Pseudo-Weight: Making Tabletop Interaction with Virtual Objects More Tangible

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ABSTRACT
In this paper we show that virtual objects manipulated on a tabletop interaction device can be augmented to provide the illusion they have a weight. This weight offers a supplemental channel to provide information about graphical objects without cluttering the visual display. To create such a *pseudo-weight* illusion on a passive device, the pressure applied with the fingers during the interaction has to be captured. We show that this pressure can be estimated without hardware modification on some touch sensitive tabletop setups (e.g., MERL's DiamondTouch). Two controlled experiments show that *pseudo-weight* is perceived effectively. The first one demonstrates that users, without training and without previous knowledge of the system, can accurately rank virtual objects according to their pseudo-weights, provided they are sufficiently distinct. The second controlled experiment investigates more formally the relation between the pseudo-weight and the actual perception of the users.

Keywords: Tabletop interaction, pseudo-weight.

ACM Classification: H.5.2 [**Information Interfaces and Presentation (e.g., HCI)**]: User Interfaces – *Graphical user interfaces, Input devices and strategies*.

INTRODUCTION
Over the past few years, tabletop interaction turned from prototypes into commercial products (e.g., the MERL DiamondTouch [4], or the Philips Entertaible [6]), and the software editor Microsoft Corp. has coined the term "surface computing" to refer its first touch-enabled products: the Surface table from 2007. These systems are significant steps towards the merge of the digital and physical worlds envisioned twenty seven years ago by Krueger et al. [8].

However the illusion of manipulating real objects on a table is not yet complete. Some physical properties such as tactile and haptic feedback are still missing when users are interacting with virtual objects. To provide feedback through these mechanical perception channels, the output device would have to be actuated. The hardware involved would be more complex, consume more power, and be more prone to failure.

In this article, we investigate the psychophysics of a software technique that creates the illusion of a weight for virtual objects. This weight is a pseudo-perception: the channel by which the feedback is provided is not the regular one (tactile or haptic) but a substituted perception channel (namely vision) coupled to a passive (force) sensor.

We first review previous works related to our research. Then we present how we have implemented the pseudo-weight on a tabletop interaction device. Two experiments are then reported: the first one demonstrates that users perceive the pseudo-weight and can use it to accurately order virtual objects. The second experiment characterizes more formally the relation between the pseudo-weight assigned to objects and its perception by the user.

RELATED WORK
Previous works have introduced the notion of pseudo-haptic feedback: haptic properties such as stiffness, friction, or feeling forces, bumps or holes, can be simulated without haptic devices. Pseudo-haptic friction/stiffness feedback was initially obtained by coupling a force sensor with a perturbed visual feedback [10]. Sugimoto et al. and Lecuyer et al. proposed to simulate forces and bumps or holes by simply varying the control to display ratio of the cursor [14, 9]. With tabletop interaction, such techniques can not be used because of the colocation of the cursor and the finger.

Early work on using the pressure on a touch sensitive device dates back to the eighties (e.g., [2]). But even recent works (e.g., [1, 12]) use the pressure as a supplemental input channel only. The coupling of the pressure with a tactile feedback is investigated by Rekimoto & Schwesig [13], but they used an actuated device to provide the feedback. Physical constraints on tabletop interaction is investigated by Patten & Ishii [11], but with mechanically enforced constraints. More recently, physical models have been used to add plausible collision and friction [5] but without using the pressure as input. ShapeTouch [3] explored the design space for interaction using virtual forces but does not deal with pseudo-weight.

PSEUDO-WEIGHT
In order to substitute a sensory channel with a pseudo-perception, we have to understand the actual perception. For doing so, we have observed users moving real objects with different weights (e.g., sheet of paper, books, etc.) on the surface of a table using one finger. The actual physics in-

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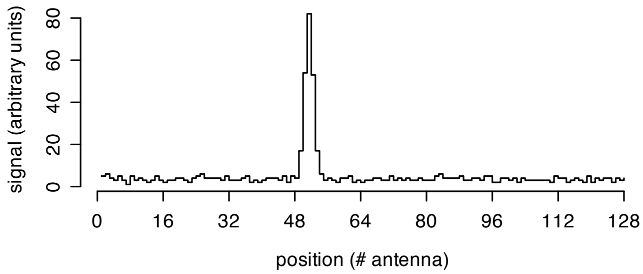

Figure 1: Typical signal reported by the MERL DiamondTouch antennas when a finger touches the table.

volved is surprisingly complex, drawing upon tribology, the science of friction. In our particular case, we observed two distinct modes: either the pressure on the object is sufficient, the object sticks to the finger and follows its movements, or the pressure is not sufficient, and the object sticks to the table and does not move regardless of the finger movements.

