Digital Vibrons: Understanding Users' Perceptions of Interacting with Invisible, Zero-Weight Matter

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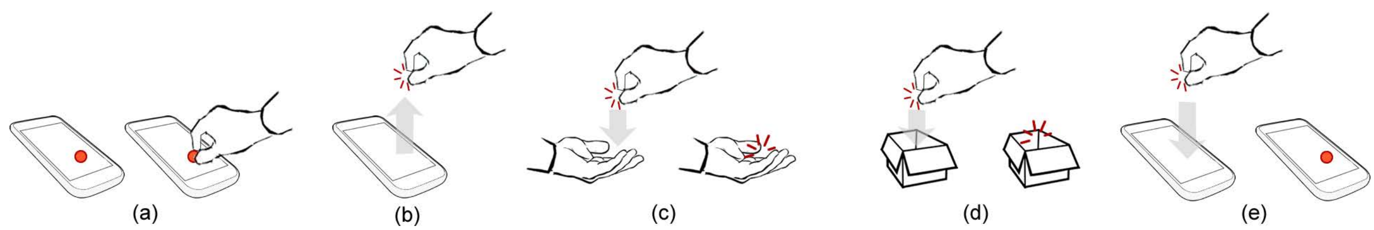

Figure 1. Digital vibrons are manifestations of digital objects in the physical world in the form of vibrations. For instance, when picked up and lifted off of the screen (a), objects turn into invisible, zero-weight digital vibrons that produce vibrations (b). While in the physical world, vibrons can be transferred to other locations, such as the other hand (c) or placed inside physical containers (d), until they return to their device and resume their visual representation on screen (e). Digital vibrons are *invisible* to the eye, have *zero weight*, yet are *detectable* by means of *localized vibrations*.

ABSTRACT
We investigate in this work users' perceptions of interacting with *invisible, zero-weight digital matter* for smart mobile scenarios. To this end, we introduce the concept of a *digital vibron* as vibrational manifestation of a digital object located *outside* its container device. We exemplify gesture-based interactions for digital vibrons and show how thinking about interactions in terms of digital vibrons can lead to new interactive experiences in the physical-digital space. We present the results of a user study that showed high scores of users' perceived experience, usability, and desirability, and we discuss users' preferences for vibration patterns to inform the design of vibrotactile feedback for digital vibrons. We hope that this work will inspire researchers and practitioners to further explore and develop digital vibrons to design localized vibrotactile feedback for digital objects outside their smart devices toward new interactive experiences in the physical-digital space.

ACM Classification Keywords
H.5.2. User interfaces: Haptic I/O; Input devices and strategies; Artificial, augmented, and virtual realities.

Author Keywords
Vibrons; touch; smart device; vibrotactile; feedback; digital matter; evaluation; user study; elicitation study; gestures.

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INTRODUCTION
Driven by increased miniaturization, smart mobile and wearable devices offer users smaller and smaller active areas for visualization and interaction [24,26,29]. Consequently, there is a need for new interaction techniques for users to access information efficiently on these devices. Researchers have been addressing this challenge with new soft keyboard designs [13], assistive stylus input [48], and custom gestures [14,25]. Other researchers looked beyond the screen and designed interactions with on-screen objects *above* or *around* the device [9,12]. The idea of transferring interactions from the device to the physical space around it was an exciting step forward with many practical benefits in terms of richer and more flexible interfaces, but it also brought new challenges for visualizing digital objects in that space. Researchers have resorted to spatial augmented reality (*s*-AR) techniques as workarounds. Although *s*-AR research has contributed many techniques to visualize digital information in the physical world [38], relying on *visual* representations delivered by video projectors requires instrumentation of the environment [17,44] or the need for users to wear *s*-AR equipment, such as sensors and projectors [11,22], options not suited for mobile interaction.

We position our work in the context of current research efforts to design interactions with digital information that users can operate *outside* their smart devices [10,36]. In this paper, we explore a new concept for such interactions: when in the physical world, digital objects are *invisible* to the eye, have *zero weight*, but manifest their presence with localized *vibrations*, until they reach again their container device. For example, imagine a user performing a more sophisticated variant of Pick-and-Drop [27] by lifting off an object of the surface of their smartphone (Figure 1a). The invisible, zero-weight object starts to vibrate on the user's fingers to signal its presence (Figure 1b). Vibrations follow the object in the physical world when the object is transferred to the other hand or placed inside a physical container (Figures 1c,d). Vibrations stop when the object returns to its native device (Figure 1e).

To formalize and implement such interactions, we introduce *digital vibrons*, a concept that we derive in analogy with notions from the physics of condensed matter [47]. In physics, a vibron denotes a quantum of intramolecular vibration determined by interactions between atoms' nuclei. Digital vibrons are vibrations induced by the *presence* and *behavior* of a digital object leaving its native container (*e.g.*, a smartphone) as result of some user action, as in Figure 1. Our choice to represent objects as vibrations finds support in the increased interest in vibrotactile feedback [9,20,30,31], readily accessible on many commercial wearables at arm-level (Myo[1]), wrist-level (smartwatches), or finger-level (Ring Zero[2]). We implemented a prototype for digital vibrons that we used to evaluate and understand users' perceptions of interacting with invisible, zero-weight matter, the main focus of this work.

