Haptic Magnetism

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***Abstract*—New interactions are often developed by mimicking the real world. Therefore, many researchers in haptics have focused on creating a realistic experience of contact between users and objects. However, dispensing with mimicry may allow us to develop novel haptic interactions. We present *Haptic Magnetism*, an interaction modality that delivers sensations of distant objects through tactile stimulation and enables interactions through pseudo-magnetic attraction and repulsion. To show the feasibility of Haptic Magnetism, we designed 12 pseudo-magnetic stimuli and assessed them in two studies. In the first study, we show that participants gain a sense of distant objects. In the second study, we evaluate a subset of stimuli to show that participants can interact with the objects based on experiences of pseudo-magnetic attraction and repulsion. Finally, we discuss how Haptic Magnetism supports guiding movements, nudging users, and revealing affordances.**

***Index Terms*—Human-computer interaction, design, haptic rendering, perception and psychophysics.**

I. Introduction

CREATING plausible experiences of touching objects has been the goal of numerous works (e.g., [1], [2], [3], [4], [5]). Central to most of this work is the assumption that we should create haptic experiences that *mimic* the contact between objects, say, a user's finger and an object in virtual reality. That assumption may be challenged. Hollan and Stornetta [6] famously argued that face-to-face communication need not be a golden standard for electronic media. Following this argument, haptic feedback can be an experience in itself rather than a mimicry of realistic contact. We, too, are inspired by this idea.

We present Haptic Magnetism, an interaction modality that enables users to sense objects at a distance solely through the sense of touch. Similar to Haptic Magnetism, researchers have created systems for using the sense of touch to sense things that cannot be usually sensed. For example, Nagel et al. [7] created the feelSpace belt, which provides haptic feedback of magnetic north, and Grönvall et al. [8] created the FeltRadio, which provides haptic feedback to sense radio waves present around the user. Although these examples can be considered instances of Haptic Magnetism, the modality can seve as an umbrella, or strong concept [9], for a wider range of interactions.

In Haptic Magnetism, interactions are enabled through experiences of pseudo-magnetic attraction and repulsion (Fig. 1 left). The feeling of this modality would be equivalent to holding a magnet in hand and moving it closer to another magnet, exerting attracting and repulsing forces. Gaining a sense of attraction and repulsion can be useful, for instance, for guiding a user to find an occluded or otherwise invisible objects, such as lost keys in another room (Fig. 1(a)), or navigating their hand to avoid a hot cooking plate (Fig. 1(b)). It can also be useful for nudging the user to select the right key on a piano (Fig. 1(c)) or for discovering interactable objects in augmented reality in an otherwise passive real-world scene (Fig. 1(d)).

In two studies, we show the feasibility of Haptic Magnetism. To investigate whether the basic feeling of pseudo-magnetism can be induced at all, we test Haptic Magnetism as the sole feedback for interactions (i.e., without visual probes). Initially, we designed 12 haptic stimuli as candidates for producing the sensations of attraction and repulsion. Then, in the first user study, we quantified how well these stimuli induce sensations of objects at a distance. We asked participants to rate their sensations of the distant object, that sensation changing with movement, and about feeling a sensation of a pull toward or a push away from the object. The three stimuli that the participants rated most frequently to provide pseudo-magnetic sensations were selected for the second study. In the second study, we ask a new set of participants to select between attracting, repulsing, and neutral stimuli in a forced choice task. The results show that users can distinguish attractive stimuli when prompted. We also ask participants to locate an attractive stimulus on a plane. We find that the participants can accurately locate the stimulus. These two findings suggest that Haptic Magnetism can enable interactions with distant objects through experiences of pseudo-magnetic attraction and repulsion solely based on the sense of touch.

Our main contributions are the concept of Haptic Magnetism and the two studies validating the concept. We discuss the feasibility of Haptic Magnetism and how the concept can help hapticians design stimuli for pseudo-magnetic sensations and to interact with distant objects.

II. Haptic Magnetism

Haptic Magnetism is an interaction modality relying solely on the sense of touch. Fig. 1, left, depicts the three principles of

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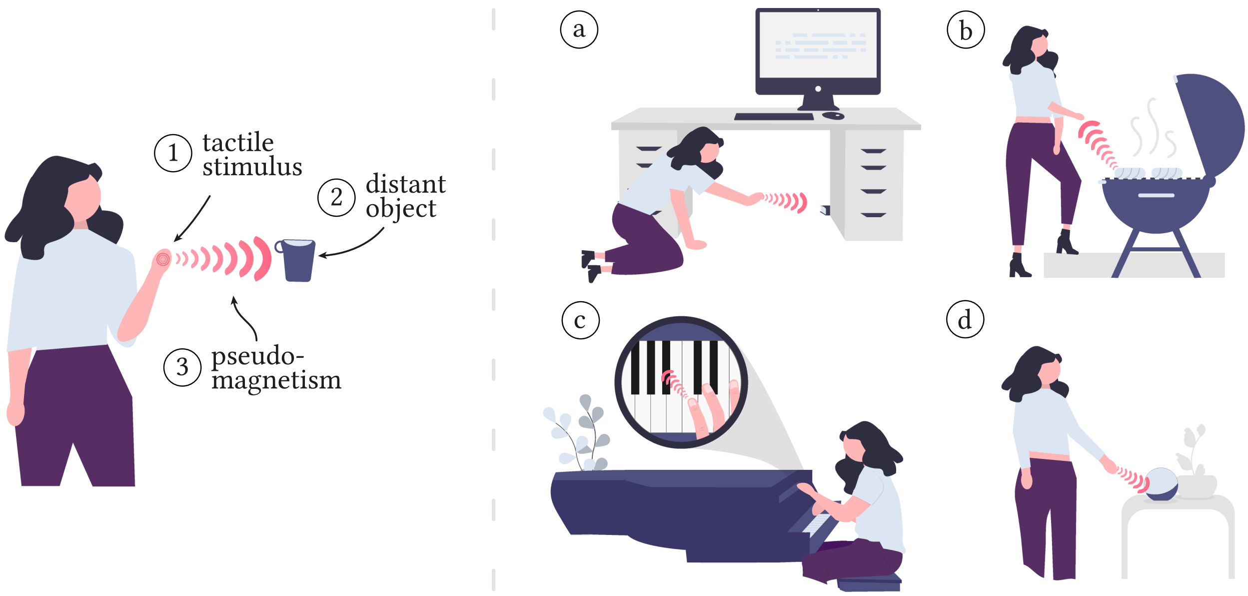


Fig. 1. *Left:* The three principles of Haptic Magnetism: A tactile stimulus ( ) enables the user to interact with a distant object ( ) through an experience of a pseudo-magnetic attraction ( ) and repulsion ( ). *Right:* Examples of interactions using Haptic Magnetism. A user being (a) attracted to find an occluded object, (b) repulsed to avoid a dangerous object, (c) attracted to select a particular object, and (d) attracted to discover an interactable object.

Haptic Magnetism that guide the design of stimuli for pseudo-magnetic sensations to interact with distant objects:

1) *Haptic Magnetism relies on providing tactile stimuli to the haptic sense.* These stimuli are produced by generic haptic devices (for a definition of generic haptic devices, see Muender et al. [5]). Thereby, Haptic Magnetism is based on illusory sensations rather than physically pulling or shearing the skin. The stimuli should express relations between the user and an object, such as the distance between them or a direction toward the object. A change in the relation should result in a change in one or more stimulus design parameters, for instance, intensity or frequency. In real magnetism, the change of the attracting or repulsing force is exponential in relation to the magnets' distance. In Haptic Magnetism, however, the change can be of any rate (e.g., linear, polynomial).

