The Influence of Visual Cues on Passive Tactile Sensations in a Multimodal Immersive Virtual Environment

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ABSTRACT

Haptic feedback, such as the sensation of 'being touched', is an essential part of how we experience our environment. Yet, it is often disregarded in current virtual reality (VR) systems. In addition to the technical challenge of creating such tactile experiences there are also human aspects that are not fully understood, especially with respect to how humans integrate multimodal stimuli. In this research, we proved that the visual stimuli in a VR setting can influence how vibrotactile stimuli are perceived. In particular, we identified how visual cues that are associated with the characteristic of weight influence tactile perception, whereas a similar effect could not be achieved for a temperature-related visual cue. Our results have technical implications – for example, suggesting that a rather simple vibration motor may be sufficient to create a complex tactile experience such as perceiving weight – and relevance for practical implementations – for example, indicating that vibration intensities need to be 'exaggerated' to achieve certain effects.

Categories and Subject Descriptors

H.1.2 [**Models and Principles**]: User/Machine Systems; H.5.1 [**Information Interfaces and Presentation**]: Multimedia Information Systems—*Artificial, augmented, and virtual realities*

General Terms

Human Factors

Keywords

Virtual reality; passive touch; multimodal experiences

1. INTRODUCTION

Virtual reality (VR) set-ups generally aim at creating a high level of realism. Yet, most current systems only support vision and audio, omitting other senses, such as haptic experiences. While adding, for example, the sensation of *passive touch*, (e.g., being touched by a character or object) would likely increase realism, implementing this is very difficult. First, there is the technical challenge: tactile devices are only able to simulate one single property of touch, such as weight or temperature of an object. In addition, it is not straightforward how to integrate the haptic sensation with other senses. Past research studied, for example, how the haptic and visual sense work together, and how they can change the perception of an object's texture [21, 26], hardness [11], temperature [15, 12], and weight [7, 29, 10, 1].

Inspired by these studies, which all used real haptic objects, our general aim is to verify if similar experiences exist in pure virtual environments. In particular, we investigate if visual signals that are commonly associated with the two characteristics *weight* and *temperature* have an influence on vibrotactile perceptions, i.e. tactile feedback created by vibration motors placed on, for example, your arm. In the ideal case, we would expect that the richer and more complex visual stimuli can influence this rather simple tactile perception in a way that creates a better, more realistic VR experience. In this study, we show that this is the case for weight but not temperature, and also identify potential issues concerning general psychophysical experiments and the body transfer illusion.

2. BACKGROUND AND RELATED WORK

2.1 Virtual Reality and Tactile Sensations

Current consumer VR devices generally address the visual and auditory component but lack in modalities associated with tactile, gustatory, and olfactory senses. While there are tools for motion tracking that support kinesthetic senses, we are still far from being able to create a full, realistic tactile VR experience. Good overviews on how to simulate haptic feedback can be found in [27] (addressing classifications and techniques) and chapter 3.3 of [6] (focusing on devices). Newer techniques not covered in these references include, for example, electrovibrations adding tactile feedback to touch screens [16]. Vibrotactile displays, i.e. vibration motors or *tactors* placed on your skin, can be used to create the illu-

ICMI 2015, November 9–13, 2015, Seattle, WA, USA.
ISBN 978-1-4503-3912-4/15/11 ...$15.00.
DOI: http://dx.doi.org/10.1145/2818346.2820744.

sion of touch through vibration. Although these approaches have proven their feasibility, not all are equally applicable. Especially for consumer use, common aims are inexpensiveness and expressiveness, to impose limited cumber upon the user, that the system should be easily scalable and reconfigurable, and that the mapping of input data to stimulus output should be straightforward [17]. The vibrotactile displays used in our work to create the illusion of passive touch satisfy all of these requirements besides the last. The *general aim of our research* is therefore to provide better insight about the integration of such devices in the overall interaction experience and increase knowledge about mutual dependencies between stimuli of different modalities.

2.2 Presence and Passive Experience in VR

According to the model by Steuer [28], presence in VR is a human experience and a consequence of immersive technologies. It has two determining dimensions: vividness with the two contributing factors breadth and depth of included modalities; and interactivity with the three contributing factors speed, range, and mapping. Many studies target increasing interactivity by focusing on improving task performance [2, 22, 4]. Yet, when the goal is to improve experiences that users can take part in passively, vividness becomes a vital part of the system, even more urgent than interactivity. Here, we focus on this less studied aspect by specifying the *sub-goal of our research* as investigating the experience of passive touch under varying visual conditions.