To simulate this behaviour, we have solved three problems, two of them were identified a priori while we did not anticipate the third one:

- capture the pressure applied with the finger to the table during the interaction (technological challenge);
- create the pseudo-weight illusion by simulating the behaviour of the virtual objects according to this pressure and to the weight assigned to them (design challenge); and
- provide insights that the system is reliable to avoid misinterpretation of an immobile object (design challenge).

Capturing Pressure

To conduct this study, we have used a MERL DiamondTouch coupled with a video projector. The DiamondTouch does not include any pressure sensor but we found that pressure can be estimated from the raw data captured for finger tracking. Fingers position is achieved by detecting variations of the capacitance caused by the fingers in an array of antennas embedded in the table [4]. We observed that the capacitance varies according to the surface of the finger in contact with the table. In turn, this surface varies according to the squeeze applied to the table. Since the DiamondTouch API gives access to the row values read from the antennas (Figure 1), we have access to a quantity that varies according to the pressure. This quantity is not a real measure of the pressure, but it allows us to create the pseudo-weight illusion as the experiments described below show (measuring the real relation is not an option because placing a force sensor between the finger and the table disturbs the capacitance measure).

The DiamondTouch uses two orthogonal arrays of antennas that produce two monodimensional images of the table projected on the x-axis and y-axis. These images consist of 128 (resp. 96) values measured periodically by the vertical (resp. horizontal) antennas. Figure 1 shows the vertical antennas that give a projection of the table on the horizontal axis. The reported values are integers ranging from 0 to 255. We consider the x-axis array only since it provides sufficient data to compute the pressure. We define the pressure, in arbitrary units, as the sum of the values that pass a threshold of 10. This threshold is necessary because the signal reported by the antennas is noisy, and is never a true 0 even in the absence of contact on the table. The sum performs a spatial integration of the signal so as to cover the whole contact surface (the spatial resolution of the antennas grid is 5 mm, and a finger typically activates 4 successive antennas).

Creating the Pseudo-Weight

Based on our preliminary observations, we have implemented the pseudo-weight by adding a *weight* attribute to each draggable object. At the beginning of an attempt to drag an object (when a finger touching the table enters an object) the current pressure is compared to the weight of the object. The object starts to move only when the pressure exerted exceeds its own weight. This makes heavy objects hard to move whereas light objects are easily dragged as in real life.

Pressure is monitored continuously during dragging. Dragging ends when the pressure falls below the weight of the object reduced by a constant. This constant is introduced so that the noise in the signal does not affect the interaction. It also models the hysteresis observed in the physical world known as static friction: friction forces are stronger when the object is immobile than when it has started to slide.

The objects are thus made sensitive to the pressure: according to their weight, the user has to drag them more firmly if they are heavier. Since more effort is needed to move the heavy object, the user should perceive it and associate this perception to a physical attribute of the virtual objects.

Providing Visual Feedback of the System Reliability

When we first confronted naive users to the system previously described, some of them did not perceive anything. They interpreted the fact that some objects did not move when they tried to drag them as a malfunction of the finger tracking. We did not anticipate that our users are used to tactile systems, like automatic dispensers, that often miss user inputs. We solved this issue by providing an additional feedback: a circle is projected at the position of the tracked fingers. Since the finger tracking is very robust, these circles follow the fingers in real time without noticeable lag. This makes the user unconsciously aware of the reliability of the tracking system and re-enables the illusion.

EXPERIMENTAL VALIDATION

To test our hypothesis, we have conducted two experiments. 12 master students volunteered to take part in this study, they all did both of them. The first experiment is designed to check that the pseudo-weight is perceived and that it can be used as an output channel for a digital table. The second experiment is designed to explore more deeply the relationship between the pseudo-weight and its perception.

