associated to the respective offset. We presented four different offsets (4 cm, 12 cm, 20 cm and 28 cm), each three times in a fully randomized order.

Participants

We recruited 18 participants (13 male and 5 female) aged between 21 and 30 (mean 26). In addition to the demographic questions, we asked the participants about their interest in VR technology on a seven point Likert scale (from 1 – no interest, to 7 – strong interest) resulting in a mean of 6 with a standard deviation of 0.8. We also asked for how many months they have already been consuming VR content, which was 12 in mean with a standard deviation of 15.

Results

Bowling Task We used the Wilcoxon signed rank test for non-parametric dependent variables to compare the two conditions regarding differences in the presence, immersion and enjoyment score. The results of the Witmer-Singer presence questionnaire showed a highly significant difference between the *with offset* and *without offset* condition, with a strong effect size ($p < .01$, $Z = -3{,}66$, $r{=}.61$). Both conditions resulted in a high median presence of 5.22 for the *without* and 5.58 in the *with offset* condition.

Regarding the immersion score of the E^2I, again a significant difference could be observed between both conditions ($p < .05$, $Z = -3.26$, $r = .54$). Again, the immersion in the *with offset* condition was slightly higher rated with a median of 5.4 compared to 5.3. The second score we got from he E^2I questionnaire was the enjoyment. Again, both conditions differed slightly but significantly ($p < 0.05$, $Z = -3.13$, $r = .52$) with a median of 5.8 in the *with offset* condition and 5.3 in the *without offset* condition. Boxplots of the results are given in figure 6.

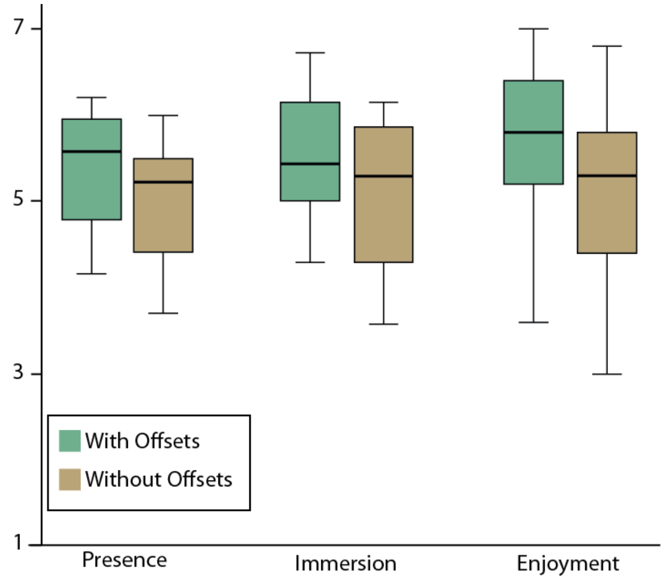

Figure 6. Boxplots of the Presence, immersion and enjoyment scores split by condition.

The results of our own questionnaire are illustrated in figure 7. Our questions all aimed at rating weight perception and estimation. The participants answered on a 5 point Likert scale how strong they would agree to the following questions (1: not agree, 5: strongly agree). On the question if they could actually feel the weight of the bowling balls, the median was at 4.0 in the *with offset* and 1.5 in the *without offset* condition. The difference was significant on the 1% level (Z=-2.67) using Wilcoxon signed rank test. A second question was whether they were able to estimate the weight of the bowling balls before releasing them. In the *with offset* condition the answers varied strongly between 1 and 5 with a median of 4, while the median in the *without offset* condition was 2 ($p < .01$, $Z = -3{,}12$). Regarding the question if they were able to estimate the ball's weight after the release the differences were no longer significant ($p > .05$, $Z = -1.53$). The median was 4 in the *with offset* and 3 in the *without offset* condition. Boxplots of the results are shown in figure 7.

After playing both conditions, the participants filled out a last questionnaire including questions targeted to learn about the participant's preferences. Most participants (67% or 12 out of 18) preferred playing with offsets, while 11% (2) preferred playing without. The remaining 22% (4) were undecided. We also asked the participants, which representation seemed to be more realistic. Overall 55% (10) of the participants stated that the *with offset* condition was more realistic, while only one (5.5%) stated the *without weight* condition was more realistic. 39% (7) stated that both conditions were equal regarding their realism as weight representation. The results are illustrated in figure 8.

