scientific reports

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Influence of duration and visual feedback on the perception of tactile illusions of motion

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Tactile illusions manifest when the perceived sensation does not align with the actual tactile stimulation. Phantom motion and cutaneous rabbit are two illusions that convey motion and direction information using only a pair of actuators, which results in reduced cost, weight, and energy consumption. This study presents two experiments involving these illusions. In the first of them, participants grasped a two-actuator haptic interface. It explored how the duration of the illusions influences the distance traveled by the illusory points. For phantom motion, duration directly affects the perceived end-point location. As duration increases, the end-point starts being sensed out of the hand, either in the interface or even in the air. On the other hand, cutaneous rabbit illusion is not influenced by duration. The second experiment investigated the influence of visual feedback on the perception of both tactile illusions. Visual stimuli were presented paired with their haptic counterpart. Results show a clear dominance of vision over the haptic mode in both phantom motion and cutaneous rabbit illusions. Characteristics such as the motion location, direction, distance traveled, or number of jumps in cutaneous rabbit were fixed by the visual stimulus, no matter the content of the haptic cue. This finding opens a world of possibilities for integrating tactile illusions in visuo-haptic experiences typical of Virtual Reality environments: simple setups with two actuators are enough to elicit clear and varied haptic perceptions when presented together with the appropriate visual stimulus.

Keywords Augmented Reality, Haptics, Haptic feedback, Multimodal interaction, Tactile illusion, Visuo-haptic illusion, Virtual Reality, Visual feedback, Visuo-haptic integration

Touch is a fundamental sensory modality in our daily life, providing valuable feedback when exploring the world around us. Haptics is closely related to touch in its broadest context. It involves active touch, i.e. how we obtain information about objects intentionally, in an exploratory way, by manipulating them[1–4]. Haptics combines inputs from touch and kinesthesia. The former acquires tactile cues from the skin mechanoreceptors[5,6], whereas the latter gains information about the position and movement of our limbs and muscle-generated force from receptors in joints and tendons, and muscle spindles[7]. When compared to other senses, touch is sometimes overcome by hearing and sight. Vision and audition dominates the interaction with our surroundings, with a bandwidth of 10^6 bps in the first case, 10^4 bps in the second, and 10^2 bps for touch[8]. If we look at other metrics, fingertips, that are among the areas with higher density of mechanoreceptors[9], can detect a variation of around $1\ mm$, being the touch spatial resolution lower than that of the vision but better than the case of audition[10].

The different modality inputs, each with its own characteristics, are integrated by the Central Nervous System (CNS). Multimodal integration has been widely studied over the last few decades, multiple models and frameworks have been proposed[11–15] and anatomical evidence has been reported[16,17]. When an individual manipulates an object that he/she is seeing, vision normally dominates the integrated visuo-haptic perception evaluating shape, size or position[18,19]. On the other hand, Lederman et al. found no evidence of a dominant sensory hierarchy regarding the perception of texture patterns, suggesting that a weighted average model may describe the intersensory integration process for both spatial density and roughness perception[20]. In a similar vein, Ernst and Banks examined the quantitative integration of visual and haptic cues in[21], proposing that the CNS appears to combine visual and haptic information in a manner analogous to a maximum-likelihood integrator. Consequently, visual dominance emerges when the variance associated with visual estimation is lower than that linked to haptic estimation. In this regard, inter-modal integration may also be influenced by perceptual illusions arising from inputs of one or multiple modalities, as will be discussed below.

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Perceptual illusions
When there is a discrepancy between the actual stimulus and that perceived by the CNS, the term sensory or perceptual illusion is usually employed[22]. Within the domain of vision, this phenomenon has been the subject of extensive research. Notable examples include the Mueller-Lyer illusion[23], the Ponzo, the Poggendorff or the Hering visual illusions[24]. These illusory phenomena also manifest in other sensory modalities. Perceptual illusions related to the haptic system have received comparatively less attention than those involving vision or audition. It may be due to the fact that they normally need to fulfill certain specific requirements to appear, that are not met in daily life activities[25,26]. While some tactile illusions, e.g. the classic Aristotle one[27], can arise just using our fingers, and some of them only require everyday objects, others need for specific equipment to be generated[28]. When comparing optical and haptic modalities, one can find that they share some illusions, such as the Mueller-Lyer or the Ponzo. Nevertheless, it is noteworthy that certain illusions exert only a partial influence on the domain of haptics, while others manifest exclusively within the visual modality[29].