A phenomenon closely related to presence is the body transfer illusion. Such an illusion causes users to perceive part of or an entire artificial body as their own. For this reason, it is believed that it can increase presence in a virtual environment [23]. Factors that enhance this illusion are first person perspective over a fake humanoid body and congruent visuotactile cues [18, 20]. It has been shown that a first person perspective of a life-sized virtual human body is sufficient to generate a body transfer illusion [25]. In our experiments we thus apply this methodology focusing on first person body experiences.

2.3 Multimodal Integration

Research from cognitive science identified important illusions with respect to multimodal integration, including the McGurk effect [19], ventriloquist effect [14], double-flash illusion [24], and the rubber hand illusion [3] (an example of the body transfer illusion). Other illusions that specifically concern the tactile and visual sense are changing surface texture and roughness [21, 26], changing object hardness [11], changing object temperature [15, 12], and changing object weight and collision force [7, 29, 10, 1]. Each of these studies used the actual tactile property to test the effect of adding visual cues. However, simulating all of these properties is not feasible in a VR system, thus a substitution is needed. The *concrete research problem addressed in this paper* is therefore to investigate whether the findings above would still apply when using vibrotactile stimuli in a passive situation rather than an active task such as in [10]. In particular, we are investigating the illusion of weight utilizing visual cues in the form of size [29] and speed [1], which were both shown to work with a contrast effect, rather than an averaging effect (the latter being the most common effect found in multimodality studies [8]). For temperature, we use object color as visual cue, similar to one of the experiments in [12].

3. OBJECTIVE

Resulting from the general aim, sub-goal, and related research problem introduced in the preceding section, we phrase our *research question* as:

> *Is it possible to create the illusion of experiencing different intensities of a certain property (weight or temperature) using a rather simple and unrelated type of touch (vibrations) together with compelling, type-related visuals (speed/size and color, respectively)?*

We address this via an exploratory investigation where the two properties weight and temperature of a 'touching' object are studied. Intensity of each property will be varied: tactile intensity is mapped to a vibration intensity; and visual intensity is controlled by different cues motivated by related work (cf. 2.3), cf. Table 1. The *objective* is therefore to measure the perceived weight and temperature intensity with a range of visual intensities. To do this, we use two psychophysical experiments in the form of a matching task (cf. 4.2). We motivate this methodology by the fact that experience is a qualitative characteristic and thus difficult to verify objectively. Although the used matching task is technically a performance verification, it verifies how humans perceive the intensity of varying multimodal stimuli, thus also allowing us to draw conclusions about their expected experience.

Property	**Cue**	**Levels (low - med - high)**		
Temperature	Color	Blue	- Gray	- Red
Weight	Size & Speed	Small & Slow	- Med & Normal	- Large & Fast

Table 1: Tactile properties with corresponding visual cues and intensity levels used in the experiments.

4. EXPERIMENTS

In the following, we outline the general setup and methodology used in our experiments (4.1 and 4.2) before describing the unique characteristics and results of the weight and temperature test (4.3 and 4.4).

4.1 Framework and Material

The same framework is used for the following two experiments. A plain indoor room was created with Unity Pro version 4.6.3f1, and scripts were written in C# using Microsoft Visual Studio 2013. Assets used to create the environment were free downloads from the Unity Asset Store. An Oculus Rift Development Kit 2 is used as head-mounted display (HMD) to create the visual stimuli and VR experience. It has a resolution of 960 × 1080 pixels per eye, and a nominal field of view of 100 degrees. Tactile stimuli are supplied via vibrations through an Elitac tactile display, with one tactor (vibration motor) and a control module attached to the participant's arm using an elastic band with Velcro, cf. Figure 1. This tactile display has 16 intensity levels on a logarithmic vibration power scale corresponding to a linearly perceived intensity scale with fundamental frequency 158±2.4 Hz at maximum vibration strength. The root mean square acceleration at maximum vibration strength is 55.5 ± 9.5 m/s^2. Sennheiser HD201 headphones are used to produce pink noise in the background to mask the sound of the tactor and eliminate all other acoustic influences.