Proof of Concept

Our initial informal experiments convinced us that the pseudo-weight was actually working, but we wanted to evaluate if (and how) a user would perceive the effects of the system if she is not aware of the system internals. The participants were only told that they "would take part in an experiment designed to evaluate a new interaction technique on a digital table". Each one was familiarized individually with finger interaction on the tabletop display by using a non pseudo-weight enhanced photo-shuffler application until she was able to manipulate the photos easily.

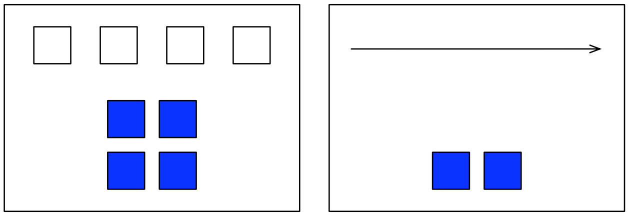

Figure 2: Experimental setups. (left) first: 4 places at the top, 4 blue squares to order at the bottom; (right) second: 2 squares to place on an axis.

Setup When the participant is ready, the experiment begins. A text displayed on the table invites him to sit conformably and provides the following instructions:

> "In the next screens, 4 squares looking identical will be presented together with 4 places to put them. The squares behave differently while interacting with them. You can try to manipulate the square below."

Four draggable squares with different weights are placed at this place. The instructions then continue:

> "Please move the squares into the places, and arrange them from left to right in growing order. When you are done, press the *next* button to start a new task."

As our goal was to test if the pseudo-weight is perceived by untaught people, the text was intentionally left vague and did not explicitly state what is the difference between the squares nor which criterion should be used to sort the squares.

When the participant depresses the *go* button, a series of 10 trials starts. Each one presents the same visual aspect: 4 blue squares grouped in front of the user and 4 places horizontally aligned on the top of the screen (see Figure 2 left). For each trial, the weights of the square are evenly distributed between 2 random extremal values. These values are constrained in a range compatible with the interaction determined a priori.

Results After the tests, the participants were asked to name the criterion they used to order the squares. Two of them did not notice any effect and could not find a name, but the 10 others cited: "force", "friction", "power" or "surface". Those terms are all related to the action of the user rather than to a property of the objects. When we suggested "weight" as a characteristic of the objects, the participants agreed upon it. We choose this term because it also has an abstract meaning.

Despite involving only 120 trials, the qualitative results are interesting. All of the 10 participants who felt something ordered spontaneously the objects in ascending weights from the left to the right: the object on the left is lighter than the one on the right in more than 70% of their trials. When considering all the participants, the heaviest object is correctly placed 66.67% of the time, the lightest one 60%. There is more confusion for the average objects: the second heaviest (resp. lightest) object is correctly placed 54.17% (resp. 51.67%) of the time. The whole 4 objects are positioned in the correct order 39.17% of the time.

These results depend highly on the difference between the weights of the objects presented simultaneously. If we redo the same analysis considering only the half of the data produced by the trials where the weights were the most separated, the order is correct 48.33% of the time. The heaviest (resp. lightest) object is correct 81.67% (resp. 68%) of the time (61.67% and 58.33% for the two other objects).

These results show that users perceive the pseudo-weight without being taught and that some information can be transmitted through this channel. It also shows that the more the weights are separated, the more they are discernible.

Controlled Experiment

The goal of the second experiment is to better understand the perception of the pseudo-weight.

Setup The experiment is roughly similar to the previous one, but only two squares are presented to the participant at each trial, and a directed axis is displayed at the top of the screen (Figure 2 right). The axis is depicted to the user as an axis "where the lightest object should be on the left side, and the heaviest on the right side". The participant is then instructed to place the two squares on the horizontal axis according to their respective weights.

Two factors are used to determine the weights of the squares: the median weight (w) and the difference between the two weights (Δw). The two variables have three possible values: $w_0 = 80$, $w_1 = 95$, $w_2 = 110$ (arbitrary units); and $\Delta w_0 = 4$, $\Delta w_1 = 8$, $\Delta w_2 = 12$. Nine possible couples of weights are then possible ($w_i \pm \Delta_j/2$, $(i,j) \in [0,2]^2$). To balance order effects, a pseudo-random series of 81 trials consisting of 9 time each couple was constructed using a 9×9 latin square.

Results The final abscissas of the light and heavy squares (x_l and x_h) are recorded and two dependent variables are computed: the median abscissa around which the two objects have been positioned $x = (x_l + x_h)/2$; and the signed deviation that separates them $\Delta x = x_h - x_l$.