The contributions of this work are as follows: (1) we introduce the concept of a *digital vibron* as vibrational manifestation of a digital object outside its container device; (2) we present a modular design implementation of digital vibrons, which we use to (3) examine users' experience and perceptions of interacting with invisible digital matter; and (4) we report results of an elicitation study to inform the design of vibrotactile feedback for digital vibrons. We hope this work will inspire researchers and practitioners to explore the opportunities of digital vibrons to deliver localized vibrotactile feedback for smart devices, wearables, and augmented spaces and, consequently, to deliver users with new sensory experiences when interacting with invisible digital matter outside digital devices.

RELATED WORK

We review in this section work on implementing awareness of virtual objects, we discuss connections between digital vibrons and tangible [15,16] and imaginary user interfaces [5,10,36], and we point to relevant work on vibrotactile feedback.

Digital objects in the augmented physical world

Representing digital objects in the physical world has been examined in the context of augmented reality research [38]. The majority of approaches in this community rely on *visual* representations of digital objects that are presented on the display of a handheld device [23,32] or are video projected into the physical world [17,44]. For example, the approach of Mossel *et al.* [23] enabled users to view, select, and manipulate digital objects in 3-D space using a handheld touch-sensitive display. Seo and Lee [32] employed depth imaging for markerless hand tracking and occlusion minimization to detect hand touches in the augmented physical space. Wilson *et al.* [44], Jones *et al.* [17], and Vatavu [40] are examples of *s*-AR work that extended augmented reality video projections and interactions with digital objects at the level of an entire room.

Besides visual representations, digital objects have also been materialized as audio and tactile signals [4,28,33,37]. For instance, Bau and Poupyrev [4] employed the principle of reverse electro-vibrations to design a wearable device that modifies the tactile sensation produced by touching a physical object. Sodhi *et al.* [33] explored whole-body gestures to enable users to touch virtual objects and feel their surface texture. Their system fires rings of air (vortexes) toward the user's hands; upon skin hit, vortexes are perceived as tactile sensation by users. Rekimoto [28] developed a tactile interaction device that exploited human illusory by inducing a virtual force in any particular spatial direction, without requiring any mechanical connection to objects on the ground. Tahiroglu *et al.* [37] employed both audio and tactile cues delivered by their prototype implemented with an optical tracking system and a sensor glove. Lai *et al.* [19] employed audio feedback to augment users' perceived physicality of tactile feedback while interacting with digital objects.

Tangible and imaginary user interfaces

Ishii and Ullmer [16] introduced tangible user interfaces (TUIs) that transform physical objects into interfaces for controlling digital content. Later, Ishii *et al.* [15] described radical atoms, a vision of interactions with materials that change their physical properties (*e.g.*, shape, colour, etc.) according to the digital content they relate to. Together, tangible bits and radical atoms create means for the digital and physical to connect in terms of one representing and/or controlling the other. We connect to these visions in two ways. First, digital vibrons are physical manifestations of *zero-weight* physical objects in the physical space, allowing users to control digital information in a similar way as Chis do, except that TUIs require physical objects with non-zero mass and volume to operate. Second, digital vibrons manifest themselves with *localized vibrations*, which create an effect on the user's skin or into the environment, much like radical atoms affect the physical properties of matter; however, in our case, the object producing effects in the physical world is invisible to the eye.

Gustafson *et al.* [10] introduced imaginary interfaces, which are screen-less devices that allow spatial interaction with no visual feedback. The concept has been examined further for imaginary devices [36] and imaginary gaming [5]. We connect to this vision, as digital vibrons are invisible to the eye; however, while feedback in the imaginary interfaces of Gustafson *et al.* [10] takes place in the users' imagination, feedback produced by invisible digital vibrons is *physical* and *tangible*.

Vibrotactile feedback

Vibrotactile feedback has found many applications, such as in navigation [21], motor learning [20], or motion guidance [30] and is extremely useful when visual or audio feedback are inconvenient or difficult to implement [34]. Adams *et al.* [1] found that tactile feedback can increase users' accuracy of mid-air gesture articulation and Freeman *et al.* [9] observed that perceived task workload decreased due to tactile feedback for above-device gesture interfaces. Spelmezan *et al.* [34] showed that increased cognitive and physical load may have negative effects on users' accuracy of detecting complex vibrotactile patterns. However, well-designed vibrotactile actuation can deliver a lot of useful information, such as feedback about interface state [9] or even human motion dynamics [30]. Brewster

[1] Myo arm-band, https://www.myo.com/
[2] Ring Zero, http://logbar.jp/ring/en/

and Brown [7] introduced tactile icons or Tactons, which are abstract messages that communicate information non-visually. Tactons are specified by frequency, amplitude, waveform, duration, rhythm, body location, and spatio-temporal patterns. Schönauer *et al.* [31] evaluated users' accuracy of recognizing vibrotactile patterns and intensities at wrist-level, which they found to be up to 80% accurate.

We connect to this prior work in the way digital vibrons produce vibrations on the user's body or in the environment. While we rely on prior work to inform practical implementations of representing objects with vibrations (*e.g.*, what vibration intensities or patterns to use?; see [31]), our main focus is understanding users' perceptions of interacting with matter that is invisible to the eye, yet detectable on the skin.