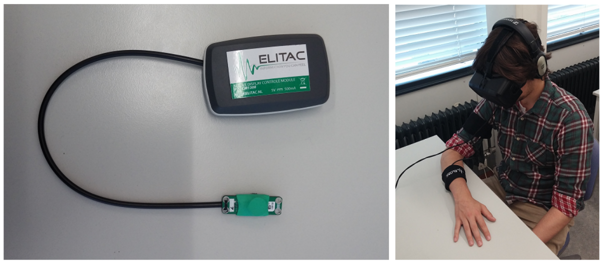

Figure 1: The measurement setup; (left) the Elitac control module and a single tactor, (right) a participant sitting in the correct position wearing the HMD, tactile sleeve and headphones.

4.2 Method and procedure

Before starting any experiment, participants were seated in a neutral room, signed a consent form and filled out a general information form. All subjects volunteered and were not reimbursed for their time. The experimenter gave instructions on how they should be positioned, and aided them while putting on the HMD and tactile display. Participants familiarized themselves with the virtual environment by looking around. In the setup, the avatar was sitting on a chair with the left arm placed on their lap under the table (out of sight), and the right arm on the table such that the lower arm was resting horizontally in front of them. The avatar was a humanoid figure (its gender matched the participant's) placed such that the participant had a first-person perspective; cf. Figure 2. Before each condition, a short training session took place, to make sure the participant understood the procedure and to induce a body transfer illusion. Because of the first person perspective, we can assume that this body transfer illusion occurs for all subjects [25].

Each subject tested two conditions: the control (no indicative visual cues), and either the weight or temperature conditions. The order of the conditions was counterbalanced over all participants. The conditions were made up of trials, each trial consisting of a matching task. A matching task uses a method of adjustment as described in [9] (Ch. 3). In a general matching task, participants are presented with a stimulus that must be adjusted such that it is above or below a certain threshold. In our experiments, a variation was used in which the participant had to adjust the tactile comparison stimulus until it matched (was perceived as equal to) the tactile reference stimulus. The participant's final choice of the matching comparison stimulus was logged. With such a task, we are able to obtain objective measurements about the perception of stimuli.

There were three tactile reference intensity levels (5, 8, 11), three visual intensity levels (0, 1, 2), two starting tactile comparison intensity levels (2 levels lower and 2 levels higher; i.e. 3 and 7 for reference 5), and four repetitions for each starting level, resulting in 72 trials in total. The reference intensity levels were chosen from a practical point of view: the levels are approximately in the center of the allowed range, such that the participants had room for adjustment in both directions. The control condition had no visual intensity levels, thus leading to 24 trials; resulting in a total of 96 trials per participant. A break of about three minutes was taken after every 24 trials (so three breaks in total), where the participant was allowed to take the HMD off. After taking part in the experiment, each participant was verbally asked two questions:

1. Did you have the feeling the virtual arm was your own arm?
2. Did you use the visual weight/temperature of the ball to deduce your answer or did you use the intensity of the sensation on your arm?

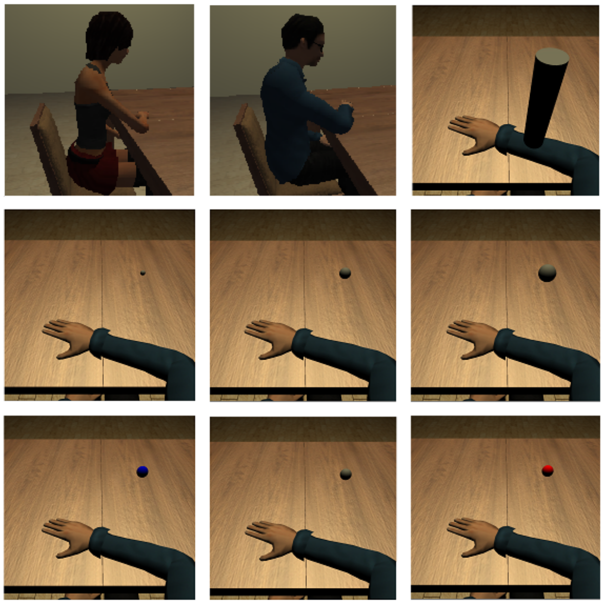

Figure 2: The virtual environment: (top-left) the female avatar, (top-center) the male avatar, (top-right) the occluder for the control condition, (center row) weight visuals where the steps in speed were exponential, (bottom row) temperature visuals.

