Abstract

This paper proposes a way of dealing with the absence of haptic sensation in augmented reality. Three visual parameters are presented, which are all designed to produce a haptic illusion of weight only through visual stimuli.

The experiment described in this paper required the user to solve three tasks in augmented reality, each containing one of the three parameters. Experimental evaluation of the application showed that people were in fact able to perceive a weight difference in at least two of the three parameters. Even though the results of the test did not turn out exactly as expected, there were still indications towards the parameters having an effect on the users, producing an illusion of weight.

The possible use of these findings extends into areas of game development, marketing and product demonstrations, as well as examining new parameters, which might strengthen the perception of weight further or give indications about other physical properties.

Introduction

Augmented reality is an area of technology which is being applied in an increasing number of applications, such as advertisement (MINI, 2009); (Nissan, 2009)), games ((Thomas, Close, Donoghue, Squires, De Bondi, & Piekarski, 2002); (Topps, 2009)), as well as small applications developed by both professional companies and amateur developers (Forrest, 2009).
While the user has great freedom in viewing the virtual object from any angle, the technology contains certain problems. Light is particularly problematic, since 2D images from the camera provide no information about positions of light sources in the real world. Inherent lack of haptic sensation presents another important issue. Parameters such as temperature, texture and weight are omitted since the virtual object only exists in augmented reality, preventing direct physical user-interaction with them. Exploring how these parameters could be replicated in augmented reality requires a full study for each. This paper will therefore focus only on weight.

In traditional augmented reality there is no physical difference between lifting e.g. a virtual car or a virtual chess piece. Replicating the actual weight of a car in augmented reality is a daunting task. An impression of the augmented car being heavier than the chess piece would be more manageable. An impression of weight could be achieved by adding weight to the fiducials or by using gloves with force-feedback to replicate weight of the objects (Biocca, Kim, & Choi, 2001). However these approaches necessitate special equipment. The freedom of augmented reality comes from only needing fiducials to create a result – this paper aims to retain that freedom.

Hence, the topic of investigation will be mediating the impression of weight to the users without the use of external equipment. Throughout the paper, three different parameters will be explored in order to determine how visual stimuli from the virtual objects can give the user an impression of weight. For more information about the technology used, see Appendix: Background.

**Human Weight Perception**

The interest within the field of weight perception dates back to 1834 and the work of E.H. Weber, who established that the impression of heaviness of an object was greater when it was wielded than when it rested passively on the skin (Weber, 1834). This indicates that the perception of weight was not entirely determined by objective assessments.

Research in object identification through haptic feedback established a series of hand gestures used in the categorization of objects (Lederman & Klatzky, 2001). In relation to this project the most important gesture was related to weight and the result of their testing revealed that unsupported holding of an object was the ideal method to determine its weight, as seen in Illustration 2.

Illustration 2: Lederman and Klatzky proved that the unsupported holding of an object was the most optimal for judging weight.

Studies in cognitive factors relating to the theories of the size-weight illusion (Charpentier, 1891), has shown that prior experience with manipulating an object with similar characteristics to a new object, can affect the weight perceived when manipulating the new object (Klatzky & Lederman, 2003). Additionally, studies by (Flanagan, Bittner, & Johansson, 2008) determined that the normal expectation of weight in objects increasing in
size can be changed by experience. For a more profound explanation of experience in weight perception, see Appendix: Experience.

**Presence and cross-modal sensory illusions**

In virtual environments, a sense of presence may be evoked in a user through cross-modal interactions; sensory illusions in which one sense fills in missing information from another sense. One example is cross-modal transfer, where actual stimulation to a sensory modality (e.g. sight) is accompanied by an artificial stimulation in another sensory modality (e.g. touch) (Biocca, Kim, & Choi, 2001).