2) *Haptic Magnetism delivers sensations of objects at a distance.* The sensation changes based on the user's movement in relation to the object, giving a constant sense of it without mimicking touch. The sensation is thus not of contact (e.g., texture or shape) but of location (e.g., distance or direction).

3) *Haptic Magnetism enables interactions through experiences of pseudo-magnetic attraction and repulsion.* The two modes of attraction and repulsion make up the interaction modality. The modes allow users to interact with objects at a distance. The interactions include guidance, navigation, nudging, and discovery (Fig. 1).

Haptic Magnetism can be used alone or in combination with other interaction modalities. For example, when objects are occluded, locating them becomes difficult even with augmented visual feedback [10]. Haptic Magnetism can provide additional guidance in such tasks. Haptic Magnetism can also be used in real or virtual environments. As the haptic sense is less dominant than vision or audio (the commonly stimulated senses), using haptics can be less intrusive and less likely to break immersion in a virtual experience [11]. Similarly, when introduced into the real world, designers can create more subtle interactions with Haptic Magnetism compared to audiovisual ones.

In the following, we expand on the scenarios presented in Fig. 1, where Haptic Magnetism enables interaction. These scenarios range from urgent to subtle interactions. Haptic Magnetism can be used for guidance, leading the user towards a book that fell behind their writing desk or towards their lost keys hidden in the fridge (Fig. 1(a)). Here the occluded or hidden object attracts a user so as to be found. Conversely, Haptic Magnetism is useful for repulsing the user away from dangerous objects to avoid them. This could be hot items on a grill or leaking gas pipes in a workplace environment (Fig. 1(b)). In these two application areas, the interaction is urgent. If the user wants to find their keys right now or needs to be warned in a dangerous situation immediately, urgency is desired such that the user can act on the information gained in a timely manner. Here the interaction is not sought after for pleasure but by necessity; users thus desire the interaction to be efficient and precise. In other scenarios, a different form of interaction is desired. Haptic Magnetism can be used to nudge the user, to support learning by reinforcing the selection of correct objects or to support decision-making. If, for instance, the user wishes to learn to play the piano, they can be attracted to hit the right key (Fig. 1(c)). Or, if they would be baking a delicious cupcake, Haptic Magnetism could repulse the user from the salt jar, placed dangerously close to the sugar jar. Similarly, Haptic Magnetism is useful for revealing affordances of objects, for instance, by supporting the discovery of multiple interactable objects through attraction but not dictating a selection of any particular one (Fig. 1(d)). In these scenarios, users want to learn a skill and the pseudo-magnetic stimulus supports the learning process.

These scenarios tell about the potential of Haptic Magnetism. Haptic interactions are commonly associated with proximity and intimacy [11], whereas Haptic Magnetism is an interaction modality allowing designers to create haptic interactions with objects at a distance.

Our description of the interaction modality Haptic Magnetism serves as a strong concept [9]. The three principles describe a class of possible user interfaces, which is more general than a concrete user interface and more specific than a theory of haptic perception. In particular, the Haptic Magnetism generalize earlier user interface ideas such as FeltRadio [8] and feelSpace belt [7], while at the same time being more concrete that general principles of sensory substitution. The three principles of Haptic Magnetism has generative power [12] in that they can be applied to make decisions about how magnetism may be used in particular applications. This also makes them differ from specific user interface ideas and general principles.

III. Related Work

In this section, we discuss work related to the three principles of Haptic Magnetism. First, we discuss realistic stimuli pushing or pulling the fingers in relation to an object. Next, we discuss studies about touching remote entities; objects, people, or phenomena. Finally, we discuss previous work that uses haptics for sensory augmentation about entities that cannot otherwise be sensed, such as the direction of the magnetic north.

A. Inducing Realistic Tactile Stimuli

The sense of touch can be stimulated with different technologies, such as vibration motors, force feedback devices, or ultrasonic haptic devices. The technologies have an influence on the perceived realism of haptic stimuli. Muender et al. [5] relate perceived realism to the specificity of haptic devices, such that devices built to produce a specific haptic stimulus are perceived as more realistic than generic devices. Such custom devices have been used to mimic realistic renderings of haptic stimuli in different contexts. For instance, Whitmire et al. [2] created the Haptic Revolver, built to provide sensations of texture, shear and direction by rotating a surface underneath the fingertip. The "Tactile Sleeve for Social Touch" [13] set out to mimic realistic touch sensations in social settings, by users receiving haptic stimuli on the forearm. Wolverine [14] and Wireality [3] are examples of purpose-built devices for realistic haptic experiences in virtual reality that physically stop the fingers at a grasped object's surface. Central to these devices is the assumption that we should create haptic experiences that mimic reality. However, without devices that are customised to pull or push the hand, it is unclear how to best stimulate the skin to convey an experience of magnetism.

B. Remote and Virtual Touch

Virtual objects or people with virtual presence cannot be directly touched. Introducing haptics to these contexts has been suggested to enhance the experience, as the typically primarily audiovisual computer interface becomes multi-sensory, allowing for a greater information flow to the user [11]. For example, receiving haptic feedback when performing a remote task through a robot has been shown to improve task-specific performance (e.g., [15], [16], [17]), and adding haptics to virtual handshakes and other forms of remote social interactions (e.g., [11], [18]) has been shown to improve presence and immersion in the social contexts.

Similarly, a sense of touch has been discussed in relation to virtual objects. Already in the Tangible Bits, Ishii and Ullmer [19] use a physical proxy that can be directly grasped to manipulate the corresponding virtual object on a tabletop display. Such passive proxies have also been used in virtual reality to provide realistic feedback of grasping objects. For example, the user's virtual hands or fingers can be redirected in a way that they touch a physical cube at the same time as the corresponding virtual cube at a different location [20] or of different size [21]. Lopes et al. [22] extends the sense of touch to provide information on how an object can be used. They present the concept of "Affordance++", which allows users to discover the affordances of objects once they are grasped. However, in all of these works the haptic feedback displays contact between the hand and the object. Even if the object or the person in these works is remote or virtual, they are not shown at a distance from the user's hand. In Haptic Magnetism, the object is sensed at a distance, and that sensation changes when moving closer or farther from the object.

C. Sensory Augmentation With Haptics

Macpherson [23] defines sensory substitution as the replacement of a missing sense by delivering information usually gathered by the missing sense to an available sense. As an extension to this idea, Macpherson describes sensory augmentation as creating a novel sense, delivered through an existing sense [23, pp. 1–10].

The idea of sensory augmentation becomes more approachable in everyday use cases. For instance, the feelSpace belt [7] delivers a sense of magnetic north, used for pedestrian navigation, and the FeltRadio [8] delivers a sense of radio waves present around the user. Applications are often within accessibility (e.g., [7], [24], [25], [26]). Instead of presenting a physical property of the real world, Culbertson et al. [27] created an illusory force with a set of wearable vibration motors to direct the user's movements. All these works can be considered instances of Haptic Magnetism, although they are not always stringently following the three principles presented. Nagel et al. [7] built a system without any notion of pulling or pushing. [26] on the other hand employed these pseudo-magnetic sensations to guide users with a custom device.