While these subjective measures were not the main focus of this study, they can provide additional insight especially when interpreting the relevance of the measured quantitative data. Duration of the experiment for one subject was approximately one hour.

4.3 Weight Experiment

4.3.1 *Participants*

Twelve subjects took part in the weight experiment. Ages ranged from 21-27 (average 22.8), eleven male and one female participant, eleven were right-handed, one was mixed-handed. Four had no prior experience with HMDs, seven had taken part in one or a few demonstrations, and one owned an HMD personally. Due to the basic characteristic of the task and related measures, we do not expect that these differences have any influence on the outcome nor did we observe any related indications – neither during the tests nor in the related data analysis. Likewise, we verified visual clarity during the training session in order to reduce any related influence due to colorblindness (two subjects) and prescription glasses (six subjects), and checked that none had any restrictions concerning touch sensations on the skin. Data of an additional thirteenth participant had to be discarded due to a system error that appeared during the test.

4.3.2 Matching Task

Each experiment consisted of the actual weight test, and a pure tactile control condition (without any visual cues). At the beginning of the weight experiment, the participant received the following instructions: 'In this experiment, you will feel a virtual object with a certain weight falling on your right arm. In each round, the object will first be blocked from your view, and the second time you will be able to see it. These two sensations on your arm may feel different. After feeling both, you must indicate whether the second ball felt as heavy as the first, or that the second felt lighter or heavier than the first. The goal is to adjust the tactile sensation such that you experience them the same.'

In each trial, the participant was presented with a reference and a comparison stimulus. The reference stimulus was a tactile-only stimulus, while the comparison stimulus was a combination of a tactile and a visual stimulus: a sphere that was small and slow, medium and normal, or large and fast. For the reference stimulus, an occluder in the form of a cylinder would appear, covering the vertical trajectory the sphere would cover; cf. Figure 2. Then two audio beeps with a 700 ms interval would occur, and after another 700 ms the tactor on the arm was activated at intensity level x for 200 ms so the participant felt a vibration. This was followed by the comparison condition, where the occluder disappeared. After one beep a gray sphere with a certain size appeared in mid-air at eye-level and remained in this position for 700 ms. Then another beep occurred, after which the sphere fell in a vertical trajectory onto the virtual arm with a certain speed. Upon contact, the tactor was activated at intensity y for 200 ms and the sphere disappeared. At this stage the participant replied whether the sensations were the same, or whether the second was lighter or heavier than the first. If they answered that they were the same, the trial was over, and a new reference stimulus was presented. Otherwise, the tactile comparison intensity was adjusted to $y+1$ if the participant answered 'lighter', or to $y-1$ if they said 'heavier'. The reference and comparison stimuli were then presented as before, but now the tactile comparison intensity was at the adjusted level. This presenting and adjusting continued until the participant felt that the sensations matched. Table 2 outlines single trial. All *tactile reference intensity - visual comparison intensity - final tactile comparison intensity* combinations were logged separately for each participant.

Step	Experiment
1	Tactile Reference α Tactile Comparison μ + Visual x
2	Tactile Reference α Tactile Comparison ν + Visual x
$\vdots$	$\downarrow$ adjust tactile
m	Tactile Reference α Tactile Comparison π + Visual x

Table 2: Outline of a single trial in the weight and temperature conditions. Gray cells indicate the presence of the occluder. Log for this example: $\alpha - x - \pi$

For the control condition, the participant was given no verbal or visual indication of the tactile property of the sphere. Terminology was changed to 'less intense'/'more intense' rather than 'lighter'/'heavier'. Also, the comparison stimulus was identical to the reference stimulus. That is, the spheres were always visually blocked by the occluder. Table 3 outlines a single trial in the control condition. All *tactile reference intensity - final tactile comparison intensity* combinations were logged separately for each participant.