In augmented environments the coupled visual and haptic sensations of a manipulated virtual object are absent, whereas in the physical world you would be able to see and feel physical properties of an object. Studies show that some users of augmented environments are able to perceive a visual-to-haptic illusion in order to create a mental model of the augmented world that matches their experience from in the real world (Biocca, Kim, & Choi, 2001).

The studies point towards two key findings:

1. Haptic illusions in the absence of touch.
2. The apparent connection of cross-modal transfer and the experience of presence, leading to visual-to-haptic illusions.

The element responsible for these results is the visual cue of a physical resistance. In the study performed, a virtual spring was attached to the virtual object being manipulated by the user. When moving the virtual object, the spring would expand until finally snapping away. It is this dynamic visualization of the existence of a physical force that most likely induced the cross-modal visual-to-haptic illusion in the user.

Research within the fields of human weight perception and cross-modal sensory illusions served as inspiration for choosing parameters that could be tested in an augmented world.

**Parameters of weight**

Three parameters have been chosen for creating potential haptic illusions of weight using only visual stimuli. These parameters will be described in this chapter.

**The size-weight illusion**

The size-weight illusion occurs when you manipulate two objects of different size with equal weight. Initially the large object will appear heavier, but during interaction the smaller object will feel heavier than the larger one. Charpentier was the first to describe the size-weight illusion (Charpentier, 1891).

“Charpentier placed two spheres of different sizes but each weighing 226 g onto subjects’ supine palms, and asked them to heft the spheres. The small sphere was judged to be heavier than the large.” (Murray, Ellis, Bandomir, & Ross, 1999).

Generally a larger object is perceived to be heavier than a smaller object but when you perceive the larger object as being lighter and the smaller object as heavier, expectations are not met. This illusion has since been documented by others and continues to be researched, but a true explanation of why the illusion occurs has not yet been established (Ernst, 2009). It will be translated to the final experiment to establish a haptic illusion of weight through visual input in augmented reality.


**Speed**

The parameter of momentum was created with the assumption that objects moving slow will be perceived as heavier than objects moving fast. Through real life experience we are familiar with the concept of *momentum* (Merriam-Webster, 2009): The heavier the moving object, the greater the amount of time or opposite force required to bring it to rest.

This is the goal for replication within the augmented world. One virtual object will move exactly as the fiducial marker does. The other virtual object will take significantly longer to begin moving with the fiducial and to stop moving again, causing it to trail behind the fiducial when moved. This will require the user to exert larger motions in order to move the “heavy” virtual object similarly to the “light” virtual object, simulating momentum.

Lécuyer et al. (Lécuyer, Burkhardt, & Etienne, 2004) implemented an efficient algorithm for creating the illusion of bumps and holes in a 2D interface. When a mouse cursor moved into a hole, the position of the cursor accelerated in the direction of the bottom of the hole and decelerated when moving out again. This algorithm can be modified to work in this weight-illusion context by registering fiducial positions rather than mouse positions.

In the augmented world, the heavy object will trace behind the fiducial when the user moves the fiducial. The heavier the object, the further it will lag behind. When the user stops moving the fiducial, the virtual object will slowly catch up to it, simulating a longer stopping distance, as per the characteristic of momentum. Illustration 3 shows how the momentum will be implemented in this application.

Illustration 3: To illustrate the real life phenomenon of momentum, heavy virtual objects will trace further behind the fiducials than light virtual objects.

**Animation**

Many augmented reality applications deal with animated virtual objects. Reality is a living environment and therefore moving virtual objects should be considered. The parameter of animation has been determined, in order to examine a possibility of creating an impression of weight in a moving virtual object. The motion of an object can often be a telltale sign of its physical properties, such as how a ball bounces off the ground. Since the goal is to test weight in animation itself, an animated virtual object will be compared to a similar, but inanimate virtual object.