The novelty of Haptic Magnetism is that it can enable *interactions with distant objects* through *experiences of pseudo-magnetism* solely through *the sense of touch*. It is an interaction modality for pseudo-magnetism since it uses the haptic modality to provide a sense of magnetism. It not only provides a sense of an object at a distance, but also changes that sensation depending

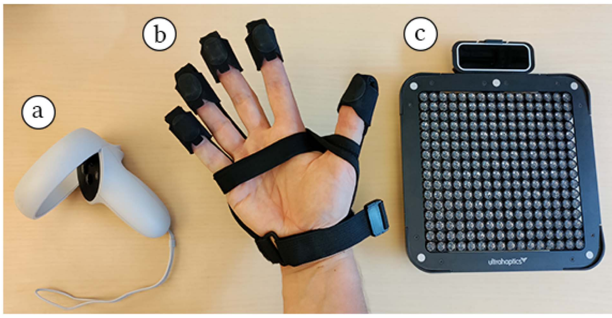


Fig. 2. The three devices used in the study: (a) a virtual reality controller, (b) a haptic glove, and (c) a mid-air haptic device.

on the distance (e.g., when moving closer to the magnet), and has modes for both magnetic forces of attraction and repulsion. Finally, it does so solely through the sense of touch, using generic haptic technologies.

IV. Study 1: Producing Sensations of Objects at a Distance

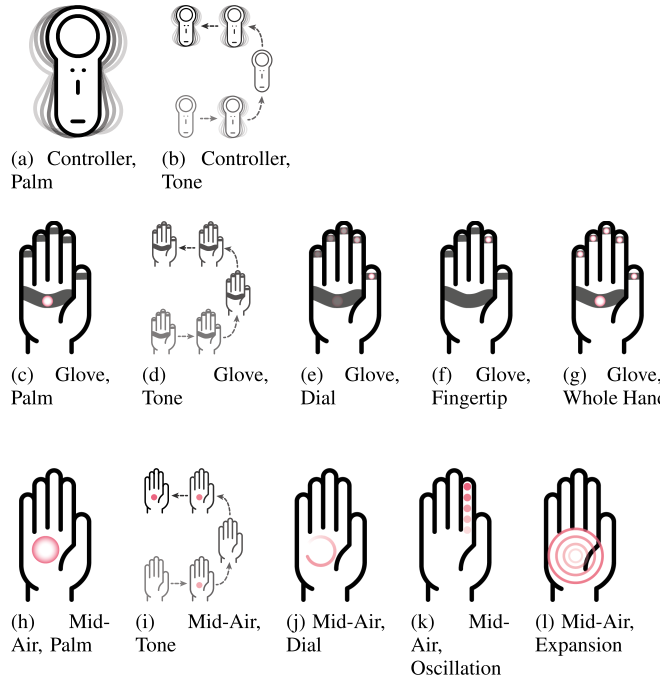
We design 12 tactile stimuli as candidates for delivering pseudo-magnetic sensations (Principle 1). The stimuli are designed based on ideas from related work and on the technical capabilities of three haptic devices: a controller, a haptic glove, and a mid-air haptic device. Participants rate the stimuli on four subjective scales, indicating their sensation of the object at a distance and its magnetic properties. The purpose of this study is to show that Haptic Magnetism can deliver sensations of objects at a distance (Principle 2) using different haptic devices.

A. Participants

We recruited 21 participants to rate the 12 haptic stimuli. The participants were between 18 and 58 years of age (mean: 29.10, std: 9.04). Seven participants self-reported as female and 14 as male. The experiment took 32 minutes on average to complete. All participants were rewarded with a gift valued at $15.

B. Study Design

The study investigates an independent variable containing 12 levels, each corresponding to one of the designed haptic stimuli. Each stimulus is dependent on a haptic device, as it is designed specifically to work on one device. We used three different devices, controller, glove, and mid-air, since each of them has a different level of versatility in producing skin vibrations on the hand. The first device was a hand-held *controller* (Fig. 2(a)) with a vibration motor, representing the most common haptic feedback device, as found in mobile phones and game controllers. The second was a haptic *glove* (Fig. 2(b)) with multiple vibration motors, meant for use in augmented and virtual reality. The third was a *mid-air* (Fig. 2(c)) haptic device, which induces skin vibrations through ultrasonic sound waves anywhere on the hand. For details on the devices, we refer to the supplementary materials.



(a) Controller, Palm (b) Controller, Tone

(c) Glove, Palm (d) Glove, Tone (e) Glove, Dial (f) Glove, Fingertip (g) Glove, Whole Hand

(h) Mid-Air, Palm (i) Mid-Air, Tone (j) Mid-Air, Dial (k) Mid-Air, Oscillation (l) Mid-Air, Expansion

Fig. 3. 12 candidate designs for pseudo-mangetic haptic stimuli. Rows indicate haptic device, used to induce the stimulus, columns indicate the comparable haptic stimuli across devices.

During the study, participants were tasked to explore the sensation of a distant object. They were asked about their perception of that object and its pseudo-magnetic properties. A trial consisted of a 20-second exploration of a candidate stimulus and of answering a questionnaire, in which participants rated the stimulus. Each stimulus was induced three times, for a total of 36 trials. The study followed a within-subjects study design, where all participants evaluated all stimuli using all devices. Conditions were blocked according to the devices, such that participants did not need to switch devices after every trial. The order of devices was randomised according to a Latin square and, for each device, the stimuli were presented in random order.

C. Design of Stimuli

For the study, we designed 12 haptic stimuli for the three devices. The design is limited by the capabilities of the devices, such that the number of stimuli designed for the controller is smaller than for the glove or mid-air conditions. We aimed both to design stimuli that are comparable across devices and stimuli that take advantage of the technological capabilities of the devices. By the principles of Haptic Magnetism, a pseudo-magnetic stimulus has its source in a distant object. All stimuli used in this study are designed to convey a sense of the distance between hand and object through different haptic patterns and modulations. This distance relation produces a linear change in the modulation, i.e., the parameter is linearly increasing or decreasing based on the distance between hand and object. For detailed descriptions of the stimuli, we refer to the supplementary materials.

TABLE I
QUESTIONNAIRE USED TO ASSESS THE QUALITIES OF THE HAPTIC STIMULI

Question	**5-point Likert scale answer options**				
I felt the object at a distance	Never	Rarely	Sometimes	Often	Always
The object reacted to my movement	Never	Rarely	Sometimes	Often	Always
The object was pushing my hand away	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The object was pulling my hand towards it	Strongly disagree	Disagree	Neutral	Agree	Strongly agree

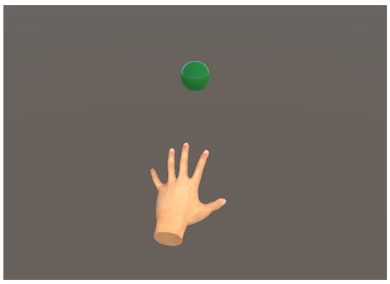


Fig. 4. Virtual reality scene used in the first study. A participant is moving their hand toward a virtual object.

The stimuli are visualised in Fig. 3. For all three devices, we designed a stimulus that is centred on the palm of the user and modulate intensity, such that the sensation is strong when close to the object or weak when far away (Fig. 3(a), (c), and (h)). Similarly, for all three devices, we designed a stimulus with constant intensity, but changing periodical beat (Fig. 3(b), (d), and (i)), such that the excitation frequency is high when close to the object, similar to the sound of a metal detector.