Step	Experiment
1	Tactile Reference α Tactile Comparison μ
2	Tactile Reference α Tactile Comparison ν
$\vdots$	$\downarrow$ adjust tactile
m	Tactile Reference α Tactile Comparison π

Table 3: Outline of a single trial in the control condition. Gray cells indicate the presence of the occluder. Log for this example: $\alpha - \pi$

4.3.3 Results

First, we discuss the method for handling the results of the weight experiment. Consider one particular participant. The mean of all final tactile comparison intensities (eight values) is determined for every combination of tactile reference intensity and visual comparison intensity. This results in twelve values per participant. These values are then standardized by subtracting 5, 8 or 11, corresponding to the tactile reference intensity. The standardized means are given in Table 4 and are visualized in Figure 3. Normality was tested using Shapiro-Wilk tests; four cases were not normally distributed, namely: *Ref5-Control* ($W(12) = 0.833; p = 0.023$), *Ref5-Visual1* ($W(12) = 0.752; p = 0.003$), *Ref5-Visual2* ($W(12) = 0.643; p < 0.001$), and *Ref8-Visual2* ($W(12) = 0.814; p = 0.014$).

The data was analyzed with a two-way repeated measures ANOVA, with factors visual comparison intensity (three levels) and reference intensity (three levels). Mauchly's Test of Sphericity indicated that the assumption of sphericity had been violated in the reference intensity factor ($\chi^2(2) = 12.530, p = 0.002$), and a Greenhouse-Geisser correction was used for this factor. The analysis gave the following results: there was a significant main effect over reference intensity ($F(1.167, 12.833) = 45.438; p < 0.00001$), a significant main effect over visual intensity ($F(2,22) = 8.855; p = 0.002$), but the interaction effect was not significant ($F(4,44) = 0.028; p = 0.998$). Pairwise comparisons with a Bonferroni adjustment showed that each reference intensity differed significantly from the others (all $p < 0.001$), and that visual intensities 0 and 2 ($p = 0.005$) and 1 and 2 ($p = 0.013$) differed significantly. Nine paired t-tests were run between control results and each visual intensity within each reference intensity. These showed that the results of none of the

	Ref5	Ref8	Ref11
Control	0.292	-0.094	-0.385
Visual0	0.177	-0.198	-0.708
Visual1	0.271	-0.073	-0.573
Visual2	0.510	0.167	-0.333

Table 4: Standardized means over all conditions of the weight experiment.

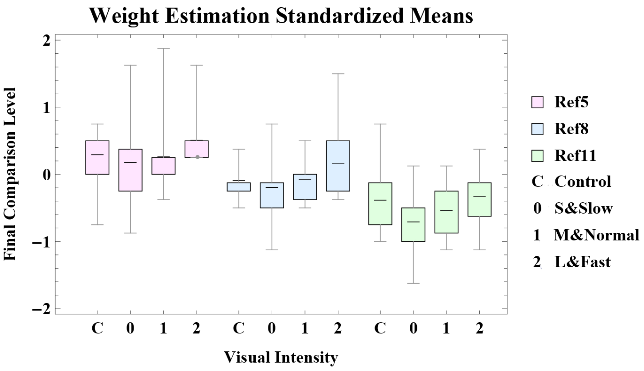

Figure 3: Boxplots of the standardized results of the weight experiment with mean markers. The labels *5*, *8*, *11* refer to the tactile reference intensity, *C*, *0*, *1*, *2* to the visual intensity.

Question	Answer	Weight	Temperature
1. Virtual arm your own	strong	3	2
	weak	5	2
	none	4	6
2. Visual or tactile	visual	2	0
	tactile	10 (4)	10 (4)

Table 5: Answers to the post-experiment questions by experiment. The number in brackets indicates the number of participants who initially used visual cues.

visual conditions differed significantly from those of the corresponding control.

Qualitative results of the post-experiment questions are summarized in Table 5 in column *Weight*. Three participants answered that they had a strong feeling that the avatar's arm was their own, five had a less strong feeling, and four responded to not feeling any connection at all. Regarding using visual weight or intensity, two participants responded that they used the size and the speed of the spheres, and the other ten used the vibration intensity, of which four stated they tried to use the size and weight, but found it unreliable after a few rounds.