Rather than having the virtual object be in constant contact with the fiducial, this chosen animation will be leaving and reconnecting with the fiducial. This should present the chance of accentuating the impact between the virtual object and the fiducial and thereby the perception of weight in the virtual object. This makes a jumping motion a good choice for the type of animation. The looks of the virtual objects are not realistic and therefore the animations will not replicate realistic motion. It will rather make use of a number of Disney’s 12 principles of animations, such as exaggeration, anticipation and timing.
(Johnston & Thomas, 1981) to help convey its message.

**Investigations**
This chapter will describe the setup and results of the final experiment in which the goal was to investigate if users could perceive a difference in weight between virtual objects, only through visual cues. Two pretests were conducted prior to the final experiment. The knowledge obtained from these pretest helped shape the design of the final experiment.

**Test setup**
Indications from previous tests showed that the user needed to be moderately immersed in the environment he was interacting in, to increase the opportunity of producing a visual-to-haptic illusion. This immersion was obtained by giving the user tasks to solve, ensuring that he was focused on the environment that he was supposed to be interacting in. There were a total of three tasks to solve, one for each weight parameter. To heighten the immersion further, the user was required to wear a head mounted display (HMD). This HMD conflicts with the initial requirement of using only fiducials, but it was necessary to better immerse the user. The test was conducted by three test conductors: An interviewer, a notary and a technical supervisor.

**General setup**
The user went through three cases, each consisting of a small task to solve. He received instructions from a test conductor and was asked to put on the HMD. As soon as the user had put on the HMD, the test started and he saw the virtual objects of the first task. Before doing any interactions he was asked to indicate if he thought there were any differences in weight between the two virtual objects. He was instructed on how to solve the task and while working with it, he was asked if he perceived any weight difference or difference in difficulty between using one virtual object or the other.

When the task was solved the technical supervisor made a weight scale appear at the bottom of the table, ranging from 0-1000 grams. The user was then asked to place the two virtual objects on this scale.

Having completed all three tasks, the user was asked which of the tasks he thought was most difficult and if he was right- or left-handed. After these two questions, the test was complete.

The following three chapters describe the tasks that the user should complete. The tasks were given in a random order for each test person.

**Size-weight**
As described in the chapter *Human Weight Perception*, the unsupported holding of an object in an up-down movement, is the most efficient for judging weight. Designing for this motion would therefore immerse the user in the task and create proper motion for weight comparison.

![Illustration 4](Image)

**Illustration 4:** The task in the size-weight parameter was for the user to keep the virtual object in his hand above the red bar – and below the red spheres – which were both moving up and down.

Adhering to the requirement of up-and-down-motion, the task for the user became making the virtual object (a candlestick) follow a virtual, red bar, moving relative to the table, as illustrated in Illustration 4.

One pretest showed that it was too complicated for the user to coordinate the movement of
both hands at once. Thus the task for the final experiment was limited to moving only one hand at a time. The user was doing the task with one virtual object for approximately 20 seconds before switching to the other virtual object.

**Animation**
The task for this parameter was similar to that of the size-weight illusion, but since the illusion of weight in this case should come from the impact of the animated character landing on the fiducial, it was not necessary to have the user move the character up and down. Instead, the user should hold the two characters above the two virtual, non-moving bars, as shown in Illustration 5. In this way there were still unsupported holding involved in the task, but without the up-down movement.

![Illustration 5: The task in the animation parameter case was for the user to keep the characters positioned on the two bars as accurately as possible.](image)

This task was tested in a pretest, and when requiring no hand movement, the task was simple enough for user to coordinate both hands relative to the red bar. The user held one character in each hand for approximately 20 seconds before switching hands, eliminating the influence of the user being right- or left-handed.

**Speed**
The momentum parameter was designed to work in the xy-plane and thus the user should not be moving the virtual object along the z-axis (up and down movement). The task was to make the virtual object (a book) follow a red square moving around on the table in front of the user. In this way, he perceived the difference in simulated momentum between the two virtual objects when moving them on the surface.