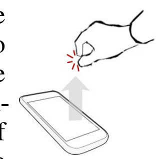
DIGITAL VIBRONS: THE CONCEPT

In this section, we describe the concept of *digital vibrons* by connecting to notions from the physics of condensed matter. We set design criteria for digital vibrons that govern their manifestation and behavior in the physical world.

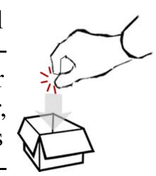
The properties of all solid matter can be divided into two main categories, *i.e.*, electrical and vibrational, as matter is composed of both light and heavy particles, *i.e.*, electrons and nucleons. While the rapid dynamics of electrons is responsible for the optical, magnetical, and conductivity properties of a solid, the slow-motion of atomic nuclei determine a solid's vibrational properties [47] (p. ix). Physicists use the term *phonon* to denote discrete quasi-particles consisting in the smallest possible (therefore, indivisible) quantity of crystal vibrational energy [35] (p. 22). The term *vibron* has been used as a synonym for a phonon[3].

In this work, we borrow the concept of a vibron and we introduce *digital vibrons* as manifestations of digital objects in the physical world, once the objects were removed from their native container device (*e.g.*, a smartphone) as a result of some user action. For example, imagine a user touching an object on a smartphone and lifting it off of the screen (Figure 1a). The result is that object "entering" the physical world, while seized into the user's finger pinch (Figure 1b). When exiting its native container device and entering the physical world, the object transforms into a digital vibron that will manifest its presence with vibrations. In this case, the user will feel vibrotactile feedback localized on the fingers holding the object. While in the user's hand, various manipulations can take place on the object, such as transfer to the other hand (Figure 1c) or placing the object into some physical container, such as an empty box (Figure 1d). Whenever the object changes its location, vibrations follow it accordingly. For instance, when the object is placed into the box, vibrations on the fingers stop, but they start inside the box. Similarly, when the object is picked up again from the box, vibrations resume on the fingers that hold the object. Finally, when the user touches the screen again, vibrations stop as the object has entered its container device and is now visible on screen (Figure 1e). The journey of the object in the physical world is now completed. To formalize this concept, we envisioned a list of features and operations for digital vibrons, which we then considered as design criteria for our prototype (see the next section that describes the technical details of our implementation):

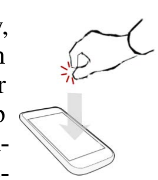
(a) *Manifestation of presence*. When digital objects are displayed on the smart device, they are visible on screen and can be touched directly. However, when taken out into the physical world, objects need to manifest their presence in some other, meaningful way. According to our analogy, objects turn into digital vibrons that produce vibrations of some predefined pattern and intensity. For instance, a short 500 ms pulse may encode an image that was picked up from the touch-screen, while a sequence of three pulses of increasing duration and intensity (*e.g.*, 500 ms, 750 ms, and 1000 ms) may reveal that the object is a video file. The way in which each object vibrates is a matter of interface design, but also of user preference.



(b) *Detachment.* Digital objects can leave their native device and start their journey into the physical world. This process takes place as result of some user action, such as touching the object on screen and lifting it off of the screen's surface. From that point on, the representation of the digital object ceases to be displayed by the smart device, and the object turns into a digital vibron that needs some other way to manifest its presence, see "manifestation of presence" above. Detachment may be implemented with taps, double taps, finger pinches, or grasp gestures. In this work, we implemented object detachment using pinch gestures that we felt to deliver an intuitive metaphor for picking up small objects from the surface of a smartphone's screen. For larger objects displayed on horizontal tabletops, other metaphors might prove more appropriate, such as whole-hand grasps or bimanual gestures; see, for instance, Wobbrock *et al.*'s exploration of users' preferences for surface gestures [46].



(c) *Physical transfer*. While in the physical world, digital objects can be transfered to various locations, for example to the other hand or they can be placed inside a physical container, such as a box. When an object changes its location, the new location takes over the object's vibrations. The next section shows how we implemented physical transfer with our prototype.



(d) *Induction.* Digital objects end their journey in the physical world and, consequently, their manifestation as digital vibrons when they are put back into their original container device. From that point on, vibrations stop and objects resume their visual representations on screen. Induction may be implemented with a gesture with opposite form and meaning to the one employed for detachment. In this work, we implemented induction with the finger pinch touching the screen.

These operations also specify properties for digital objects in the physical world: objects should be *manifestable*, *detachable*, *transferable*, and *inductable*. We used these criteria to guide the technical design of our prototype; see next section.

[3] https://en.wiktionary.org/wiki/vibron

PROTOTYPE

We designed and implemented a system prototype to demonstrate and evaluate the digital vibrons concept. Our prototype consists of three types of hardware and software components designed to be (a) worn by the user (*wearables*), (b) attached to physical objects in the environment (*enablers*), or (c) installed on touch-screen smart devices (*controllers* and *visualizers*, implemented in software):

(a) *Wearable (actuator worn on finger).* A Precision Microdrive Pico Vibe vibration motor (model number 304-108)[4] attaches to the index finger of the user's dominant hand using a small Velcro hook and loop fastener; see Figure 2a. We chose this specific actuator model due to its small size (4 mm in diameter and 8 mm in length), very small weight (1.1 g), yet short rise and stop times (49 ms and 76 ms, respectively) and well perceivable vibration speed (10,000 rpm). The actuator was encased in a 3-D printed housing to prevent direct contact with the actuator's rotational mass, and a spring was added to decouple the housing from vibrations in order to maximize the vibrating effect perceived by users on skin [31]. The total mass of the actuator and housing setup is under 6 g. The actuator is powered by a control unit implemented around a Spark Core *v*1.0 board. We designed the unit to be easily attachable to the user's lower arm using a Velcro hook and loop fastener. The total mass of the unit is 55 g.