For the haptic glove and the mid-air haptic device, we designed a set of comparable stimuli: a circular stimulus, with increased drawing speed as the user's hand, is moved closer to the object (Fig. 3(e) and (j)). Lastly, we designed four stimuli taking advantage of features unique to each haptic device. For the haptic glove, we designed a stimulus on the index fingertip, with intensity modulation (Fig. 3(f)), such that intensity is high when close to the object, and a stimulus using all six actuators in the glove at once, also with intensity modulation (Fig. 3(g)). For the mid-air haptic device, we designed a point stimulus on the index finger, moving along the finger, when moving closer to the object (Fig. 3(k)) and a circular stimulus, with radius modulation (Fig. 3(l)), such that the circle becomes smaller when closer to the object.

D. Task

In the study, participants were tasked with exploring a stimulus and rating their perception of a distant object and its pseudo-magnetic properties. Virtual reality was used to control the environment from other objects and the view of the haptic devices. The stimulus originated from a sphere with a diameter of 10 cm, posing as the distant object. Participants could at any time see a virtual representation of their hand and, during the trial, see the virtual object, as depicted in Fig. 4. The virtual object was placed 70 cm away from the participant (i.e., out of arms reach) at approximately chest height. Participants were asked to move their hands to an initial starting point, indicated by a translucent hand. Afterwards, they could freely explore the stimulus by moving their hand towards and away from the object for 20 seconds. When that time had passed, the participants were asked to answer a questionnaire.

The questionnaire consisted of four 5-point Likert scale questions, as listed in Table I. In the first two questions, participants were asked to rate their perception of the distant object, both in terms of their feeling of the object and the object reacting to their input (hand movements). We ask these questions to find evidence of whether the participants can connect the haptic stimulus to the object at a distance and feel that the stimulus is changing in relation to their movement, which is important for Principle 2. In the last two questions, participants were asked to rate the degree to which they felt the pseudo-magnetic properties of the stimulus. These questions relate to the perception of pseudo-magnetism and give a first indicator of whether the stimuli can be perceived as feeling attractive, repulsive, or both.

E. Procedure

Participants were welcomed and seated at a desk with all haptic devices visible. The participants were introduced to the purpose of the study, emphasising that they should be aware of the haptic interaction between them and the virtual object present in the task, but without explicitly mentioning magnetism-related terms (e.g., attraction, repulsion, pull, push). This approach was taken to help the participants focus on understanding the intention behind the designed stimuli, allowing them to answer the questionnaire with the haptic stimulus in mind. After this, participants filled out an informed consent form and a demographics questionnaire. Participants entered the virtual environment and were introduced to a haptic device by trying a sample stimulus before trying the device. The sample stimulus was not from the set of designed stimuli but rather a haptic stimulus with maximal intensity on the palm of the hand. Participants could control for how long they would feel the sample stimulus. Each time the task was completed on a device, the participant could remove the virtual reality display so as to see (and equip themselves with) the next haptic device. After all trials were completed, participants were informed about the intention of Haptic Magnetism and could ask questions and leave comments to the experimenter.

F. Data Processing

We started the data analysis by removing outliers. We considered as outliers those participants whose ratings varied extremely little across stimuli. These ratings could be different among the questions but consistent across the stimuli for each question (e.g., always strongly agreeing to feeling an object at

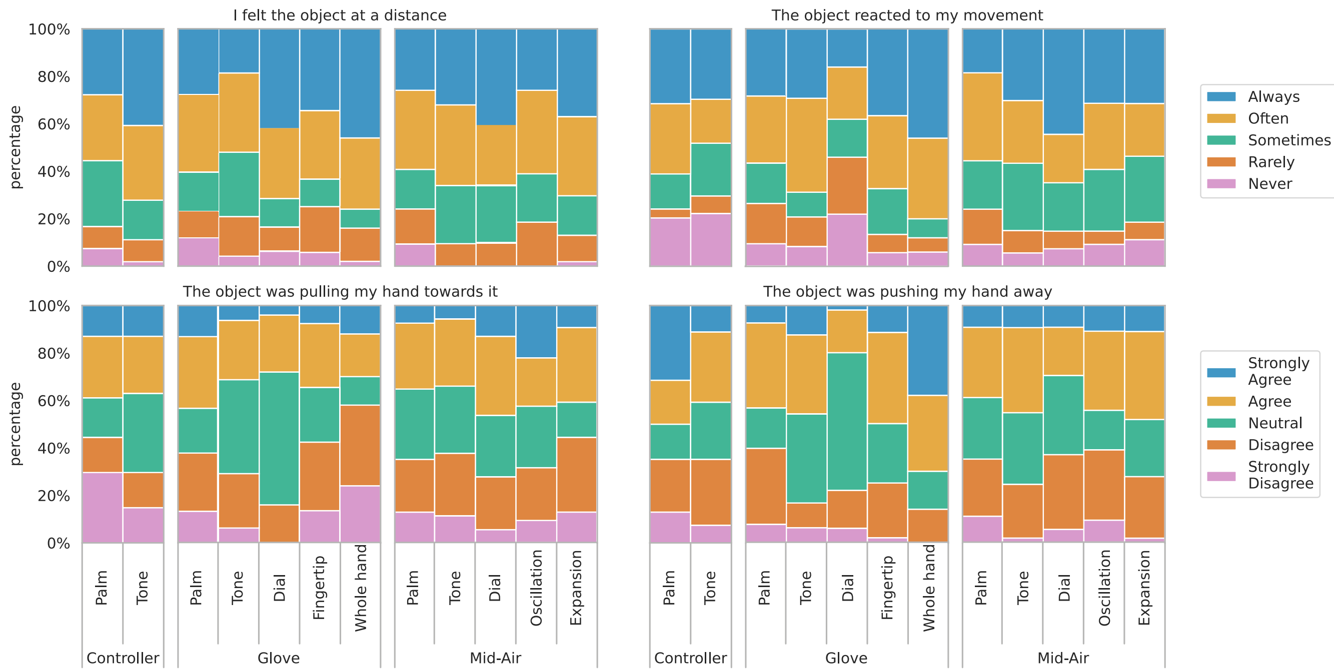


Fig. 5. Frequencies of the ratings for each of the four questions on their respective 5-point scales across the 12 stimuli. Ratings were obtained from 18 participants.

a distance and always disagreeing to feeling a pull). With three repetitions to each stimulus and 12 stimuli, such consistency was strikingly visible among individual plots of the ratings. To confirm this perception, we marked participants as outliers if the mean standard deviation of their rating fell below the threshold of one-third. There were three such outliers.

G. Results

In this section, we report the results of Study 1. First, we explain our method for data processing and analysis. Then, to investigate which stimuli are best suited to provide a sense of Haptic Magnetism, we analyse the ratings for the four questions. We analyse how participants rated the 12 stimuli using the four questions, and what may the interactions between the ratings imply about the Haptic Magnetism of the stimuli. To investigate the interactions among the stimulus ratings we use a repeated measures ANOVA to find significant differences. Where we find significance, Tukey's post hoc test is used to test for individual differences. The data is available at https://osf.io/62pyj/.

1) Feeling a Virtual Object: Fig. 5, top row, presents the distributions of the ratings for each stimulus in the first two questions about feeling a virtual object. Here, we analyse these ratings and their frequencies.

The frequencies of the ratings show that the participants experienced feeling the object at a distance in most of the stimulations. They answered the question *"I felt the object at a distance"* (Fig. 5, top left) with "Often" or "Always" on average 64.60% (std: 7.03) of the stimulations. Out of the 12 stimuli, the [Glove, Whole Hand] stimulus was felt most frequently (76% of the stimulations) at a distance. However, Tukey's post hoc test showed no significant differences among the 12 stimuli.