The presence of multiple senses during the exploration of an object gives rise to crossmodal interactions. According to the aforementioned integration model, vision may influence the haptic perception of object properties, and, if judged more reliably, even overwrite it to a certain degree, and vice versa[30]. Consequently, perceptual illusions may arise in one of the modalities induced by the other. In this regard, the authors of[31] modified the visual perception of a surface by providing haptic feedback. Concretely, the surface appeared to be slanted in the direction specified by the haptic signal. Another haptic-induced visual illusion was reported in[32], whose authors found that the number of light flashes perceived by volunteers could be modulated by conveying a different number of taps to the index finger. Srinivasan et al. designed a series of experiments to study the impact of visually spatial cues on the perception of mechanical stiffness of two virtual springs[33]. Volunteers pressed the springs using a force-reflecting haptic device, and felt the displacements and forces through their hands while seeing the deformation of the springs on a screen. Despite systematically varying the relationship between the visual deformation of the springs and the actual deformation, participants ignored the kinesthetic cues regarding hand position and based their judgment on the relationship between the visual position information and the sensed force.

Motivation
Similarly to the mentioned works, the authors of the present article wondered if the perception of tactile illusions of motion, that are those that elicit an illusory motion based on haptic cues, may be affected by providing visual feedback. These kind of illusions hold particular relevance for devices providing haptic feedback, that are increasingly common in Augmented and Virtual Reality (A/VR) systems, either commercially available[34–36] or involved in research. Haptic feedback plays a key role in A/VR in many fields[37] and haptic and visuo-haptic illusions have been already explored in multiple works to overcome the limitations of VR technology[38,39]. Tactile illusions of motion fit in a natural manner in virtual experiences that usually involves moving objects and effects. Furthermore, due to the minimal number actuators required for their rendering, its use enhances the compactness, weight and energy consumption in human-computer interfaces. This, in turn, results in user comfort and more immersive experiences[40,41].

On the negative side, however, evoking these tactile percepts requires specific hardware and equipment that depend on the characteristics of the rendered illusion. This makes tactile illusions of motion a less adaptable and reusable tool in VR human-machine interactions, that usually imply changing scenarios. For this reason, a visual-based modulation of the haptic perception would confer a valuable versatility to this resource by reducing the need for hardware modifications, as the visual input is naturally provided in VR tasks and experiences.

The reasons exposed above motivated an investigation involving two experiments. The first of them examines how the perception of the haptic motion may be altered, in an intramodal fashion, by varying the duration of the tactile illusion. It formed part of a preliminary work that is here extended overcoming some previous constraints. The second experiment incorporates visual feedback that is presented simultaneously together with the haptic stimulus. It aims to provide insights into the potential expansion of the motion perception boundaries compared to those reached when using only haptic stimulation.

The structure of this paper is as follows: Section "Background" describes the tactile illusions of motion involved in this work, how they are perceived and how to recreate them. It also details the previous work that gave rise to the first experiment, as well as the goals of this research. The experimental setup with which the participants interact during the experiments is explained in section "Materials". Section "Methods" covers the experimental methodology, describing the sample of participants, the experiment protocols and the haptic and visual stimuli involved in the haptic and visuo-haptic illusions. The results of both experiments are presented and discussed in section "Results and discussion". Finally, the conclusions of this work are provided in section "Conclusions".

Background
Some tactile illusions on the skin are based on misjudgments of the stimulus localization. For example, when two stimuli are delivered with the same intensity simultaneously at relatively nearby points on the skin, they are usually perceived as an only illusory point at the center between the actual stimuli. This is a robust illusion known as *funnelling effect* or *phantom sensation*. The location of the elicited point can be modulated by manipulating the relative intensity of the two real stimuli[42]. Intuitively, one can conceptualize the displacement of the illusory point through the dynamic adjustment of the intensity of both stimuli.

Tactile illusions of motion: phantom motion and cutaneous rabbit
The above idea was reported by Alles in[43]. An experiment was conducted to evaluate a phantom sensation display for kinesthetic feedback placing vibrotactile actuators in the participants' arm. The volunteers perceived how the phantom point continuously moved from one vibrotactile actuator to another. The envelope of the signal