4.4 Temperature Experiment

4.4.1 Participants

Ten participants took part in the temperature experiment – eight male, two female, ages from 22-24 (average 23.2), nine right-handed, one ambidextrous. Four had no prior experience with HMDs, four had taken part in one or a few demonstrations, and two had worked on projects using one. None were colorblind, two wore prescription glasses, and none had any restrictions concerning touch sensations on the skin. Again, we do not see any influences of these parameters on the evaluation results. Data of three additionally tested subjects had to be discarded due to one system error and two premature terminations due to the subjects being unfit as a result of strain on their eyes.

4.4.2 Matching Task

The method used during this experiment is equivalent to that described in Section 4.3.2, now using the terminology 'temperature' instead of 'weight', and 'colder'/'warmer' instead of 'lighter'/'heavier'. In addition, all spheres have the same size and falling speed, but different colors: blue, gray and red, which are commonly associated with cold, neutral, and warm temperature, respectively; cf. Figure 2.

	Ref5	Ref8	Ref11
Control	-0.113	-0.150	-0.463
Visual0	0.075	-0.213	-0.250
Visual1	0.050	-0.338	-0.475
Visual2	-0.188	-0.188	-0.425

Table 6: Standardized means over all conditions of the temperature experiment.

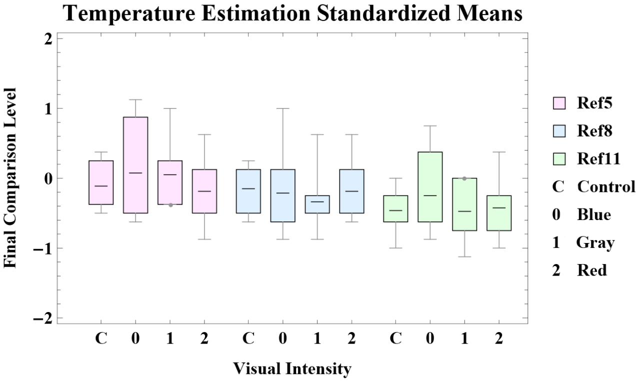

Figure 4: Boxplots of the standardized results of the temperature experiment with mean markers. The labels *5*, *8*, *11* refer to the tactile reference intensity, *C*, *0*, *1*, *2* to the visual intensity.

4.4.3 Results

The results were standardized as in the previous experiment, see section 4.3.3. The standardized means are given in Table 6 and visualized in Figure 4. Normality was tested using Shapiro-Wilk tests, which showed that three cases were not normally distributed: *Ref5-Control* ($W(10) = 0.843; p = 0.048$), *Ref5-Visual0* ($W(10) = 0.840; p = 0.044$), and *Ref8-Visual1* ($W(10) = 0.810; p = 0.019$).

Mauchly's Test of Sphericity indicated that the sphericity assumption had been violated in the interaction effect ($\chi^2(9) = 18.643; p = 0.032$), so a Greenhouse-Geisser correction was used for this effect. A two-way repeated measures ANOVA showed that there was no significant main effect over reference intensity ($F(2,18) = 2.028; p = 0.161$), no significant main effect over visual intensity ($F(2,18) = 0.946; p = 0.407$) and there was also no significant interaction effect ($F(2.037, 18.332) = 1.817; p = 0.190$).

Although there was no significant main effect over reference intensity in the results of the temperature experiment, the results of both experiments are combined to investigate this effect further. Three independent samples t-tests were run for each reference intensity, which showed that only the results for reference intensity 5 differed significantly between groups ($t(86) = 3.293; p = 0.001$). In the same way, three independent sample t-tests were run for the control results, which showed that again only the results of reference intensity 5 differed significantly between groups ($t(20) = 2.479; p = 0.022$). Normality was tested for each reference intensity with Shapiro-Wilk tests, which showed that reference intensities 5 and 8 were not normal ($W(88) = 0.959; p = 0.007$ and $W(88) = 0.950; p = 0.002$). Sphericity was violated according to Mauchly's Test ($\chi^2(2) = 28.988; p = 0.000001$) so a Huynh-Feldt correction was used. A one-way repeated measured ANOVA with factor reference intensity (three levels) showed that there was a significant main effect ($F(1.578, 137.298) = 58.238; p < 0.0000001$), and pairwise comparisons with Bonferroni correction showed that each comparison was significant ($p < 0.000001$).

Qualitative results of the questions are summarized in column *Temperature* of Table 5. Two participants answered that they had a strong feeling the avatar's arm was their own, two had a less strong feeling, and six responded to not feeling any connection at all. All participants used the vibration intensity to come to an answer, of which four stated they thought they may have been influenced by the color of the sphere.