(b) *Wearable (actuator and push button setup worn on hand).* A hardware setup consisting of one actuator (same model as before) and one small push button (12 mm in side-length) attaches to the palm of the non-dominant hand; see Figure 2b. The purpose of this setup is to enable users to move digital objects from one hand to the other. On a first button press, the actuator starts to vibrate, signaling the fact that the digital object was successfully transferred to the hand wearing the setup; on a second press, vibrations stop as the object has left that location. Note that the push button is merely a simple way to let our system know that the user has moved the digital object to the other hand. While we adopted a push button for rapid prototyping, future versions can easily implement this trigger using capacitive or ultrasonic proximity sensors. This setup is controlled by the same Spark Core unit.

(c) *Enabler (actuator and push button setup installed in the environment).* To extend digital vibrons to the surrounding space, a similar setup of actuator and push button attaches to any physical object in the environment. However, for such setups, we chose a more powerful Precision Microdrive Pico Vibe vibration motor (model number 306-109)[5] that produces vibrations at the higher speed of 12,800 rpm with a negligible increase in size (6 mm in diameter and 12.2 mm in length) and similar short rise and stop times as the other model (34 ms and 80 ms, respectively). For our testing, we placed the actuator inside a plastic box leaving the button on the outside; see Figure 2c. When the button is pressed, the actuator in the box starts to vibrate with some predefined pattern, meaning that the object is now in the box. On a second press, vibrations coming from inside the box stop, but they continue on the actuator placed on the finger that touched the box.

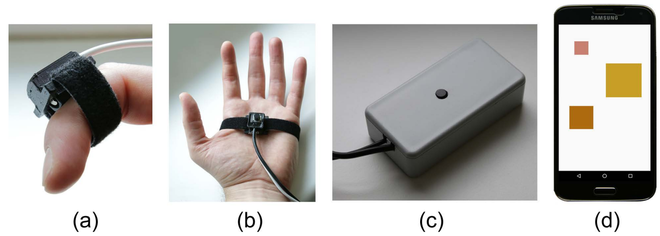


Figure 2. Our prototype composed of (a) actuator worn on the index finger of the dominant hand, (b) actuator and push button for the non-dominant hand, (c) actuator and push button installed in a box, and (d) digital objects abstracted as squares of various sizes on the smartphone.

(d) *Controller and visualizer (software running on a smart device).* We implemented a custom Java application to visualize digital objects when they are located on a smart device. We used a Samsung Galaxy S5 smartphone with a screen size of 130 mm diagonal, 432 dpi, running Android 5.0. Digital objects are shown abstracted as colored squares of various sizes; see Figure 2d. The Java application communicates with the Spark Core control unit via a wireless connection and implements the control logic for all the actuators registered in the system, according to the locations of the digital objects; *e.g.*, the application starts an actuator with appropriate vibration intensity when a digital object reaches that location and stops vibrations at that location once the object has left it. Multiple digital objects can be found at the same location (*e.g.*, the user has picked up several objects repetitively from the touchscreen). In that case, objects vibrate one at a time, in the order in which they were queued.

We controlled actuators at different intensity levels of vibration, as informed by design guidelines from the literature [31]: *high* intensity (corresponding to typical operating amplitude of 0.85 G and voltage of 3 V for our actuators), *medium* intensity (0.55 G and 2 V) and *low* intensity (0.2 G at 0.9 V). Digital objects were shown on the screen of the smartphone as squares with three different side-lengths: *small* (10 mm), *medium* (17 mm), and *large* (25 mm); see Figure 2d. We employed a one-to-one mapping between the size of the object and how intense the object vibrates, *e.g.*, larger objects vibrate more intense than smaller objects when picked up and manipulated in the physical world.

Our specific hardware design optimizes mobility and perception at skin-level receptors [31,39]. The wearable parts of our prototype (*i.e.*, actuator for the index finger on the dominant hand, actuator and push button for the non-dominant hand, and control unit) weigh less than 80 g in total (value that is comparable to existing commercial wearables[6]) and, consequently, can be worn effortlessly even during prolonged usage.

[4] https://catalog.precisionmicrodrives.com/order-parts/product/304-108-4mm-vibration-motor-8mm-type

[5] https://catalog.precisionmicrodrives.com/order-parts/product/306-109-6mm-vibration-motor-12mm-type

[6] For example, the Myo armband weighs 93 g and the Samsung Gear S smartwatch weighs 84 g.