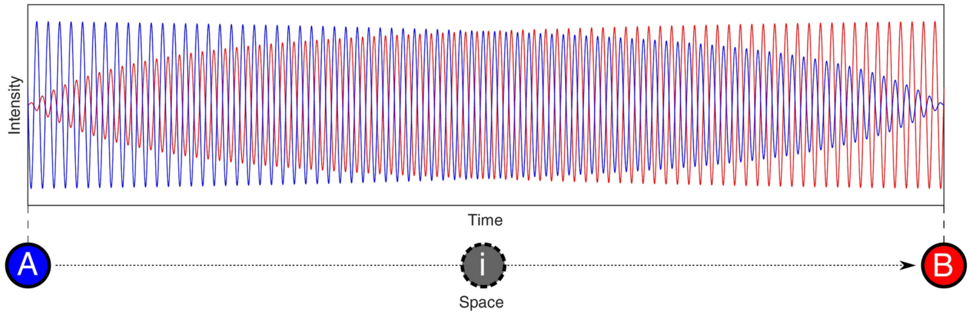


Fig. 1. Rendering of *phantom motion* tactile illusion. The illusory vibrotactile point **i** moves from real actuator **A** to real actuator **B**. The intensity of vibration of actuator **A** (in blue) decreases from its maximum to zero while that of actuator **B** (in red) increases from zero to its maximum.

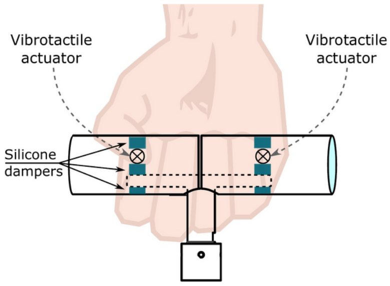


Fig. 2. Experimental device in[50] (image by the authors).

transmitted to the first actuator should decrease as the envelope of that one in the second actuator increases, with both of them following a logarithmic shape (see Fig. 1). This illusion is commonly known as *apparent motion* or *phantom motion* (PM). Another illusion of motion based on errors in localization is the saltation illusion, named *cutaneous rabbit* (CR) by Geldard and Sherrick in[44]. CR is rendered by delivery of a series of short pulses in rapid succession in one point and, afterwards, in another. Instead of perceiving the taps in the first location and, just after, the taps in the second, the stimulus seems to move progressively across the space between the actuators, from the first to the second, in small hops. Note that, unlike PM, in CR both actuators are not activated simultaneously. Both PM and CR are robust illusions[28,45] and have been used in this work as will be explained below.

Previous work

There is a group of tactile illusions related to a non-veridical perception of distance. They are normally affected by the time between stimuli[46] or the duration (or velocity) of the illusion itself. For example, authors of[47] found that, when moving a point across the skin of participants, the distance traveled was perceived as shorter at faster rates. Similarly, in an experiment in[48], a brush was swept along a linear path on the forearm skin at different velocities. Even if the length of the contacted skin was the same at all velocities, the estimates of stimulus distance decreased as the stimulus velocity increased. This effect was also observed with illusory motions as was reported in[49]: a device equipping two vibrotactile actuators at its ends, and designed to be held with one hand, rendered the PM illusion on the hand palm. The distance covered by the moving point was shorter, again, as the motion velocity increased.

In a previous work[50] of one of the authors of the present article, a cylindrical-shaped haptic device was designed to be grasped with one hand during a series of experiments. It was equipped with two actuators positioned approximately at the left and right ends of the palm (see Fig. 2, the central end of the T-shape between middle and ring fingers). The device was hidden under a table covered with a piece of cloth, so that the volunteers were unable to see it. PM with varying durations was generated by the actuators. It is noteworthy that PM duration is directly related to the velocity of the moving point, given the fixed spacing between the actuators. As the duration of the PM increased, some participants began to perceive an increase in the distance traversed by the point, with end-point locations out of the hand palm and even out of the device boundaries.

One of the starting points of this work is to test if adding visual feedback improves the ratio of participants who sense the perceptual illusion of the end-point out of the hand/object. The experiment conducted in[50] faced certain limitations, necessitating further investigation to establish a robust basis for comparison. Some of these limitations include a small sample size, and a particularly low spatial resolution, which hindered the ability to accurately provide the end-point location. The participants did not select an end-coordinate but a region inside which the point stopped. Each region was $45.7\,mm$ wide so the answers were far from accurate. On the other hand, the experimental device should be redesigned. Both actuators were mechanically linked through an internal support structure (in dashed line in Fig. 2). Despite the incorporation of silicone dampers to mitigate vibrations, those generated by the left actuator were perceived in the right half of the device, and the vibrations generated by the right actuator were sensed in the left half. This inter-actuator distortion worsens the PM perception, what eventually may compromise the experiment results.