![Illustration 6: The task in the momentum parameter case was to move around the virtual object to be inside a red, virtual square, moving in the xy-plane.](image)

Similar the case of the size-weight case, this task could be solved using one hand only. After approximately 20 seconds of solving the task with the first virtual object, the user repeated the task with the other virtual object.

**Results**
The test was conducted on a total of 30 test subjects, aged between 10 and 50, with 21 of the test subjects being male and 9 being female.

Users’ perception of weight in each case indicated that some of the parameters had an effect. For the size-weight case the results were the most conspicuous, with 24 users stating that they did indeed perceive a difference in weight. The majority of the users (18 of 24) thought the big candlestick was heaviest. According to the size-weight illusion, the users should initially have perceived the big candlestick as the heaviest by looking at it. When lifting the virtual objects, which were in reality of the same weight, they should then have perceived the smallest one as being heavier. After having interacted with the virtual objects, five people did change their mind from initially having thought that the two candlesticks were equally heavy or the big one being heavier, to thinking that the small candlestick was heavier. In comparison only two people changed their mind in to thinking that the big candlestick was heavier.
The momentum case indicated the slow book as being the heaviest, matching initial intentions of the case. After having solved the task 18 users found that there was a weight difference between the books and 15 of these found that the slow book was heavier than the fast book. The books were completely similar in size, shape and texture, except that one book had a “1” printed on the front where the other book had a “2” printed. In the qualitative interview being conducted during the task solving, several users commented that the task was more difficult to solve with the slow moving book, but they did not know why it was more difficult. They did not notice one book moving slower than the other, but only noticed that the task was more difficult. However, 13 users changed their opinion about the weight of the slow book during the task. Before interacting with the books, five people perceived a weight difference and four of them thought the fast book was the heaviest, even though knew nothing about the movement of the books at this point. As mentioned, the number of test persons perceiving the slow book as the heaviest after the test was 15, which is a higher rate of people having changed their mind than in the other two test cases (5 in the size case and 3 in the animation case).

The last parameter was that of animation. This was the least successful parameter with only 14 people noticing a weight difference. 11 of these commented that the standing character was the heaviest, which contradicts the original idea of the parameter. Based on the animation principles from Disney, the animation of the character should add weight to the impact between the character and the fiducial, but the users thought the jumping character was the lightest, since it was able to jump and the other character was not. All the results can be seen in Table 1.

<table>
<thead>
<tr>
<th>Virtual object</th>
<th>Perceived difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Big candlestick</td>
<td>Yes 18</td>
</tr>
<tr>
<td>Small candlestick</td>
<td>No 6</td>
</tr>
<tr>
<td>Non-animated character</td>
<td>Yes 11</td>
</tr>
<tr>
<td>Animated character</td>
<td>No 3</td>
</tr>
<tr>
<td>Book 1 (slow)</td>
<td>Yes 15</td>
</tr>
<tr>
<td>Book 2 (fast)</td>
<td>No 3</td>
</tr>
</tbody>
</table>

Table 1: The table shows how many people felt a weight difference in the three test cases, after having solved the tasks. If a weight difference was perceived, the number in the “Yes” column shows how many test subjects perceived a specific virtual object as being heavier.

Additionally, almost all test persons overrated the weight. The actual weight they held (the weight of the fiducial blocks) was around 100 grams, but the mean perception of weight for each of the six virtual objects ranged from 375 to 520 grams. This is predominantly evident by looking at the users’ estimate about the characters’ weight. They were divergent to any character the user would have met in the real world. It was a biped, but it only had hands, feet, body and head, creating only a faint similarity to a human. The character was therefore the most unfamiliar virtual object to the user, which might have lead to it being harder to judge for the users. The average perceived weight of the two characters was 393.33 grams for the jumping character and 520 grams for the standing character, a difference of 32.2%. This was a greater difference than found in the two other cases, where the difference in mean weight was 28.3% for the candlesticks and 17.3% for the books.