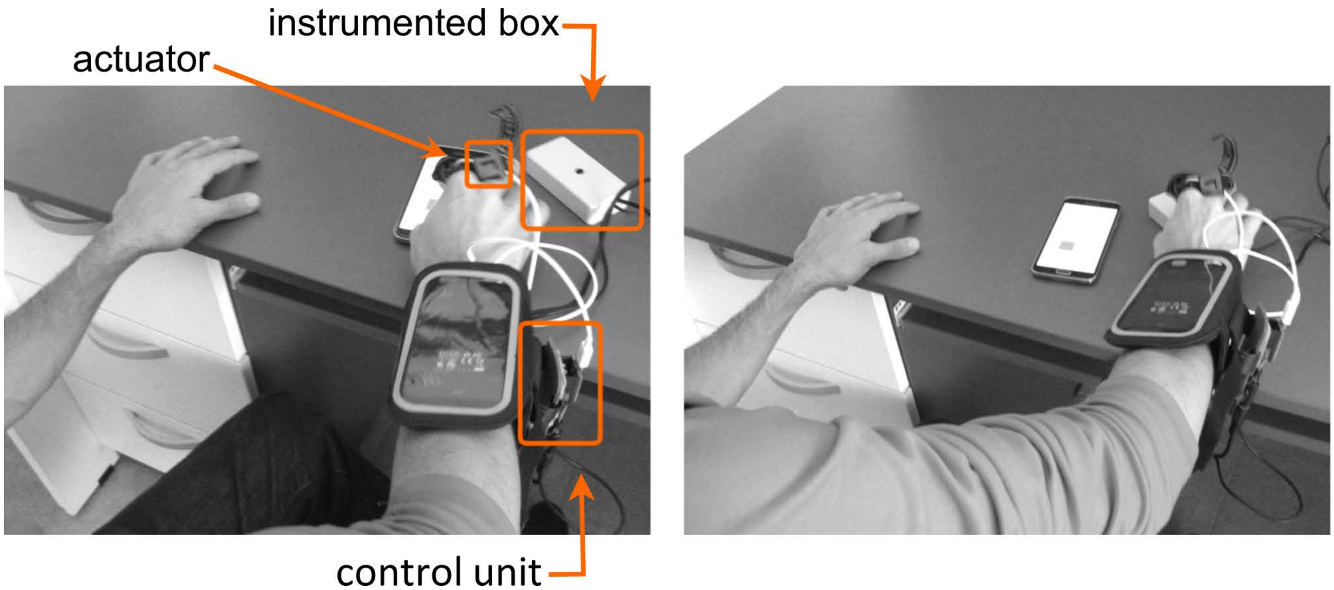


Figure 3. Snapshots of one of the experimental tasks performed by our participants: one square is picked up from the smartphone (left) and placed into the box next to it (right). From the pick-up moment until the digital object reaches the box, a small actuator attached to the user's index finger vibrates to signal that object's presence in the physical world; when the object is released into the box, vibrations transfer from the finger to the box.

EXPERIMENT

We conducted an experiment to understand people's perceptions of the digital vibrons concept as well as their experience interacting with digital vibrons implemented in our prototype.

Participants

Twenty participants (8 females) were involved in the experiment. Participants' ages ranged between 21 and 55 years ($M = 28.5$, $SD = 9.5$). All except one participant used smartphones on a daily basis. Two participants were left-handed.

Apparatus

We employed our prototype described in the previous section, composed of wearable and enabler setups (actuator and actuator & push-button), and visualizers on the smartphone.

Task

Participants were introduced to the concept of digital vibrons and they were presented the functionality of our prototype. Participants were then encouraged to interact with our prototype to experience vibrations produced when digital objects were lifted off of the smartphone, held in hand, moved to the other hand, released into the box, and moved back to the smartphone. Objects were displayed on the smartphone as colored rectangles of various sizes. Participants were given freedom to try out our prototype for as long as they wished and until they were confident about the way interactions with digital vibrons worked and felt. (Participants' actual times spent with our prototype, as we measured later, were between 2 and 11 minutes, with an average of 4.5 minutes and $SD = 2.0$ minutes.) At the end, participants filled in questionnaires collecting their perceptions and experience of interacting with digital vibrons.

Measures

We employed a set of subjective measures to collect participants' perceptions of digital vibrons. Due to the novelty of our topic (invisible, zero-weight matter), we considered that an extensive set of measures was needed to capture and characterize in detail the multi-faceted aspects of experience when interacting with digital vibrons, such as perceived presence, enjoyment, distractedness, desirability, and usability. In designing our measures, we were inspired by methodology used by previous work that focused on understanding users' perceptions of novel interactive technology [41]. We evaluated the various aspects of user perception using 5-point Likert scale ratings denoting participants' degree of agreement with various statements, as follows:

1. PERCEIVED-PRESENCE, measured on a 5-point Likert scale as participants' evaluations of the statement *"I think that vibrations on the hand are useful to indicate the presence of picked-up objects."* The levels of the Likert scale were: strongly disagree (1), disagree (2), neither agree nor disagree (3), agree (4), and strongly agree (5).

2. PERCEIVED-PRESENCE (variant), measured on a 5-point Likert scale as participants' evaluations of the statement *"I think that vibrations on the box are useful to indicate digital objects in the physical world."* While the previous measure evaluates vibrations applied to the hand actively engaged in the interaction, this second measure asks about vibrations in the environment, which may not necessarily be related to the actual task the user is performing at one time.