Aims of the study

In accordance with the above, the main objectives of this research are the following:

1. Investigating if the duration of tactile illusions of motion influences the out-of-the-hand/out-of-the-object end-point location. As explained, the experiment in[50] is redesigned, but also widened. In addition to PM, another tactile illusion of motion, namely CR, is included in the study. Besides, unlike the previous work, the effect of the motion direction is also considered. With this purpose, "**Experiment 1: haptic stimulation**" is carried out.
2. Shedding light on whether the visual modality can affect the perception of the tactile illusion of motion PM and CR. Moreover, if out-of-the-hand/out-of-the-object phenomena appear, comparing them with those elicited exclusively with haptic stimulation. To this end, "**Experiment 2: visuo-haptic stimulation**" is conducted.

Materials

In this section, the design and implementation of the experimental setup used in the experiments are described.

Vibrotactile actuators and signals

The actuators are two basic elements in this study. Their function is to generate the vibrotactile stimuli, so that the experiment volunteers perceive the tactile illusions. They are of the voice coil type and have been custom-made in accordance with the recommendations outlined in[51] and as showed in[52]. They were characterized in[53]. Similar actuators were also successfully used in prior studies by the authors such as[50,54,55]. A custom design enables their adaptation to the interface, ensuring a proper fit with a vibration direction normal to the hand palm. The fact that they are voice-coil (same working principle of common speakers) facilitates their operation through the use of audio technology. The signals that elicit the illusions have been created in MATLAB. For PM, the recommendations in[43] and[56] were considered, with a frequency for the carrier of 250 Hz, that is within the range for lower perception thresholds in the skin[57]. On the other hand, CR is designed as in[44], with a total of 10 pulses (5 per actuator) with a width of 2 ms.

Experimental setup

The experimental setup is illustrated in Fig. 3. The primary component is the vibrotactile interface, which is U-shaped with a circular section. The actuators are embedded in its base center. They are separated a distance of 70 mm, so that if gripped by its central area, vibrations are perceived approximately in the left and right ends of the user's hand palm. It should be noted that the interface is covered and therefore not visible (the assistance of the experimenter is needed to grasp it). For this reason, its length has been chosen in a way that is long enough to prevent the volunteer from touching accidentally the curved left and right ends during the gripping, which may bias his/her perception.

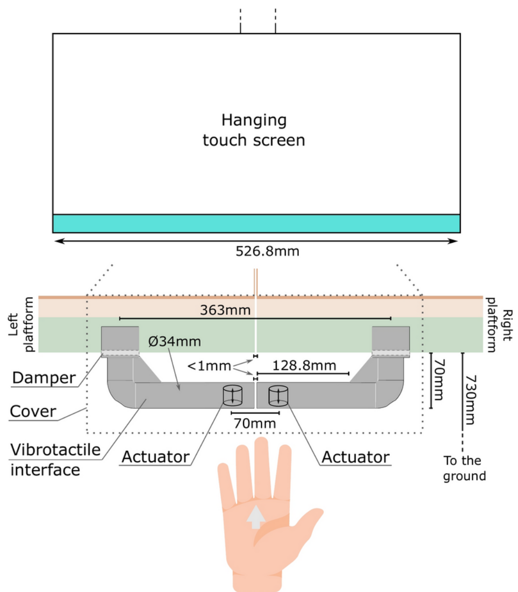


Fig. 3. Experimental setup (not to scale).

The configuration of the setup was designed with the objective of preventing vibrotactile interference between the actuators. As previously discussed, when the vibrations generated by one actuator extend into the space occupied by the other actuator, the perception of the volunteers undergoes a deterioration. It is imperative to generate precise and robust tactile illusions to ensure that the volunteers' feedback is exclusively based on their perception. In accordance with this objective, the configuration of the setup was designed to ensure that the surfaces with which one actuator comes into contact are isolated from those with which the other actuator comes into contact. Note in Fig. 3 that the vibrotactile interface comprises two L-shaped halves, each containing one actuator. Both are perfectly aligned in the interface center and are separated by less than $1\ mm$. This spacing is enough to keep the mutual mechanical insulation and, at the same time, not to affect the gripping experience, that is felt comfortable and similar to that of an one-piece interface. The ends of the interface are attached to the bottom side of two platforms, that also keep the above separation with the same purpose. Concretely, the right end of one laboratory table and the left end of another were used. Over the platforms, there is a screen that shows messages to the user and gathers his/her responses. It is a HP E24t G4 FHD model. Note that this monitor does not rest on the platforms to avoid acting as a mechanical connection between them. The volunteer interacts through the screen touch input using his/her free hand.