Similarly often, the participants experienced the feeling that the object reacted to their movement (Fig. 5, top right). They answered the question *"The object reacted to my movement"* with "Often" or "Always" on average 59.15% (std: 10.67) of the stimulations. Again, the [Glove, Whole Hand] stimulus was felt most frequently (80% of the stimulations) to react to their movement. The ANOVA revealed a significant difference in absolute value of ratings (on the 5-point scale from "Never" to "Always") for this question (F(11, 618) = [2.99], $p < .01$, $\eta^2 = 0.02$). The post hoc test showed significantly lower ratings for the [Glove, Dial] stimulus compared to the [Mid-Air, Dial] ($p < .01$, 95% C.I. = [0.17, 1.85]) the [Glove, Finger] ($p < .01$, 95% C.I. = [0.14, 1.83]) and the [Glove, Whole Hand] ($p < .01$, 95% C.I. = [0.36, 2.08]) stimulus.

2) Feeling a Push and a Pull: Fig. 5, bottom row, presents the distributions of the ratings for each stimulus in the two questions about feeling the virtual object pull or push.

The frequencies of the ratings show, that the participants experienced feeling a push or a pull less in than half of the stimulations. The participants answered the question *"The object was pulling my hand towards it"* (Fig. 5, bottom left) with "Agree" or "Strongly agree" on average 36.83% (std: 5.7) of the stimulations, and the question (*"The object was pushing my hand away"*) on average 43.86% (std: 12.02) of the stimulations.

There are no significant differences among the 12 stimuli in the absolute values of ratings (on the 5-point scale from "Strongly Agree" to "Strongly Disagree") of feeling a pull. The ratings for push, however, showed a significant effect (F(11, 618) = [3.12], $p < .01$, $\eta^2 = 0.02$) higher for the [Glove, Whole

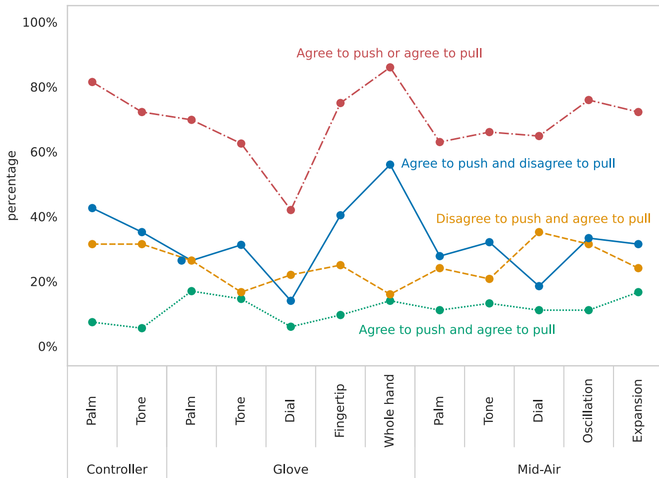


Fig. 6. Frequency of answer combinations for each stimulus. For instance, the green line ...... shows the frequency of participants disagreeing to both feeling a pulling and a pushing sensation. Ratings were obtained from 18 participants.

Hand] stimulus than the [Mid-Air, Dial] ($p < .01$, 95% C.I. = [0.26, 1.69]), [Mid-Air, Oscillation] ($p < .01$, 95% C.I. = [0.15, 1.58]), [Mid-Air, Palm] ($p < .01$, 95% C.I. = [0.21, 1.64]), [Glove, Palm] ($p < .01$, 95% C.I. = [0.18, 1.62]), [Glove, Dial] ($p < .01$, 95% C.I. = [0.27, 1.73]), and [Controller, Tone] ($p < .01$, 95% C.I. = [0.13, 1.56]) stimuli.

The frequency distributions for pulling and pushing do not seem consistent across stimuli: the participants often rated pull and push equally high, or the ratings varied between the trials within the same stimulations. Many participants commented in the experiment, that for some stimuli they found it hard to judge whether they felt a pull towards or a push away from the object. This is also reflected in the high mean standard deviations for the ratings (1.18 for pulling and 1.10 for pushing).

3) Feeling Magnetism: Next, we determine what the ratings of push and pull may imply about experiences of magnetism with the 12 stimuli. Fig. 6 presents four types of interactions between the frequencies of ratings of "Agree" or "Strongly Agree" to the feeling of push or pull.

Overall, all but [Glove, Dial] stimulus are most often (over 50% of the stimulations) rated to convey sensations of a pull or a push. The red line _._ shows those frequencies of rating either pull or push high ("Agree" or "Strongly Agree"). Therefore, the peaks on this line indicate that the stimulus in question most frequently conveys experiences of magnetism in some direction (pull or push). Similarly, the peaks on the green line ......, which shows the frequency of the participants rating both pull and push high, indicate that those stimuli most frequently convey experiences of magnetism but do that in both directions. The frequencies here are lower as it is less common to agree on both the sensations of pull and push.

The highest point for the controller on both the red _._ and the green ......> lines is the [Controller, Palm] stimulus. In addition, the [Controller, Palm] stimulus seems to also convey a clear sense of the direction of magnetism, because the difference between the frequencies of the experiences of pull and push are also larger than in the [Controller, Tone] stimulus. This can be seen with the yellow line _ _ which shows the frequency of the participants rating pull high but push low, and the blue line __ which shows the frequency of the participants rating push high but pull low. The [Controller, Palm] stimulus frequently conveys an experience of push.

The highest point on the red line _._ for the haptic glove is the [Glove, Whole Hand] stimulus, indicating that it most frequently conveys a sense of magnetism in some direction. The third highest point on the red line _._, [Glove, Palm], is more frequently experienced to provide a sense of magnetism to both directions as indicated by the green line .... Yet, the clearest sense of the direction of magnetism is provided by the [Glove, Whole Hand] stimulus, as the blue line __ shows, conveying an experience of push.

The highest point on the red line _._ for the mid-air haptic device is the [Mid-Air, Oscillation] stimulus. However, the [Mid-Air, Expansion], which is the second highest point on the red line _._, most frequently provides a sense of magnetism to both directions as indicated by the green line .... The [Mid-Air, Expansion] also conveys a clearer sense of push (the difference between the blue __ and the yellow _ _ lines) than the [Mid-Air, Oscillation] stimulus.

We further explored the interactions between the ratings through correlations. Ratings about the pull and push sensations are weakly to moderately negatively correlated (mean: -0.30, std: 0.19). Both [Glove, Whole Hand] and [Controller, Palm] are moderately negatively correlated, with correlation coefficients of -0.54 and -0.56 respectively. This shows that participants often treat the questions as being opposed, for instance by agreeing to feeling a pull and disagreeing to feeling a push.

4) Summary: This study aimed to show that participants can gain a sense of distant objects through a set of haptic stimuli. Since participants are agreeing to the statements *"I felt the object at a distance"* and *"The object reacted to my movement"* for many stimuli, we show that participants feel objects at a distance through most of the designed stimuli. Thus, we show that it is possible to design stimuli that induce a sensation of distant objects, providing evidence for Principles 1 and 2. We also show that participants can gain a sensation of pseudo-magnetism, as agreement towards feeling a pulling or a pushing experience is high, but participants are not in agreement on the mode. It is thus unclear still, whether Principle 3 holds. We have shown the aim of the study, but have also identified a need to investigate how to induce pseudo-magnetic experiences.