3. PERCEIVED-AMOUNT, measured on a 5-point Likert scale as participants' evaluations of the statement *"I think that vibrations on the hand are useful to indicate the number of picked-up objects."*

4. PERCEIVED-SIZE, measured on a 5-point Likert scale as participants' evaluations of the statement *"I think that vibrations of various intensities are useful to indicate the size of picked-up objects."*

5. PERCEIVED-ENJOYMENT, measured on a 5-point Likert scale as participants' evaluations of the statement *"I think that vibrations on the hand are enjoyable."*
6. PERCEIVED-DISTRACTEDNESS, measured on a 5-point Likert scale as participants' evaluations of the statement *"I think that vibrations on the hand are distracting."*

We also evaluated participants' desirability to employ our technology and the perceived usability of digital vibrons with the following two measures:

7. DESIRABILITY, measured with the Microsoft Reaction Cards method[7] [6]. Participants were asked to describe digital vibrons using any of a set of 118 selected words with either positive or negative connotations, such as *stimulating*, *innovative*, *unattractive*, *cutting edge*, *distracting*, *fun*, *complex*, etc.; see Benedek and Miner [6] for description of the procedure and the complete set of words on the web[8]. We evaluate DESIRABILITY by examining the frequencies of words with positive and negative connotations.
8. PERCEIVED-USABILITY, measured with the System Usability Scale tool (SUS) [8]. SUS consists of 10 statements for which participants rate their degree of agreement using 5-point Likert scales, and answers are aggregated into a score ranging from 0 (low usability) to 100 (perfect score).

Next to evaluating participants' experience with digital vibrons, we also wanted to collect their expectations of how vibrations should feel like for particular objects, *e.g.*, images or music files. Guessability studies [45] and the agreement rate methodology [42,43] represent a good approach to discover and analyze similarities between such users' expectations. We ran such a study to discover frequently-occurring mappings that would lead to discoverable features (*e.g.*, object type) for digital objects represented as vibrons. To this end, we described vibrations to participants as composed of *patterns* (*e.g.*, a series of pulses) of given *intensities*, for which we demonstrated three levels with our prototype, *i.e.*, *low*, *moderate*, and *high* intensity; see the Prototype section for a description of these levels. Participants were asked to think of suitable patterns and intensities for the following ten types of digital objects, common on smart devices: *image file, video file, PDF file, music file, application icon, phone contact, generic element from a list, short text, paragraph of text*, and *graphical object*. We then computed the consensus between participants' proposals of vibration patterns and intensities for each object type. The consensus reached by n participants for which proposals $\pi_1, \pi_2, ...\pi_n$ were collected is given by the agreement rate formula of Vatavu and Wobbrock [42,43]:

$$AR(r) = \frac{\sum_{i=1}^{n} \sum_{j=i+1}^{n} [\pi_i = \pi_j]}{\frac{1}{2}n(n-1)} \qquad (1)$$

where $[\cdot = \cdot]$ represents Iverson's bracket notation (see Knuth [18]) that evaluates to 1 if the condition in the brackets is satisfied, and to 0 otherwise. For instance, if 11 of 20 participants agree that the vibration pattern for a *phone contact* should be a short pulse followed by a long pulse, and the rest 9 participants consider that the pattern should be just a long pulse, the agreement rate over *phone contact* is $AR = .479$. Note that agreement rates take values in the range $[0..1]$ with 0 denoting no agreement between participants (*i.e.*, every participant's proposal for object r is different from the rest) and a score of 1 denoting perfect agreement (*i.e.*, all participants suggested the same proposal for object r); see Wobbrock *et al.* [45] and Vatavu and Wobbrock [42,43] for more discussion and examples. The application of the elicitation methodology [42,43,45] allowed us to collect two more measures:

9. AGREEMENT-RATE. We compute the consensus (eq. 1) between participants' proposals regarding vibration patterns and their intensities for various types of digital objects.
10. FIT-TO-OBJECT, an average score between 1 (*i.e.*, low fit) and 5 (*i.e.*, great fit) reflecting participants' self evaluations of how well their proposed vibration patterns and intensities describe various object types.

RESULTS

We analyze in this section participants' feedback in terms of their experience and their insights on good mappings between vibrotactile feedback and various types of digital objects.

Perceived experience

We measured our participants' perceptions of digital vibrons using the PERCEIVED-★ set of measures (measures 1−6; see the previous section). Our participants strongly believed that vibrations were useful to indicate the presence of digital objects when they enter and transition the physical world ($Mdn = 5$ for PERCEIVED-PRESENCE (hand) and $Mdn = 4$ for PERCEIVED-PRESENCE (world), respectively); see Figure 4. A Wilcoxon signed-rank test showed that participants considered vibrations on the hand more indicative of objects' presence than vibrations coming from inside the box ($Z = -2.460$, $p < .05$), probably because of the close proximity of the actuator attached to the hand, but the effect size was

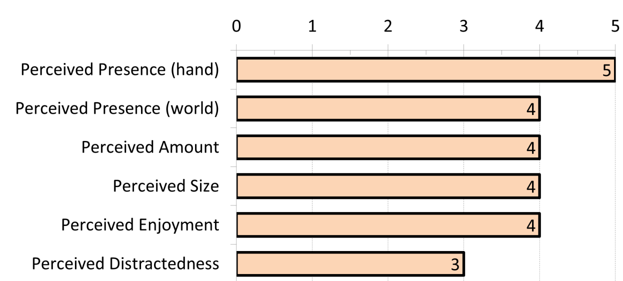


Figure 4. Median values ($N = 19$)[10] of our participants' perceptions of digital vibrons, which we collected with 5-point Likert scales. Scale items were: *strongly disagree* (1), *disagree* (2), *neither agree nor disagree* (3), *agree* (4), and *strongly agree* (5).