5. DISCUSSION

The experiment addressed the research question: *Is it possible to create the illusion of experiencing different intensities of a certain property (weight or temperature) using a rather simple and unrelated type of touch (vibrations of different intensities) together with compelling, type-related visuals (speed/size and color, respectively)?* Using a matching task, we speculated that related quantitative measures enable us to identify if people are likely to associate such tactile experiences with these properties and if or how concrete intensity levels have to be set when visual stimuli change. We expected that the richer visual stimuli can be used to change a user's tactile perception – ideally in a way that enables us to simulate more complex tactile experiences.

This conjecture was verified for the weight property, but not for the temperature property. In the weight experiment, the consistent increase in equally perceived tactile intensities when visual intensity was increased means the sensation felt on the skin was estimated 'lighter' when the visual sphere looked heavier, even though the true tactile vibration intensities were held constant. This is consistent with the speed-force illusion [1] and the size-weight illusion [29]. However, after analysis of the post-experiment responses, it was clear that almost all participants eventually used the intensity of the vibrations in order to respond in each trial. This means that the visual cues caused participants to subconsciously generate an expectation which changed not only the intensity of the felt sensation, but possibly also the type. However, consciously no association to weight was made. While we can thus *not* conclude that people will associate such related vibrations with the characteristic of weight, these observations are essential for system design when including tactile feedback into such a VR setting. Roughly speaking, if a visual stimulus suggests a higher weight, but the matching tactile feedback is experienced as less intense, there is a high likelihood that the illusion of weight is not only not apparent but even 'destroyed'. The added modality would then not increase the experience but make it even worse, whereas an adjustment of intensity as suggested by our results will guarantee a 'perceived' match of both modalities.

Although the observed contrast effect is in line with various studies concerning weight, pressure and force [5], the question remains why it occurred here. An assumption was that the visual stimuli would contribute to the perception of weight, which means that when the visual intensity is increased, the tactile intensity must be decreased. However, if these stimuli actually weakened the weight perception rather than contributed, then the tactile intensity must in fact be increased when visual intensity was increased. This is reasonable since the weight estimation of the comparison stimulus is decided indirectly through cognitive processes, while that of the reference stimulus is decided directly through sensory processes. On the other hand, we cannot state that the participants indeed perceived weight; participants may have, for example, estimated transferred energy per unit area of skin contact, i.e. maximum pressure. When assuming constant mass, a larger area of skin contact would lead to a lower level of perceived pressure.

In the temperature experiment, no significant differences were found over visual intensity. The question that arises is why this occurred for the property weight, but not for temperature. The participants could either not associate vibrations with temperature, or color with temperature, or both. An explanation concerning the first scenario is that impact induced by the weight of an object can either be felt through a vibration, or is easier to translate from a vibration than the temperature of an object – a reasoning that can be supported by examining different receptors found in human skin. Mechanoreceptors respond to mechanical pressure and distortion, and there exist different types: Pacinian corpuscles, Meissner corpuscles, Merkel receptors, Ruffini end organs, and receptors in hair follicles. Each one responds to vibrations in a certain frequency range. Since impact and vibration are of the same nature, i.e. they both cause skin distortion, it may be the case that both sensations can be felt, and which is finally chosen is caused by surrounding/congruent factors. In the case of the change in weight, the participants were visually expecting a sense of impact to occur, and not a vibration. Changes in temperature, on the other hand, are sensed through thermoreceptors, causing the perceptual 'gap' between vibration and temperature to be too large to bridge despite the visuals. The second scenario, i.e. that participants could not associate temperature with color, was disproved in a study by Ho et al. [13]. By objective performance measurements, it was shown that humans make a cross-modal correspondence between color and temperature, specifically in the direction color-temperature, and not temperature-color.