V. Study 2: Validating Pseudo-Magnetic Experiences

The goal of the second study is to find how pseudo-magnetic experiences can enable interactions with distant objects (Principle 3). We chose three stimuli to induce pseudo-magnetic experiences, which in the first study were rated to provide the strongest magnetic sensations of objects at a distance. A novel set of participants perform two interactive tasks that represent the use cases of Haptic Magnetism: (1) selecting which of two objects magnetically attracts (Fig. 1(c) and (d)), and (2) locating the source of magnetic attraction on a plane (Fig. 1(a) and (b)).

A. Participants

We invited 15 participants to complete the two tasks in the study. The participants were aged between 24 and 35 (mean: 27.47, std: 3.40). Seven participants self-reported being female and eight being male. The experiment took 43 minutes on average to complete. All participants were rewarded with a gift valued at $25.

B. Study Design

The second study followed a within-subject design with the two tasks and the stimulus as an independent variable. In the first task, the participants chose which of the two visually identical objects felt attractive to them. The objects emitted either attractive, repulsive, or neutral versions of one of the three stimuli. The neutral means no haptic stimulation is provided. The attractive and repulsive are opposites for each stimulus. For example, in the case of the [Controller, Palm] stimulus, the attractive cue is a weak intensity when close to the object and strong when far away, and the repulsive cue is the opposite. As the object's location on the left and right may also influence the choice, we posed six conditions for each of the three stimuli (two objects and three versions of the stimulus): neutral-attractive, attractive-neutral, neutral-repulsive, repulsive-neutral, attractive-repulsive, repulsive-attractive. We repeat these conditions three times for a total of 18 trials with each stimulus. The order of the three stimuli is counterbalanced so that the tasks are performed with one device at a time, and the order of the 18 trials within the stimuli was always fully randomised.

In the second task, the participants received only the attractive cue from each of the three stimuli and were asked to locate the source of the stimuli on a plane. This task was always performed last because getting to know only the attractive cue here could have primed the participants to always choose that in the selection task. The task of locating the stimulus on the plane was performed 15 times for each of the three stimuli. The source of the stimulus on the plane was fully randomised.

C. Selection of Stimuli

We selected one stimulus for each device based on their ratings in the first study. For the controller, we chose the [Controller, Palm] and for the haptic glove the [Glove, Whole Hand] stimulus, as they most frequently provided the sense of magnetism to either direction and also the clearest sense of direction (pushing away from the object). For the mid-air haptic device, we chose the [Mid-Air, Expansion] stimulus, as it most frequently provided the sense of magnetism to both directions, and here as well more frequently toward pushing away.

As all of the three selected stimuli are rated more frequently to provide a pushing sensation, we use those as the repulsive versions of the stimuli. To induce an experience of attraction, we reversed them. Thereby, in the attractive versions, the intensities of the [Controller, Palm] and the [Glove, Whole Hand] stimuli are decreasing and the diameter of the circular pattern in the [Mid-Air, Expansion] stimulus is expanding, when moving closer to the object.

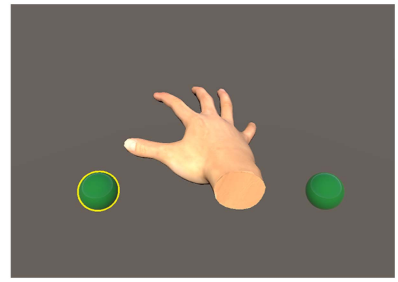


Fig. 7. Virtual reality used in the first task of the second study. A participant is moving their hand toward one of two virtual objects. The yellow highlight shows the object closest to the hand.

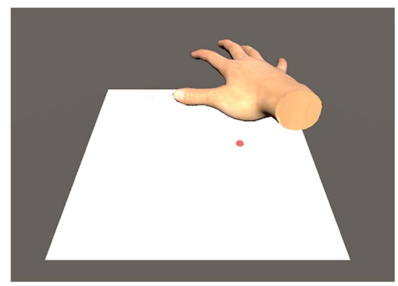


Fig. 8. Virtual reality used in the second task of the second study. A participant is moving their hand to locate a magnetic stimulus.

D. Tasks

The purpose of the first task is to investigate whether attraction can be distinguished from repulsive and neutral variations of the stimuli and thereby used as a sole source of information in decision making. Additionally, the results of this task should reveal whether a stimulus can be reversed and thus be used for both attraction and repulsion. In the task, the participants were asked to select which virtual object among two objects 30 cm apart felt attractive to them (Fig. 7). The selection is made by taking the dominant (virtual) hand close to an object, and when it highlights as an indication of closeness, pressing a button on a controller in the non-dominant hand to confirm the selection. For each trial, we log the selection and measure the completion time from starting the trial to selecting one of the spheres.

The purpose of the second task is to find how accurately the origin of an attractive stimulus can be located and thereby used as a sole source of information for locating objects. In the task, the participants were asked to point out a location on a white 30 × 30 cm plane at which they believed the stimulus had its source (Fig. 8). The selection was made by placing a small cursor that moved on the plane below the centre of the participant's (virtual) palm on the desired location and confirming the selection by

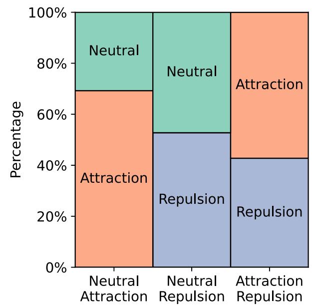


Fig. 9. Frequency distribution of selected stimuli in the first task.

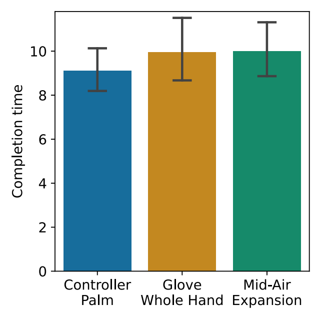


Fig. 10. Time in seconds used to select a stimulus in the first task. Error bars show 95% CI.

pressing a button on the controller in the non-dominant hand. For each trial, we log the location of the selection and calculate the selection error as a distance to the actual origin of the stimulus and the completion time from starting the trial to selecting the location.

E. Procedure

The experimenter welcomed the participants and they filled out an informed consent form and a demographics questionnaire. Participants were introduced to Haptic Magnetism as a concept and were explained how the haptic stimuli would be rendered on their dominant hand. Then, the participants entered the virtual environment and were introduced to a haptic device by trying a sample stimulus, similar as in the first study. Again, the sample stimulus was not from the set of designed stimuli, but rather a haptic stimulus with maximal intensity on the palm of the hand. Each task was introduced shortly before the start of the task. For the first task, the experimenter emphasised that the participant should pick the attractive stimulus and that they should go after their intuition. For the second task, the experimenter emphasised that the precision of the selection was important for the task. Each time a set of trials was completed on a device, the participant could remove the virtual reality display, as to see (and equip themselves with) the next haptic device. After all trials were completed, participants could ask questions and leave comments to the experimenter.

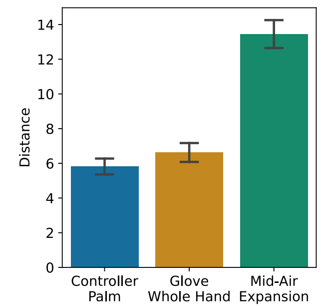


Fig. 11. Distance in centimetres between stimulus source and selected location in the second task. Error bars show 95% CI.

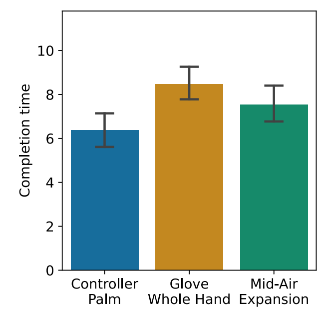


Fig. 12. Time in seconds used to locate a stimulus in the second task. Error bars show 95% CI.