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[8]Microsoft Product Reaction Cards, http://www.microsoft.com/usability/UEPostings/ProductReactionCards.doc

[10]Although $N = 20$ people participated in our experiment, we lost the responses of participant P_{13} to the PERCEIVED-★ questions, making our sample size $N = 19$ for this analysis.

Figure 5. Word clouds generated from our participants' selections of words from the Microsoft Reaction Cards [6] to describe digital vibrons: all the words (N=250, left image) and the top-5 most relevant words (N=70, right image). Note the high frequency of positive words, such as *creative*, *useful*, *fun*, *attractive*, or *easy to use*. NOTE: word clouds were generated with the on-line tool available at http://www.wordle.net.

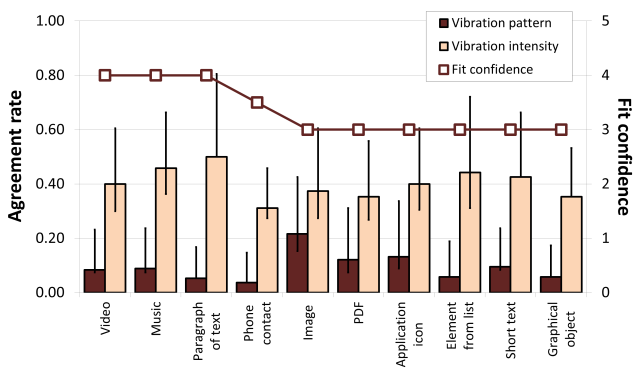

Figure 6. Agreement rates for participants' proposals of vibration patterns and intensities for various types of digital objects. NOTES: objects are shown on the horizontal axis in descending order of participants' confidence in their proposals; error bars show 95% CIs.

small ($r = .064 < .100$). We also found a significant positive correlation between the two presence measures (Spearman's $\rho_{(N=19)} = .509$, $p < .05$).

Participants also considered that the intensity of vibrations was useful to indicate the size of picked-up objects ($Mdn = 4$ for PERCEIVED-SIZE), while vibration patterns were useful to indicate the number of objects ($Mdn = 4$ for PERCEIVED-AMOUNT). There was a significant positive correlation between these two measures (Spearman's $\rho_{(N=19)} = .528$, $p < .05$). Vibrations applied to the hand were perceived as enjoyable ($Mdn = 4$), while there was neither agreement nor disagreement overall in terms of vibrations being distracting ($Mdn = 3$). Mann-Whitney U tests did not detect any significant effect of participants' GENDER (at $p = .05$ level of significance) on any of these measures.

We also measured our participants' perceptions of the usability of digital vibrons with the System Usability Scale (SUS) tool. Overall, perceived usability was 75.1 ($SD = 12.0$, $CI_{95\%} = [69.5, 80.7]$), a value that falls between "good" (73.0) and "excellent" (85.0) on Bangor *et al.*'s 7-point adjective ratings scale [2]. The usability score also falls within the "high acceptability" range, according to Bangor *et al.*'s analysis of SUS scores [3]. A Mann-Whitney U test did not detect any effect of GENDER on SUS (75.4 for men versus 74.7 for women, $U = 47.500$, $Z = -.039$, $p > .05$, *n.s.*).

Our participants employed an average of 12.5 words ($SD = 6.4$) that they picked from the Microsoft Reaction Cards [6] to describe their perceptions and experience with digital vibrons. Figure 5 illustrates two word clouds showing the frequencies of all the words employed by our participants (left image) as well as the frequencies of the top-5 most representative words (right image). The most frequently employed words to describe digital vibrons were *creative* (6.4% of all word choices), *fun* (6.4%), *attractive* (4.8%), *easy to use* (4.8%), and *useful* (4.8%), which are all words with positive connotation. Although a novelty bias is expected, words with negative connotation (*stressful*, *too-technical*, *uncontrollable* and *undesirable*) represent less than 2% of all word choices. This result that makes us believe that, even after novelty fades out, perceptions would still remain positive to a great extent. A Mann-Whitney U test did not detect any effect of GENDER on the number of words employed by participants (12.5 and 12.5, $U = 47.500$, $Z = -.039$, $p > .05$, *n.s.*).

Consensus over vibration patterns

We asked participants to think about vibration patterns that would describe well object types commonly found on smartphones, such as image and music files, phone contacts, short text paragraphs, etc. We then matched these proposals against each other and computed agreement rates using eq. 1.