Detection Threshold Task

The second task was the comparison of the weight of two virtual spheres while lifting them. We examined two different weights regarding the participant's ability to distinguish fine

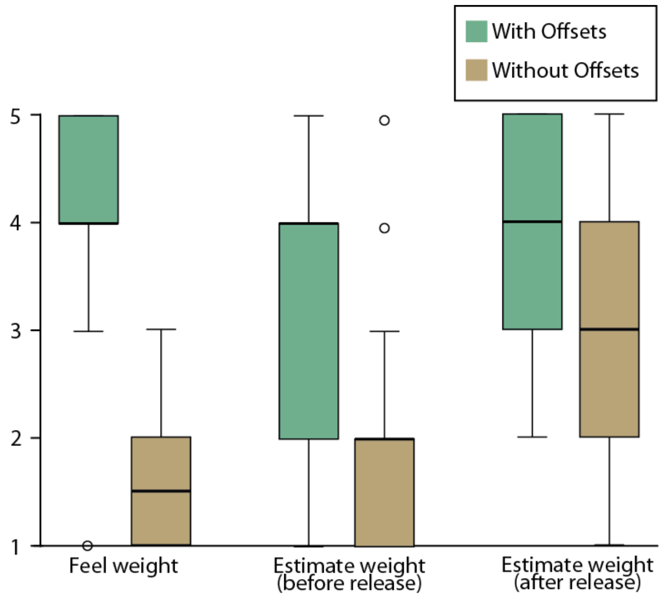

Figure 7. Boxplots of the results of our own questions regarding weight perception and estimation.

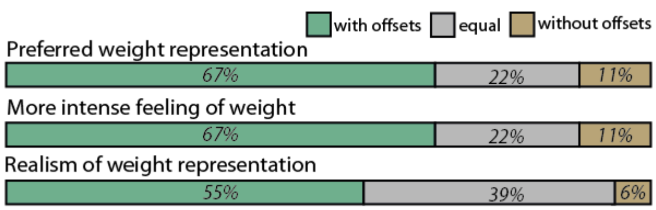

Figure 8. Illustration of the participants' rankings of the two conditions.

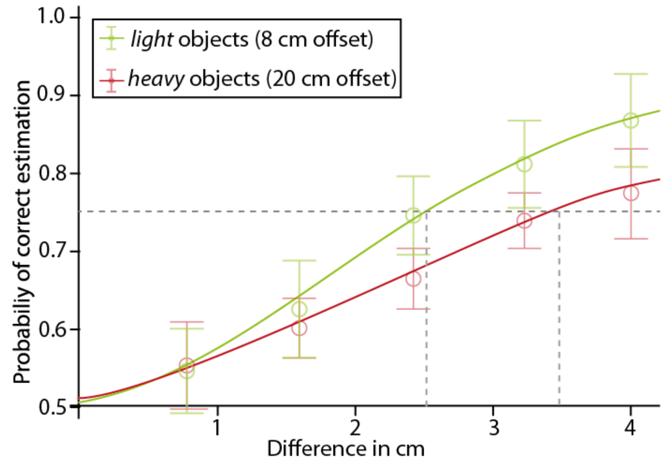

Figure 9. The probability and variances of correct estimations as well as a trend line when comparing two weights using different offsets.

differences of offsets. The probability of detection reached 75% at a difference of 2.5 cm with an initial offset of 8 cm. This means that the participants could distinguish between objects with an offset of 8 cm and 10.5 cm. The detection thresholds for *heavier* objects with an initial offset of 20 cm was slightly higher, reaching the 75% at a difference of 3.6 cm. Participants could therefore distinguish between the offsets of 20 cm and 23.6 cm. The levels of detection therefore only varied by around 1 cm between *light* and *heavy* objects. We tested both reference weights for differences using a MANOVA (Wilks' Lambda). We found that the ability to distinguish different offsets is significantly (p=.00) influenced by the initial offset. The results of the detection thresholds are shown in figure 9.

Weight Association Task

The last task was to state a real, absolute weight, that the participants associate with a given offset. We presented four different offsets three times in a fully randomized order. The results show a strong tendency towards perceiving objects as heavier when presented with a larger offset, but also shows how strongly the associations vary. While the standard deviation for the 4 cm offset object was at around 0.8 kg, it increased to around 3 kg for the 28 cm objects. The median of the 4 cm offset was thereby at around 0.5 kg, which increased to around 3.5 kg for the 28 cm offsets. The results of the weight association task are illustrated in figure 10.

Participant's Feedback

We asked the participants for general feedback about the bowling games and asked them to describe what they felt and perceived during both games. All participants except one stated that the balls' behavior differed while holding. Some wrote that they could perceive an offset between their real and virtual hand's position, but accepted this as part of the virtual world.