F. Data Processing

There were no outliers detected in the data collected in the second study.

G. Results

To investigate whether attraction can be distinguished from repulsive and neutral variations of the stimuli, we first analyse the results from the selection tasks. We then analyse how accurately the origin of an attractive stimulus could be located in the second task. The data is available at https://osf.io/62pyj/.

1) Selection Task: Fig. 9 shows the frequency distribution of whether participants selected an attracting over a neutral stimulus, a repulsing over a neutral stimulus, and an attracting over a repulsing stimulus. These frequencies show that the participants selected the attracting stimulus over the neutral stimulus in (69.26%) of the trials and an attracting over a repulsing stimulus in (57.25%) of the trials. This suggests that attraction can be distinguished from repulsion and neutral in a forced-choice task, although in the ratings of Study 1 the distinction was often less clear. Participants also tend to pick haptic stimulation over no haptic stimulation (attraction 69.26% and repulsion 52.77% over neutral). This suggests that to induce experiences of magnetism, the reverse stimuli among these three tested ones would work better than no stimuli at all. We found no significant differences with an ANOVA in the time participants used to choose a stimulus (Fig. 10).

2) Precision Task: Fig. 11 shows the distances between the selected location and the true source of the attractive stimuli. These distances show, that the participants were able to locate an

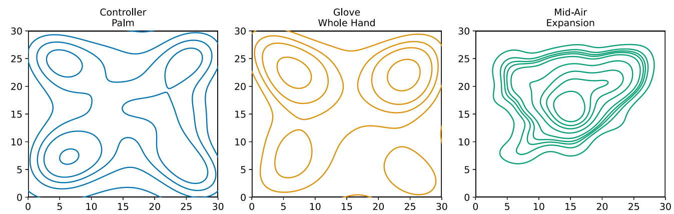


Fig. 13. Distribution of selected stimulus location, grouped per stimulus. The locations are plotted as a kernel density estimation, showing the likelihood of where participants supposed the source of the stimuli. The box around the distribution shows the 30 × 30 cm boundary in which the participants could select locations.

object based on their experience of an attractive stimulus. Both the [Glove, Whole Hand] stimulus and the [Controller, Palm] stimulus perform well with an average error of 6.64 cm (std: 4.08) and 5.91 cm (std: 3.49), respectively, in locating the source of the attractive stimulus. However, the [Mid-Air, Expansion] stimulus provided little or no help for locating the source, having a 13.50 cm (std: 5.79) error on the 30 x 30 cm plane with targets spun randomly across it.

Fig. 13 shows the distribution of the selected locations on the plane for each stimulus. Here we see that participants generally estimated the [Mid-Air, Expansion] stimulus to be in the centre of the boundary. This suggests that participants, as also seen in Fig. 11, find it difficult to locate the source of the [Mid-Air, Expansion] stimulus, and usually select a rather central location, perhaps reflecting the insecurity in detecting the source. In contrast, the estimated sources of [Glove, Whole Hand] and the [Controller, Palm] stimuli are distributed more evenly across the boundary, although showing that participants generally estimated the source to be in one of the four quadrants of the plane. We found no significant differences with an ANOVA in the time participants used to choose a stimulus (Fig. 12), suggesting that participants are equally thorough in performing the task with all stimuli. The time spent on this task is slightly higher than in the previous task, reflecting the instruction that participants should focus on the precision of their estimation.

3) Summary: The aim of Study 2 was to show that pseudo-magnetic experiences can enable interactions with distant objects, to show that Principle 3 holds. We find that participants can distinguish pseudo-magnetic modes when prompted, showing that participants gain an experience of pseudo-magnetism. As a result of the second task, we show that participants can estimate the location of a pseudo-magnetic stimulus accurately, implying how these experiences can enable interactions with distant objects. With these two findings, we gain evidence for Principle 3.

VI. Discussion

We have conceptualised Haptic Magnetism, which enables users to gain a sense of objects at a distance. Here, we first discuss the feasibility of Haptic Magnetism, which we investigated in two studies. We then discuss how to design pseudo-magnetic stimuli to extend the presented designs. Finally, we discuss the kinds of applications seen in previous work which, if altered to use pseudo-magnetism, could benefit from Haptic Magnetism.

A. The Feasibility of Haptic Magnetism

Haptic Magnetism is an interaction modality that extends a user's sense of touch to enable interactions with objects at a distance. The modality operates by three principles:

1) Haptic Magnetism relies on providing tactile stimuli to the haptic sense.
2) Haptic Magnetism delivers sensations of objects at a distance.
3) Haptic Magnetism enables interactions through experiences of pseudo-magnetic attraction and repulsion.

As discussed earlier, these three principles are the foundation of Haptic Magnetism, guiding the design of pseudo-magnetic stimuli. Thus, if we show these three principles to be feasible, we show that Haptic Magnetism is feasible. The designs presented and evaluated as part of the first study show the feasibility of Principle 1. We show that it is possible to design tactile stimuli that do not rely on force or kinesthetic feedback but still deliver sensations and experiences as sought for by Principles 2 and 3. We have shown that there exist haptic stimuli, that can deliver a sense of attraction and repulsion at a distance. An instance of this is the [Glove, Whole Hand] stimulus.

Participants gain a sense of the object at a distance through tactile stimulation and feel that the object interacts with them as they move their hands in the first study. By extension, we show Principle 2. In the first study, participants felt sensations of being pulled towards or pushed away from an object.

The notion of attraction and repulsion is confirmed in the first task of the second study by a different set of participants. We also show that participants can extract information from the haptic stimulus in the second task, allowing them to locate objects without audiovisual feedback. Together this shows that Principle 3 holds, as interactions can be enabled through the information, rendered haptically as a pseudo-magnetic attraction or repulsion, gathered from the environment.

With our approach to evaluating the perceptual qualities of Haptic Magnetism, we study the basic feeling of pseudo-magnetism. This feeling is solely induced through the sense of touch. In that way, we have shown that foundational aspects of the concept hold.

B. Designing Stimuli for Haptic Magnetism

Haptic interactions are getting integrated into audiovisual computer systems allowing for richer user experiences. Often these haptic interactions are associated with proximity and intimacy [11], as well as mimicing realism [5], [28]. For the concept of Haptic Magnetism, we have drawn inspiration from the works of Sadeghian and Hassenzahl [29] and Willett et al. [30], who in turn are inspired by comics of superheroes and their superpowers to enhance visual interactions in virtual reality and visualisations. Engaging with works of fiction can help designers start a creative process also when designing non-realistic haptic stimuli. Users of these non-realistic stimuli have shown to accept and engage with them in the two works on visual feedback, but also when asked about their experience of mid-air haptic stimuli [31]. Therefore, while designing non-realistic stimuli is not trivial, they carry a promise of new experiences.

Based on our two studies, we recommend designers consider three factors when designing pseudo-magnetic stimuli:

1) We recommend considering the relationship function that modulates the value of stimuli parameters: The function describes a relationship between the user and the object, such as distance or direction. The relationship should be relevant to the interaction. Possible parameters to modulate include intensity, size of a haptic shape, or stimulus location.

We created the 12 stimuli presented in Study 1 for Haptic Magnetism. The stimuli are designed to convey a sense of the distance between hand and object through different haptic patterns and modulations. As the studies show, some stimuli induced a sense of object at a distance and of magnetic properties. Thus, while we seem to be on the right track, there might be designs that more strongly induce pseudo-magnetic sensations.