Overall, the agreement rates of vibration patterns were small and fell between .037 and .216 ($M = .094$, $SD = .052$); see Figure 6. These scores represent either *low* or *medium* agreement, according to the recommendations for interpreting agreement magnitudes of Vatavu and Wobbrock [42] (p. 1332). However, despite their small magnitudes, V_{rd} tests showed that all agreement rates were significantly greater than zero (at either $p < .01$ or $p < .001$ levels of significance). We also detected a significant effect of OBJECT-TYPE on AGREEMENT-RATE ($V_{rd(9,N=200)} = 59.792$, $p < .001$), which shows that different types of objects influenced participants to think of different patterns of vibrations. The largest agreement between our participants over vibration patterns was reached for *Image file* (.216), followed by *Application icon* (.132) and *PDF file* (.121). Table 1 lists the most frequent proposals for each object type. While most of the proposals were simple consisting of one pulse of variable duration (*i.e.*, long, medium, or short

OBJECT TYPE	FREQUENT PROPOSALS (PATTERNS)	FREQUENT PROPOSALS (INTENSITIES)
Image file	long pulse (42%), short pulse (26%)	low (58%), moderate (32%)
Video file	long pulse (26%), long-long (16%)	high (58%), moderate (37%)
PDF file	series of (unspecified number of) short vibrations (37%)	low (53%), moderate (37%)
Music file	long pulse (25%), rhythmic vibration (15%), 3× short pulses (15%)	high (63%), moderate (37%)
Application icon	medium pulse (37%), short pulse (16%)	low (58%), moderate (37%)
Phone contact	medium pulse (16%)	low (42%), moderate (37%)
Element from list	short pulse (21%), long pulse (16%)	low (68%)
Short text	short pulse (26%), long pulse (16%), 2× short pulses (16%)	low (63%)
Paragraph of text	medium pulse (16%), short-long (16%)	moderate (74%)
Graphical object	short pulse (17%), medium pulse (17%), long pulse (17%)	moderate (53%), high (37%)

Table 1. Participants' frequent proposals of vibration patterns and intensities for representing objects as digital vibrons.

pulse), a few were more elaborate, such as three consecutive short pulses to denote a *PDF file*, combinations of two pulses of different duration (*e.g.*, short-long, short-medium, long-short, etc.), or repeated pulses (*e.g.*, 3 short pulses to denote a *music file* object). One participant (P_6) was very precise about the specific duration of each pulse type, such as 500 ms for short, 1000 ms for medium, and 2000 ms for long pulses.

Agreement rates computed from proposals for vibration intensities were much larger ($M = .402$, $SD = .057$), because participants completed this task by choosing their options from a list of intensities (*low*, *moderate*, and *high*) that were demonstrated to participants while they were trying out our prototype. All agreement rates were significantly greater than zero, as shown by V_{rd} tests performed for each object type ($p < .001$). We also detected a significant effect of OBJECT-TYPE on AGREEMENT-RATE ($V_{rd(9,N=200)} = 24.172$, $p < .010$). The highest agreement was received for *Paragraph of text* (.500), *Music* (.458), and *Element from list* (.442), all these scores representing high agreement levels, according to the guidelines of interpreting the magnitude of agreement rates recommended by Vatavu and Wobbrock [42] (p. 1332). Overall, the *low* intensity was preferred by our participants for 37.3% of the time, *moderate* intensity for 38.7%, and *high* intensity for 24%.

Summary of evaluation results

Evaluation results showed very positive adoption of our concept, with participants appreciating vibrations very useful to indicate the presence of digital objects in the physical world as well as object properties (*e.g.*, type, size, etc.). Also, results of Table 1 represent a good starting point to inform design of vibrotactile feedback for implementing digital vibrons associated to various object types. Furthermore, the high frequency of positive adjectives describing the perceived experience (*e.g.*, *creative* (6.4% of all word choices), *fun* (6.4%), *attractive* (4.8%), *useful* (4.8%)) are very encouraging and recommend further exploration of the opportunities offered by the vibrons concept; the next section points to several such directions.

FUTURE WORK

Digital vibrons are invisible digital matter with the capability to transform objects from a visual representation into a tactile one. Working with this idea, a number of future work opportunities can be explored. For instance, deeper formalization of digital vibrons can be envisaged, *e.g.*, can a theoretical model be created for digital vibrons by implementing other analogies with the physics of condensed matter? How do digital vibrons interact with each other in the physical world? What type of manipulations (besides moving in space) can take place on invisible digital matter? etc. Finding answers to such questions will create a new framework for thinking about and designing physical-digital interactions mediated by digital vibrons.

On the technical side, the design of our prototype can also be improved in several ways, such as by using capacitive or ultrasonic promixity sensors to replace push buttons and by enabling wireless communication between actuators and the control unit. Further development of manifestations of digital vibrons is envisaged, as inspired by the rich design space of Tactons [7]. By defining and examining the design space for digital vibrons, new design decisions can be adopted for implementing interactive prototypes, other than those we adopted in this work, that would lead to investigations about digital vibrons into new directions, *e.g.*, implementing continuous versus intermittent feedback, using other on-body locations for providing vibrotactile feedback, or imagining different options for mapping digital objects into vibration properties. We leave the exploration of such a design space for digital vibrons as future work. Ultimately, one can imagine a rich software infrastructure to support various platforms in the form of plug-ins for commercial devices that deliver vibrotactile feedback, such as smartwatches, Ring Zero, Myo, etc.

CONCLUSION

We examined in this work users' perceptions of interacting with invisible digital matter in the physical space. To this end, we introduced the concept of digital vibrons as physical vibrational manifestation of zero-weight, invisible matter. The data that we collected showed that users received very positively our concept and implementation, which recommends future exploration of digital vibrons for designing new interfaces for smart mobile interaction scenarios. We believe that this first work on digital vibrons has barely scratched the opportunity of formalizing interactions with invisible, zero-weight digital matter living outside their smart device containers. We are eager to see how the community will employ our concepts and findings to design enriched user interfaces with digital objects permeating the physical-digital space.

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