All participants except two commented that they could actually recognize a difference of the balls' weight in one condition, while they criticized the respective lack in the other condition. One participant stated to know that the offsets should be a metaphor for weight, but without actually perceiving a different weight. The same participant also stated that the offsets would destroy the immersion when grabbing heavier balls, though it also destroyed the immersion, when the weight was not visualized at all.

Some participants wrote that the weight representation led to a feeling of weight from hands to the shoulder in the offset condition and compared it to an elastic band which was sufficient to get the feeling of weight. Another wrote:"*The heavier balls felt more heavy, but I can not explain why. I had to put more effort into lifting heavier balls.*" Three participants stated that they were able to differentiate between the weights in the offset condition, but without being able to associate a real weight.

Three participants stated that the weight of the balls was surprising them when not having the offset representation. One of them additionally wrote that it would have felt wrong without any feedback of weight. Another described the lack of offsets as counter-intuitive since the balls weights only had an influence after releasing.

Discussion

The results of the two presented evaluations can be split in two main parts. First of all the perceptional part, with the focus

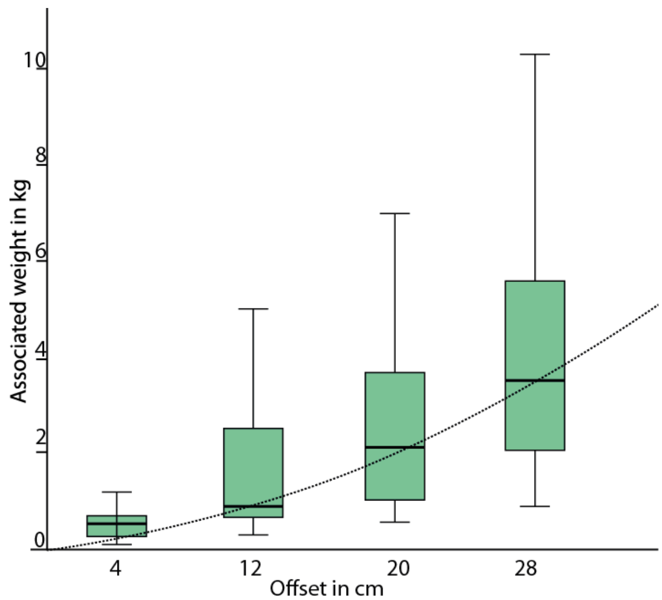

Figure 10. Participants' weight associations of different presented offsets.

on standardized questionnaires, as well as a set of individual questions regarding the weight perception and estimation. Other results more focus on the possible design space, including minimal differences regarding the presented offsets to be recognized, as well as the maximum of desired and accepted offsets.

Overall the metaphor of displaying weights by visually applying tracking offsets was well understood by most of the participants. While some only understood the metaphor others stated to actually feel the weights when presenting offsets. This was also emphasized by the stated preferences. Only two of the 18 participants preferred the condition without, while 12 preferred the condition with offsets. We could also show, that such a representation can positively influence the feeling of presence, immersion and enjoyment. Though all scores did not differ strongly regarding the median, the difference was significant. We assume, that the overall high presence, immersion and enjoyment scores made it hard to capture more pronounced differences. In addition, the questionnaires are not primed towards measuring the perception of weight in VR. We therefore included some own single items which should cover the missing items in the standardized scores. Here we could observe very obvious differences. While the median answer regarding if participants could feel the weight of the balls was at 1.5 (very close to 1: do not agree) without offsets, it was rated 4 (close to 5: completely agree) in the with offsets condition. A similar result was found for the question regarding weight estimation before the ball was released. We therefore argue, that applying tracking offsets to simulate weight in VR generates a feeling of weight and also allows the estimation of its magnitude. But though participants stated that they were able to estimate the weights, we observed very large variances between the participants' estimations which increased with the presented offset.

We also found that people are willing to accept very high offsets up to 42 cm as weight metaphor, while being able to detect differences of around 2.5 cm. This forms a large design space to represent a variety of different weights. Though all participants accepted large offsets, we suggest applying such extreme values only for short interactions while focusing on offsets below 24 cm for longer interactions. These are values all participants agreed to be a good and comfortable weight metaphor.

Since we only rendered the participants hands in our VR applications – as it is a common state of the art – we did not have to focus on aspects like inverse kinematics. If the whole human body should be displayed, such discrepancies between tracking and displaying need also to apply to other joints. However, this can be easily achieved by using existing inverse kinematics algorithms.