The diagram of Fig. 4 shows all the elements involved in the experiments and their connections. The experimenter's computer is responsible for generating the graphical interface displayed in the experimental setup screen. This interface has been developed with MATLAB App Designer. This software is also in charge of conveying the stimuli of the specific tactile illusion when required. Besides, the signals need certain amplification so that, between the computer sound card output and the actuators, a FOSI Audio TDA7498E amplifier processes them. The experimenter adjusts the gain to ensure that the perception of vibrations is clear and comfortable.

Methods

The experimental protocols described below were performed in accordance with the relevant guidelines and regulations of the University of Málaga. The methods were evaluated by the Experimentation Ethics Committee of the University of Málaga, which gave its favorable report (register number 157-2022-H). All volunteers were unaware of the experiment purposes and took part in the investigation after giving informed consent.

Participants

The sample of this study comprised 42 volunteers. Half of them participated in Experiment 1 (haptic stimulation) and the other half in Experiment 2 (visuo-haptic stimulation). This way, the first group was formed by 21 participants, 13 males and 8 females, whose ages range from 21 to 61 years, with a mean of 40.4 and a standard deviation of 15.5 years. On the other hand, the second group was composed of 13 males and 8 females between 18 and 68 years old, with a mean age of 36.7 and a standard deviation of 14.5 years. Apart from keeping the same number of males and females for both experiments, volunteers were randomly assigned to one group or the other. Their background was diverse (profession, hobbies, etc.) and they reported not to suffer from any kind of motor, sensory or neurological impairment or disorder.

Protocols

In the experimental sessions, participants approached the setup of Fig. 3 and took seat in a height-adjustable chair. The vibrotactile interface was located behind a cloth cover, preventing the volunteers from seeing it. They grasped it by its center with their dominant hand palm upwards, with the assistance of the experimenter. Note that they were unaware of the dimensions and shape of the interface (apart from what they can guess through the grip, e.g., it seems a cylinder). This measure had the purpose of mitigating potential bias when answering to distance-related questions, as will be explained below. Participants read the experiment questions and answered them through the touch screen in front of them. During the sessions, they wore noise-cancelling headphones playing brown noise at a comfortable volume, ensuring that auditory cues did not influence their perceptions. Figures 5 and 6 present examples of a volunteer performing the experiments.

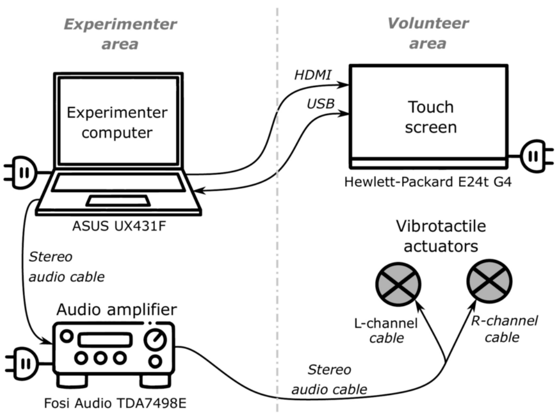


Fig. 4. Experimental setup connection diagram.

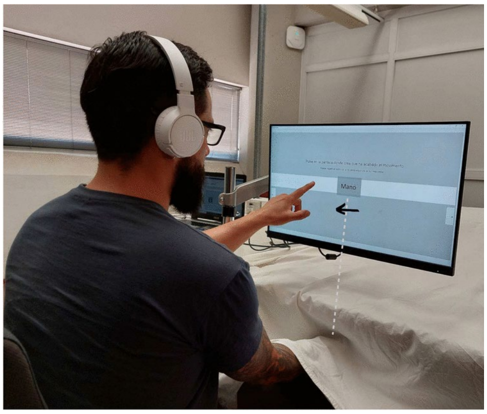


Fig. 5. Example of a volunteer interacting with the setup during Experiment 1.

Fig. 6. Example of a volunteer carrying out Experiment 2.

Practice session
Volunteers took part in a practice session. Its aim was to familiarize them with the tactile illusions they were going to perceive later in the experiments, so that they could clearly recognize them and were convinced of their responses. The session consisted of two parts. Firstly, a PM oscillating between the actuators was presented (i.e. the illusory point moved along the axis between the actuators, going from one to the other). The experimenter helped initially the participant to identify the moving point by telling the motion direction every time it changed. Once the volunteer demonstrated the ability to recognize the PM, the second stage commenced, involving then the generation of multiple PMs with random movement directions. In this stage, the volunteer was tasked with describing the tactile illusion to the experimenter without aid. The practice session ended when the descriptions were accurate. The process was repeated for the CR illusion. Although it depended on each participant, the session usually did not take more than a few minutes.