An interesting observation can be made when looking at the results with respect to the order of presentation. Because we used a method of adjustment, we had to present the reference stimulus first, followed by the comparison that subjects had to adjust. This is in contrast to references (e.g., [9]) suggesting a counterbalanced representation in order to avoid a shift in results; generally, for psychophysical experiments, it is assumed that the second stimulus is often judged as 'greater' than the true equality. While in our case, 'greater' does not necessarily correspond to a higher vibration intensity, it does however suggest that a shift in one direction may occur. A significant main effect was found over tactile reference intensity in the weight experiment, but not in the temperature experiment. The combined results, however, show this effect as well. This means that low vibrotactile intensities are experienced as weaker than they really are, and high vibrotactile intensities as stronger. Because this shift is not consistently in the same direction, it may indicate an interesting aspect with respect to the design of psychophysical experiments worth investigating in future research.

Another noteworthy aspect appears when examining the post-experiment answers with respect to the so-called rubber hand illusion [3] – a body illusion experiment where subjects 'experience' a rubber hand as being their own due to a visual stimulus on the artificial hand (e.g., being stroked by the object) that is congruent to a real tactile sensation on their (visually hidden) real hand. The results from Table 5 suggest that participants in the weight experiment were able to generate a stronger rubber hand illusion than those in the temperature experiment. This in turn suggests that when visual and haptic information are 'more congruent' then a strong rubber hand illusion occurs, or the other way around, i.e. that when a strong rubber hand illusion occurs then visual and haptic information are 'more congruent'. The findings of [20] are in line with the first suggestion; correct visual perspective together with correlated multisensory information trigger a strong illusion. However, in [18] it was observed that incongruent cues are not experienced as incorrect when the illusion was strong, which is in line with the second suggestion. It is clear that these elements are strongly related, however at this stage it is unclear how.

Two rather curious artifacts worth mentioning are first, that the results from the control condition in the case of tactile reference intensity 5 differed significantly between experiment groups, and not in the case of intensities 8 and 11. However, the control conditions were identical in both experiments and thus this difference should only be caused by chance. Second, from the answers to the post-experiment questions it was clear that the body transfer illusion was not very strong for most participants. This is in contrast to our assumption that a first person view will be sufficient to achieve this (which in turn was based on related research; cf. Section 2.3). Because a first person experience is not essential for the tests presented in the paper, we do not suspect any related impact on our results. The observed effect does however raise an interesting question for future research. Is this lack of body transfer just due to the used setup (e.g. several participants noted that finger movements in the real world were not directly mapped to the virtual world) or does the introduced combination of modalities, i.e., tactile and visuals have an effect as well?

6. CONCLUSION AND FUTURE WORK

The work presented in this paper was motivated by the goal to gain a better understanding of passive touch perception and to investigate if a simple vibration feedback has the potential to improve VR experience when used in combination with richer visual stimuli. In a series of experiments, we have shown that visual cues that give an indication of weight, specifically size and falling speed, can change the perceived intensity of a vibration felt on the skin upon collision. Precisely, the sensation felt on the skin was estimated 'lighter' when the visual ball looked heavier. This means that future VR systems with the goal of creating different weight intensities would need to substantially exaggerate the weight by vibration in order for it to seem realistic for humans. This was not the case when using vibrations to simulate a temperature in combination with color as a visual cue. We conclude that it is not possible to let humans perceive different temperatures through vibrations and accompanying visual color cues; while other temperature-indicating cues may produce other results, our study suggests that such an investigation may not be worthwhile.

The results of this research also identified two more general open problems. The first was of fundamental ground regarding general psychophysical experiments, namely what the consequences are of presenting reference and comparison stimuli successively and in the same order. Specifically, our results suggest that in the case of vibrotactile stimuli, the bias in judgement due to unbalanced presentation is not consistently in one direction as was previously thought. The second problem concerned body transfer illusion, and questioned whether the body transfer illusion was a consequence or a cause of accepting incongruent stimuli as plausible. This is an important practical observation, because both possibilities show that only one is needed in the design of a compelling multimodal experience.

As this study was an exploratory investigation, the successful result for weight simulation opens various opportunities for interesting future research. An initial idea is to broaden the range of acceptable touch; this study was only able to add the concept of weight to this range using visual speed and size, but it is not misplaced to insist that this could happen for other properties. An intriguing question of course is then what kind of accompanying visuals are necessary to accomplish this. Lastly, this study only used two modalities: haptic and visual. It is worth investigating whether audio cues strengthen the effect found in this study and thus have the potential to create even better, more immersive experiences.

7. ACKNOWLEDGMENTS

Our thanks go to Elitac B.V. for supplying the necessary hardware and valuable support during this research.

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