LIMITATIONS OF THE APPROACH

All pseudo-haptic effects require sight and are no longer present when the focus of attention shifts. In our study, we compensated for this by offering a variety of balls, nudging participants to compare differences between balls (as commonly done by beginners in real bowling). Regarding the bowling application, our results suggest that this was enough to get the feeling of weight. Still, the feeling of weight with perceivable tracking offsets has to be regarded as a metaphorical perception. While the participants stated to actually feel the weight, we believe that if first playing with a real physical weight would decrease the scores. We therefore argue that pseudo-haptic effects are very useful to communicate different weights, which increases the respective perception, but still will never be able to create a true and natural perception of weight. Another aspect of weight perception is tactile feedback like pressure which is felt when lifting an object. Our proposed approach does only consider tactile feedback in form of the controller held in the user's hands, which does not change during grabbing. Though, we could show the expressiveness and possibilities that are introduced by solely visual and software based weight representations.

Our results indicate, that participants accepted offsets of around 42 cm. This value has to be interpreted with care. This value was gathered in a short term interaction of lifting and translating an object. We believe that such huge offsets should thus normally be avoided or used with care. We suggest to stick to the 24 cm maximum which was what participants stated to like.

DESIGN CONSIDERATIONS/INSIGHTS

The following insights are derived from our user studies and experiences we collected while working and designing with our weight approach.

Embrace the Offset: Our results indicate that even obvious and perceivable tracking offsets can be used as a metaphor for weight and most probably for other VR features (e.g. resistance). While it is possible to design such visual offsets as subtle that they can not be recognized, our results strongly encourage designs where participants experience differences between tracking and visually displayed positions. Participants also preferred obvious offsets of around 24 cm and even accepted offsets up to 42 cm. In our case it did even raise the levels of presence, immersion and enjoyment. In prior evaluations, pseudo-haptic effects were designed as subtle as possible, without having the user perceive the actual offsets. This way, a given weight can be perceived as little heavier or lighter. Using our approach with the knowledge of having more degrees of freedom with perceivable offsets, even a very lightweight controller can be designed to convey a huge variety of different weights, ranging from light too heavy.

Use Relative not Absolute Weights: Our approach has to be seen more as a weight metaphor, which creates the perception of weight but cannot be mapped to a certain weight. As we let our participants guess the weights of different offsets, indeed larger offsets were associated with different weights, however there was a large variance in their guesses. Therefore, we suggest to work more on relative weight differences (e.g. sword vs stick) instead of having only one weighted object and focusing on this inside the experience.

Use Weight as a Natural Limit Inside Experiences: Instead of forbidding certain kinds of interactions to keep the user inside a certain limit (e.g. door does not open) we suggest using our weight metaphor as a natural form of limitation. Instead of making the door a non-interactive element one can make it to heavy to open. This creates the perception of a real and living virtual environment. Instead of forbidding to lift certain objects they can just be designed to be to heavy so the user can try to interact but naturally understands that it is currently not possible.

Accurate Tracking is Essential: The acceptance of tracking offsets as weight representation does however not mean that less accurate tracking would be sufficient. Accurate tracking is essential for applying our algorithm, as tracking errors would lead to unpredictable behaviours and thus most probably to a strong decrease of presence. Tracking has to be very accurate, but the visually displayed position of body parts may vary from the real one. This especially means that the relative precision of motions needs to remain untouched. We also assume, that equal approaches can be designed to display other effects in virtual reality which would need additional hardware or would be even impossible with another technique.

CONCLUSION

In this paper we presented a solely software based approach for tracking based VR interactions to generate a visual perception of weight. Our approach is based on introducing a controlled and perceivable tracking offset whereas heavier weights are represented as a higher offset. To gain a deeper understanding of the perception and effectiveness of our approach we conducted two user studies. We were able to show that people associate different tracking offset as different weights. Using a *two-alternative forced-choice* task we could quantify the detection threshold between two weights for *light* (approx. 2.5 cm) and *heavy* objects (approx. 3.6 cm). We also found, that users like even obvious and perceivable offsets of 24 cm as weight representation. By testing our approach not only for measuring perceptual thresholds, as it was done in related works, but also in a fully immersive VR game, we contribute to the positive effects on haptic perception as well as presence, immersion and enjoyment. We could show that our pseudo-haptic approach results in a significant better experiences than the currently non-existent simulation of weight.

Since our approach does not require any additional hardware, we argue that our approach can easily be implemented inside all current tracking based VR applications.

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