Experiment 1: haptic stimulation
The duration of the experiment was approximately 25 min, encompassing the initial experimenter explanation and a 2 min break in the middle of the session.

Haptic stimuli   As mentioned in section "Background", the tactile illusions of motion used are PM and CR. Table 1 enumerates the fourteen PM illusions created. Half of them are left-to-right and the other half right-to-left motions. Seven different durations were considered. PMs with duration below 0.25 s and above 3 s were excluded. The former were difficult to perceive whereas, in the latter, some undesired effects started arising deteriorating the illusion[47]. Moreover, six CR illusions were used (see Table 2), three of them in one direction and three in the other. Three different durations were rendered by varying the Inter-Stimulus Onset Interval (ISOI), defined as the time between pulses.

Instructions   During Experiment 1, illusions of Tables 1 and 2 were randomly presented. However, PM and CR were not mixed to facilitate concentration. The first series of illusions to be delivered, whether PM or CR, was randomly assigned to avoid an order effect. The steps to complete the experiment were:

Stimulus	Duration (s)	Motion direction
#1	0.25	L → R
#2	0.5	L → R
#3	1	L → R
#4	1.5	L → R
#5	2	L → R
#6	2.5	L → R
#7	3	L → R
#8	0.25	L ← R
#9	0.5	L ← R
#10	1	L ← R
#11	1.5	L ← R
#12	2	L ← R
#13	2.5	L ← R
#14	3	L ← R

Table 1. Characteristics of PM illusions for Experiment 1.

Stimulus	Duration (s)	ISOI (s)	Motion direction
#1	0.380	0.02	L → R
#2	0.560	0.06	L → R
#3	0.740	0.08	L → R
#4	0.380	0.02	L ← R
#5	0.560	0.06	L ← R
#6	0.740	0.08	L ← R

Table 2. Characteristics of CR illusions for Experiment 1. For all of them, the number of pulses is 10 and their width of 2 *ms*. The duration of the illusion is affected by the variation of the ISOI.

Stimulus	Duration (s)	Motion direction
#1	0.5	L → R
#2	1	L → R
#3	2.5	L → R

Table 3. Characteristics of PM for Experiment 2.

1. Pressing the "Start" button on the screen to initialize the experiment: a message indicating the tactile illusion that will be tested first appears on the screen (PM or CR) and a "Next" button is enabled.
2. Pressing the "Next" button, after which a message instructing to close the eyes and a three seconds countdown appear. The first PM/CR illusion is then triggered. The stimulus is delivered twice, but there is a "Repeat" button that can be used as many times as wished. The instruction *"Press on the screen where you perceived the motion ended"* is visualized. As can be seen in Fig. 5, there is a vertically-centered horizontal bar covering all the screen. At its center, there is a shaded area that is aligned with the haptic interface and approximately represents the device surface the hand palm is in contact with. This helps the volunteers to express if the end-point is sensed in or out of the hand.
3. Pressing with his/her free hand index finger on the screen where he/she perceived that the motion ended. The spatial coordinate is then recorded. Note that it corresponds to the perceived end-point of the PM/CR motion. The distance covered, taking as origin of the motion the center of the vibrotactile interface, is calculated. The touchscreen allows to record this location with a resolution of $0.27\,mm$.
4. Two minutes rest. Afterwards, he/she continues with the remaining series of illusions as instructed above.

Experiment 2: visuo-haptic stimulation
Carrying out the experiment took around 35 min, including the initial experimenter explanation and a break of 2 min in the middle the session to allow the participant to rest.

<u>Visuo-haptic stimuli</u> In this experiment, haptic and visual cues are delivered together giving rise to visuo-haptic stimuli. The haptic stimuli are gathered in Table 3 for PM. For the case of CR, only one left-to-right stimulus

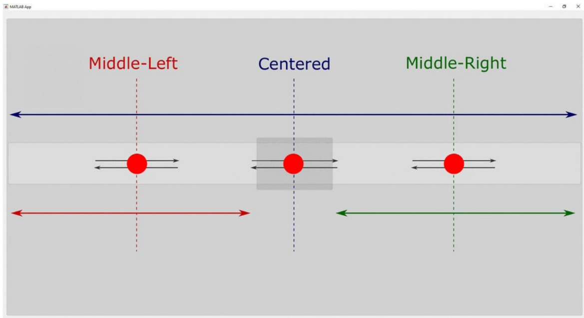


Fig. 7. Possible locations of visual stimuli in Experiment 2.