Furthermore, the standard deviation of the users’ perceived weight of the virtual objects was also higher for the characters. The standard deviation for the standing character was 59.86 grams and for the jumping character it was 46.04 grams, which again indicated that the users were more in doubt about the weight.
of the unknown characters than the more familiar books and candlesticks.

Figure 1: The users were most in doubt about the weight of the two characters, but generally the users perceived the virtual objects to be a lot heavier than the actual weight of the blocks they had in their hands.

**Analysis**

The results gained from the test indicated that it is possible to produce illusions of weight in augmented reality. Out of 90 possible answers, 56 stated a perceived weight difference, indicating the idea of weight in augmented reality to be valid. The various weight parameters differ greatly in their efficiency of conveying weight to the user. Of the three parameters, size-weight had the most users perceiving a weight difference with 80/20 percent distribution of yes and no answers, while momentum had 60/40 and animation being more akin to 50/50. The reason for this might be that the visual difference in the size-weight case was constant and unaffected by technical limitations (e.g. imprecise camera tracking): The size of the candlesticks never changed and was ever-present. The animation case could very well be affected by technical issues, while the difference in the momentum-case was hidden at first, while the momentum-case could have suffered from the fact that the books did not move smoothly across the table.

The size-weight case was not the best in achieving the intended results. It produced results contradictory to what was expected, as did the animation-case. Only the momentum-case was sufficient in producing results as intended. This might be because its weight-criteria were most true to the real world. The motion of the books started and stopped as expected from momentum. The real size-weight illusion, the user should hold objects of different sizes whereas this experiment gave him fiducial blocks of identical size, making it less like the real version. The animation case suffered from the camera tracking being somewhat unstable, such that the inanimate character appeared to be moving from side to side. A further indication that this case worked as intended is the clear difference in the distribution of yes- and no-answers from the beginning of the test to the end of the test. The case suggested that users should not perceive any weight difference without moving the books and being to perceive weight after moving the books. Only 5 people perceived a difference before interaction, which is very low and satisfies expectations. After interaction, 18 people perceived a weight difference, which also satisfies expectations. The reason for the other two cases being less successful might be that the size-weight case could have been affected by fiducials of similar size, where the real-world example had objects of similar weight but different sizes. The animation case could suffer from technical limitations such as inadequate frame rate.

The test results indicate that the virtual objects did in fact have an actual influence on the perception of weight. Even though the fiducial blocks had equal weight, 30 out of 90 answers determined the weight difference of these blocks to be equal to or greater than 200 grams. With one fiducial block weighing roughly 100 grams, this weight difference equals two actual blocks. This difference is noticeable enough to indicate that of these 30 answers, the actual weight of the blocks was not the sole reason for this weight difference.
Conclusion
This paper explored three different parameters to determine how visual modifications to virtual objects can give the user an impression of weight in augmented reality. The three parameters were: Size-weight illusion, animation and momentum. Three tasks featuring the respective parameters were designed for the user to solve. They were included into a final experiment that would determine the validity of them.

After having conducted the experiment on 30 users, the results indicated that it was in fact possible for the users to perceive weight in augmented reality. Out of 90 possible answers, 56 stated a perceived weight difference between the virtual objects. However, there were differences between how effective the three parameters were in the test. The most efficient parameter in providing a general perception of weight was the size-weight parameter, while the parameter satisfying initial expectations to the highest degree was the momentum parameter. The results indicate that it is possible to achieve haptic illusions in augmented reality, using only visual stimuli, but that the effect achieved might not always be consistent and will most likely require a combination of several parameters to create an illusion that will affect the vast majority of users.

These results rationalize further investigation of parameters that could influence the perception of weight in augmented reality. It would be interesting to explore the combination of the size-weight and momentum parameter, since these each had significant strengths that could potentially increase their current influence on weight perception when combined. The animation parameter did not produce any results significant enough to warrant its inclusion in future perspectives. While the results and indications shown in this paper have not provided solid evidence towards perception of weight in augmented reality, they at least point to the concept as being plausible and worthy of further investigations.