We first test the hypothesis that the squares are placed in the right order (i.e. $\Delta x > 0$). As in the first experiment, there is a lot of inter-subject variability: the least effective participant is only slightly better than random (55,56% of correct ordering), whereas the highest success rate was 90,12%. On average, the success rate is $68.52 \pm 9.56\%$[1]. A repeated measure analysis of variance (ANOVA) shows that the only significant effect on the success is the difference between the weight of the two objects Δw ($F = 10.69$[2]).

The mean position x also depends highly on the user. A repeated measure ANOVA shows that the main factor affecting the position x is the weight w ($F = 175.12$). Figure 3 shows x as a function of w with the means connected. They form a quasi-straight line ($r^2 > 0.998$ for the linear fit). Similarly, Δx is essentially a function of Δw ($F = 11.62$). The linear fit is also very good ($r^2 > 0.98$).

These results show that the discriminability of two pseudo-weights is directly linked to the amplitude of the difference separating the weights, which was expected. A more notable result is that the mapping between the weight assigned to the

[1] $m \pm \sigma$: the mean (m) and standard deviation (σ) across users.

[2] Reported F statistics all have a p value smaller than 0.0001.

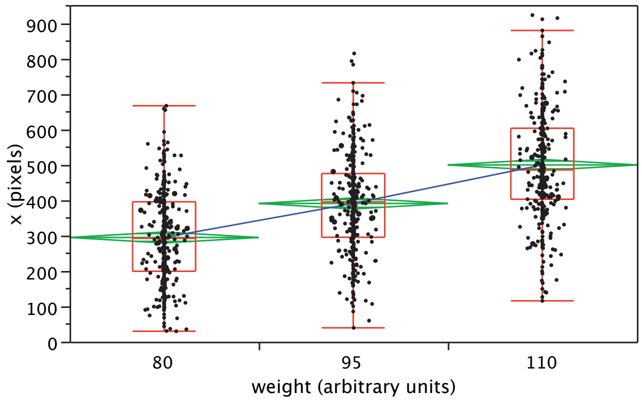

Figure 3: Position vs. weight (diamonds show 95% confidence intervals, box plots .25 and .75 quantiles).

objects and the position where the participants put them is linear. It means that the arbitrary weight scale created by our software implementation of the pseudo-weight is the same as the psychophysical scale the user has modeled after her experience of the real world. This result validates a posteriori our definition of the pressure as a function of the capacitance signal, and the physical model on which we have based the pseudo-weight implementation.

CONCLUSION & FUTURE DIRECTIONS

We have shown that virtual objects can be augmented with a pseudo-weight on a passive touch sensitive surface provided that pressure can be monitored. We have shown that on a regular DiamondTouch table, this information can be deduced from the raw capacitance. We have shown that this input channel, coupled with an adequate visual feedback, can provide a pseudo-perception. In addition, pseudo-weight conveys information: our experiments show that it allows users to rank objects which are visually identical.

The technique has some weaknesses. The first one is that the real tactile signal is contradictory with the simulated behaviour: the real object below the finger (the table) is immobile, even when the virtual objects is dragged. This limits the palpability of the illusion, but this limitation seems impossible to overcome without introducing tangible objects [11] or active feedback [7]. The second weakness is that the perception scale depends on the user. Several factors affect the range of pressure computed from the capacitance: a different finger size or a dryer skin changes the capacitance while the same real pressure is exerted. A sensor really responsive to the pressure would solve this problem.

This technique is nonetheless promising since it offers a supplemental channel to provide information about graphical objects without cluttering the visual display. It can be used to transmit weights in a broad sense i.e. any attribute that can be mapped on a continuous scale (e.g., for an icon, the size of the file it represents). We have observed that, contrarily to other interaction techniques involving a smart coupling in the perception-action loop, the pseudo-weight is noticeable for spectators of the interaction. They easily interpret the visual feedback provided by the degree of flexion of the finger as it is totally natural. This property is valuable since tabletop devices are often used for collaborative work.

In the future, we would like to study how the pseudo-weight could be exploited in collaborative environments (e.g., making objects harder to move if they are in someone else focus could improve awareness of such situations). On a more theoretical side, studying how the visual clues (e.g., size, shape or texture of the objects) interfere with the pseudo-weight could provide interesting results.

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