Stimulus	Length (cm)	Location	Motion direction
#1	3.5	Centered	L → R
#2	7	Centered	L → R
#3	7	Centered	L ← R
#4	20	Middle-Left	L → R
#5	20	Middle-Right	L → R
#6	40	Centered	L → R

Table 4. Characteristics of visual moving points to be paired with PM in Experiment 2.

Stimulus	Length (cm)	Location	Motion direction
#1	7	Centered	L → R
#2	7	Centered	L ← R
#3	20	Middle-Left	L → R
#4	20	Middle-Right	L → R
#5	40	Centered	L → R

Table 5. Characteristics of visual jumping points to be paired with CR in Experiment 2. Each of them was rendered with 6, 10 and 15 "visual" jumps.

with the characteristics specified in section "Vibrotactile actuators and signals" was used: 5 pulses per actuator (10 in total), 2 ms of pulse width, and an ISOI of 50 ms.

Visual modality was incorporated through the screen, with the visual cues designed to be paired with their haptic counterpart. Therefore, PM-linked and CR-linked visual stimuli were created. In both of them, a moving red dot following a horizontal trajectory is displayed on the screen. In the PM case, the dot moves continuously. In the case of CR-linked cues, the visual point moves "in steps" or "jumping", that is to say, it appears in one location, then it disappears and appears in a new position, and so on. The appearances of the dot are inspired in the CR jumps and are equally spaced. The visual cues are characterized by their *length*, *location*, and *motion direction*. Their duration is that of the paired tactile illusion.

As in Experiment 1, there is a vertically-centered horizontal bar covering all the screen, with a shaded area aligned with the hand grasping the haptic device (see Fig. 6). The red dot moves inside this bar. Figure 7 shows three screen areas that have been defined to describe the motion location. If it is *Middle-Left*, the dot trajectory would be within the range of the horizontal coordinates covered by the red line between arrows, symmetric with respect to the red vertical dashed line. The same would happen with the blue line for *Centered* location (motion symmetric with respect to the blue dashed line), and for the green line in the case of *Middle-Right* location (motion symmetric with respect to the green dashed line). Note that only dot motions in the *Centered* region can cover the whole screen.

Table 4 shows the PM-linked visual cues, which were paired with each PM from Table 3 yielding a total of 18 visuo-haptic stimuli. Finally, Table 5 lists the 5 visual stimuli designed to be paired with the CR stimulus. Each cue in the table was rendered for 3 different number of "visual" jumps: 6, 10 (the same as the haptic CR), and 15. Thus, this makes a total of 15 CR-related visuo-haptic cues.

The described stimuli may be grouped according to their similarities and differences. On the one hand, as shown in Fig. 8, taking into account that the screen and the haptic interface centers are horizontally aligned, and the distance between the vibrotactile actuators is 7 *cm*, in visual stimulus #2 of Table 4 and #1 of Table 5 the red dot is exactly covering 7 *cm*, going from the real horizontal coordinate of the left actuator to that of the right one.

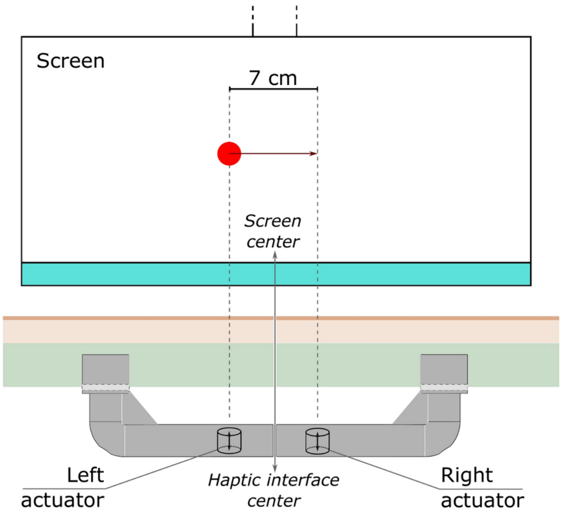


Fig. 8. For the case of the stimuli #2 of Table 4 and #1 of Table 5, the red dot moves paired with the haptic stimuli exactly from the horizontal coordinate of left actuator to that of the right actuator.