Our designs are based on a linear function describing the distance relationship between the user's hand and a virtual object. That is, all stimuli are implemented with at least one distance-dependent design parameter. For instance, the drawing speed of a circle is dependent on the distance between hand and object in the [Mid-Air, Dial] stimulus. This approach proved promising in the first study, but alternative functions that could produce a stronger sense of magnetism remain future work. For example, the design of the relationship function could be non-linear or be dependent on another relation (e.g., direction) or a combination thereof. If the function were exponential, designers could archive a sudden strong magnetic sensation, similar to when two physical magnets get close and "snap" together.

2) We recommend considering the haptic device used for the pseudo-magnetic stimulus: As haptic devices have different modes of stimulation and intended functionality, we suggest implementing Haptic Magnetism on devices used for other interactions in the created application. In virtual reality, controllers are often used to interact with the virtual environment, so it is apparent to use such devices for pseudo-magnetic effects. Our studies show that a standard controller is a promising device for inducing pseudo-magnetism. In augmented reality or the real world, a mid-air haptic device is an option, as it is less intrusive than the other presented haptic devices. However, the imprecision of the [Mid-Air, Expansion] stimulus should be considered.

In our 12 designs, the haptic stimuli depend on the capabilities of the device, although some characteristics and parameters are translatable between devices. The stimuli are limited in design by the device inducing the haptic sensation. The controller can only vibrate its whole casing, simulating the whole hand at once, while the haptic glove can stimulate the fingertips and palm, but only in specific areas. The ultrasound mid-air haptic device can stimulate anywhere on the hand, although with limited concurrency, intensity, and interaction space. But, even with these limitations, the devices were shown to be feasible for Haptic Magnetism. Introducing Haptic Magnetism to less generic devices can increase the performance of the modality but with decreased device versatility. Such devices could employ asymmetric vibrations, similar to those of Culbertson et al. [27], or kinesthetic feedback, to shear the skin and thereby guide users as implemented in the Haptic Revolver [2], to induce a sense of magnetism.

3) We recommend considering the spatial span of the pseudo-magnetic effect: This span relates to the distance at which the relationship function reaches its maximal and minimal values. We suggest adjusting the span to the modulated parameter since subtle changes in intensity are hard to perceive for users. Generally, a small span should be used only to deliver precise information.

In the second study, we were limited by the interaction space of the mid-air haptic device, which is an approximately $50 \times 50 \times 50$ cm large imagined box 15 cm above the device, where a lot of intensity is lost at the edges of this boundary. Thus we sought to create two tasks that could be implemented using the mid-air haptic device. As a result, the first task was limited to two objects, as they needed appropriate spacing such that participants could feel the distinct magnetic stimulus over a distance. The interaction space of these stationary devices can be extended by using systems like PUMAH [32], but as we used off-the-shelf devices, this work is limited to standard use.

It is not immediately obvious how to generalise a specific stimulus design to a new device, as stimulus and device are confounded. We see an indication of a correlation between the area of skin stimulated and the perceived strength of pseudo-magnetism in the results of Study 1. Although this hypothesis needs further investigation, such a correlation can help designers start their process of designing stimuli. During the studies, participants generally stated that the mid-air haptic feedback felt less clear and intense. They cited this as a reason for their difficulty locating the source of the pseudo-magnetic stimuli in the second task of Study 2. Although only anecdotal evidence from participants' statements, this could be part of the reason for worse performance in the same task. Thus, when designing for Haptic Magnetism, designers should design clear and intense stimuli to induce magnetic sensations.

C. Designing Interactions With Haptic Magnetism

We envision Haptic Magnetism to become an extension of and alternative to existing interaction modalities. Additionally, Haptic Magnetism allows for novel interactions previously restricted by the limits of other sensory modalities. Haptic Magnetism has flexible uses, as seen in the examples of applications we presented earlier (for instance, in Fig. 1). We see the use of the modality within guidance, navigation, nudging, and discovering affordances or feedforward interactions. This is likely an incomplete list, but we hope that Haptic Magnetism can act as a framework for designers to create new haptic experiences through pseudo-magnetic stimulation. We provide the following ideas for future work:

1) Using Haptic Magnetism in with other interaction modalities: Our approach to investigating the perception of the stimuli, contrary to showing their practical use, helps to consolidate a strong foundation for the concept on which future designs of stimuli and applications can stand. We investigated the perception of pseudo-magnetic haptic stimuli and thereby showed that the concept of Haptic Magnetism is feasible. Haptic Magnetism only relies on the haptic sense and is thus usable outside of common audiovisual interfaces, such as augmented or virtual reality devices and smartphone or desktop interfaces. The concept can, however, be used in conjunction with these interfaces. Exploring how Haptic Magnetism could, combined with other interaction modalities, allow for richer experiences remains future work.

2) Providing an intuitive and clear sense of attraction and repulsion: Through our studies, we show that users can feel haptic stimuli to be magnetic when prompted. They seem to build an intuition of which stimuli they find attracting or repulsing, although they might not always be certain on the mode. As a part of the results of the first study, we see that participants are not consistent in their rating of feeling a stimulus to attract or repulse them towards an object. This could be due to the purposely limited instructions given and the freedom to rate the stimuli simultaneously on both scales of pulling and pushing. The second study already suggested a clearer sense of attraction when the participants encountered a forced-choice task between the two options. The clarity of attraction could be further increased by providing a reference by letting participants try out a real-world magnet before the study. However, such extensive instruction would defeat the idea of Haptic Magnetism not mimicking reality and yet being intuitive. Yet, other types of instructions or prompts for learning the meaning of the stimulations could enhance the clarity of sensations. This too remains future work. We thus hypothesise that users may gain a greater sense of magnetic stimuli when receiving specific instructions on which stimulus is attracting or repulsing, for instance, through an application tutorial.

3) Testing the concept of Haptic Magnetism in new applications and tasks: We have suggested multiple application areas for Haptic Magnetism. The studies do not address all possible application areas we discuss, as the concept is novel and flexible in its use-cases. Replicating tasks and studies by other researchers working on these areas would help validate our suggestions. For instance, replicating the tasks developed by Lopes et al. [22], designed to evaluate "Affordance++", with Haptic Magnetism instead of electronic muscle stimulation is an option to show the usefulness in the discovery of affordances, using a more subtle form of feedback. The feelSpace belt [7] could be extended to also repulse from navigating in the wrong direction to show the usefulness of Haptic Magnetism in larger environments, such as the real world. Haptic Magnetism could also be implemented in a scene with many magnetic objects. Lilija et al. [10] investigated interactions in occluded areas by creating a view of the area in augmented reality. Replicating the task on this work while using pseudo-magnetic stimuli instead of visual stimuli, or using them in combination, could show the usefulness of Haptic Magnetism in occluded interactions and for multi-modal interactions. Tasks here include placing, dragging, and rotating objects, which also are interesting use cases for Haptic Magnetism. Thus, while this concept passed a hard feasibility test as a sole interaction modality, its application in combination with other modalities and in specific tasks and application areas remains future work.

VII. Conclusion

Haptic technologies allow us to feel virtual objects, mimicking the experience of contact with a surface of a physical object. In this article, we break open a design space for abstract haptic stimuli previously under-explored by the haptics community. We present *Haptic Magnetism*, an interaction modality allowing users to interact with distant objects through experiences of pseudo-magnetic attraction and repulsion. We show that Haptic Magnetism enables novel interactions solely through haptic stimuli and finds applications also outside audiovisual interfaces.

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