References


APPENDIX

Background
The system that is used to perform the tests of this paper is based on the ARTag system, which is an augmented reality system, based on the tracking of fiducial markers. The word *fiduciary* means “of, relating to, or involving a confidence or trust” (Merriam-Webster, 2009), so the fiducial markers are simply markers trusted by the system. The ARTag system has a list of fiducials, supplied in the SDK, which the system already recognizes, but if necessary the program can produce references for new fiducials as well.

There is other tracking software available for tracking of fiducials, such as the Studierstube Tracker (Wagner, 2009) or the ARToolKit (Lamb, 2009) and ARToolKitPlus, which is the old version of the Studierstube Tracker, but they all share the same basic system setup as ARTag. Some of the systems (ARToolKitPlus and Studierstube) have slightly better tracking, resulting in less jittering of the virtual objects. However, the ARTag can also produce a relatively steady image with the right configuration of the camera and the right combination of fiducials. Furthermore, the ARTag system and the process of working with it, is very well documented in the book *Augmented Reality: A Practical Guide*, which is written by Mark Fiala – the creator of ARTag – and Stephen Cawood. This makes it a good choice of development environment for this project and also for further research in this area, as the system is so approachable.

The idea of the ARTag system is – as it is the case with the examples of the Introduction chapter – to have a webcam or other camera device recording the real world and then let the user watch a monitor, displaying the augmented world. In ARTag, the fiducials consist of 10x10 unit grid of black or white. There is a two unit border where the color is either pure black or pure white. The inner 6x6 unit grid is then a mix of black and white, which makes up the unique pattern of the given fiducial (Cawood & Fiala, 2008).

Illustration 7: An example of a fiducial marker from the ARTag system. It is created in a 10x10 grid, where the inner 6x6 grid is what makes the unique pattern.

In order to produce a more secure tracking, the ARTag system is able to look for an array of pointers. In this way, the tracking becomes more stable, because the program has more trusted points to rely on. Furthermore, part of the marker can be occluded by objects in the real world and still be tracked by the program. The method of the actual tracking is out of scope for this project and will therefore not be explained here. However, a deeper explanation can be found in the Appendix of the book by Cawood and Fiala.

The code that is used in the implementation of this paper is using the ARTag to know if a fiducial marker or array of markers has been found. The program then draws virtual objects using OpenGL and sets the origin of the modelview matrix to what was returned from the ARTag tracking.
Experience

Augmented reality essentially allows for any virtual object to be created and imported into the real world. However, since the users’ perception of weight was the primary focus, it is important to investigate factors that can affect their weight-perception. One such factor is previous experience. If users interact with a given virtual object, would they rely on experience with real life versions of the same object in order to judge the weight of the virtual object? The reason that previous experience is an important topic for investigation, is that use of experience might interfere with, override or remove an actual perception of weight in a virtual object altogether. If not taken into consideration, a user might rely solely on previous experience and guess or “know” how heavy an object appears without any actual perception of weight.

Weight-perception in augmented reality is currently a very barren field of research and as such no real evidence exist to directly support or dismiss the influence of experience in weight-perception in augmented reality. However, research has been done to show that experience can alter perception of weight of real objects (Flanagan, Bittner, & Johansson, 2008). This research determined that the normal expectation of weight in objects increasing with size can be changed by experience.

Interaction with augmented reality can easily become an unfamiliar experience for users, since the characteristic of virtual objects prevents direct physical interaction, but even when dealing with unfamiliar objects, experience is still likely to have an influence on how the user perceives them (Ludden, Schifferstein, & Hekkert, 2009). Sensual incongruities have been investigated when dealing with surprises in products. When users were presented with products which were immediately unfamiliar to them, previous experience still played an important role. Even though the users had not interacted with other objects of the same type, they still drew on previous experience with objects sharing characteristics such as shape or material. This research suggests that experience will always play a role in weight perception, whether the objects are familiar or not.