This way, the pairs formed by these visual stimuli and any of their haptic counterpart have been called *congruent* visuo-haptic stimuli (in the case of CR, only for the case of 10 visual jumps). On the other hand, the rest of visual stimuli were designed introducing certain discrepancies with respect to their paired haptic cues. This allows to explore how these differences affect the visuo-haptic perception. Stimuli inside this group has been named *non-congruent*, and the dissimilarities between both modalities are the following:

- There is a **horizontal shift**, to the left or to the right, between the visual dot trajectory location and the location of the actuators. The visual stimuli involved are #4 and #5 in Table 4, and #3 and #4 in Table 5.
- The **distance covered** by the visual dot differs from the distance between the actuators. The visual stimuli involved are #1, #4, #5 and #6 in Table 4, and #3, #4 and #5 in Table 5.
- The visual dot and the illusory vibration point move in **opposite directions**. The visual stimuli involved are #3 in Table 4 and #2 in Table 5.
- The **number of jumps** is different for the haptic and visual CR. This includes all the stimuli of Table 5 for the cases of 6 and 15 visual jumps.

Instructions In Experiment 2, the participants were asked to focus their attention on both the visual dot on the screen and the haptic stimulus in the hand. Figure 6 shows a volunteer watching the moving dot on the screen while, simultaneously, perceiving a PM illusion in his right hand. As in Experiment 1, PM and CR were not mixed. The first group to be delivered, either the one of PM or that of CR visuo-haptic cues, is randomly assigned. This way, participants were given the following instructions:

1. Pressing the "Start" button on the screen to initialize the experiment. A "Next" button is enabled and a message indicating the kind visuo-haptic (PM or CR) stimuli to be tested is shown.
2. Pressing the "Next" button. Immediately afterwards, the first pair of stimuli (visual plus haptic) are triggered. The stimuli are presented twice to ensure the participant perceived the stimulation in both modalities. A "Repeat' button is enabled and the following instruction appears: "*Evaluate the level of coherence between the moving dot on the screen and the vibrating moving point in your hand*". Five buttons are enabled to allow the participant to evaluate the inter-stimuli degree of coherence in a numbered (1-5) Likert scale: *Completely different* (1), *Different* (2), *Similar* (3), *Very similar* (4) and *Identical* (5). They may use the "Repeat" button as many times as needed before answering (see Fig. 9). The experimenter explained that the level of coherence (LoC) was a global measure of the the degree of similarity between stimuli, considering aspects such as covered distance, velocity, motion location and direction, etc.
3. In the case of the PM series, the response is recorded and Step 2 is repeated until finishing with all the pairs of stimuli. In the case of CR, there are two additional questions after assessing the degree of coherence. The first refers to the number of jumps: "*Where did you perceive more jumps?*", with three available options to choose from: *More in the hand*, *The same in the hand and on the screen*, and *More on the screen*. The second question involves location and direction: "*Do the location and direction of the jumping motion in the hand and on the screen match?*" *Yes* and *No* buttons are enabled.

The participants had rest periods of approximately 2 min between the first and the second group of stimuli.

Results and discussion
Experiment 1: haptic stimulation
The results of Experiment 1 are given and discussed below.

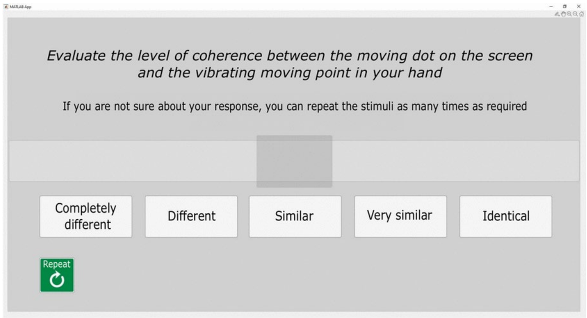


Fig. 9. Visual interface to evaluate the inter-stimuli level of coherence in Experiment 2.

Experiment 1: results

Before performing statistical analyzes, data were pre-processed to identify possible inconsistencies. Data collected from one participant was rejected from the sample due to poor performance in the practice session; this volunteer did not correctly report the direction of motion. 24 reports, representing the 9% of the total for PM, and 1 report, that is the 0.4 % of the total for CR, correspond to sensing the end-point beyond the touch screen boundaries. In this cases, the recorded coordinate was that in the left/right screen limit ($26.34\,cm$). Q-Q plots and Shapiro-Wilk statistical method were used to check for normality. According to the results, data from PM and CR are not normally distributed, and therefore, non-parametric statistical strategies were required. The final data bases of perceived end-point locations for PM and CR are plotted in Fig. 10.

Wilcoxon Signed-Rank test for repeated measures was used to compare the median perceived end-point of PM by direction for each duration. Then, Bonferroni-Holm method was used to calculate the corrected *p*-values to avoid Type I errors. According to the results, shown in Table 6, there is not a statistically significant effect of direction on the perceived end-point in the PM illusion.

Using a Friedman test for repeated measures, a statistically significant effect of duration was found on the perceived end-point of PM, with $\chi^2 = 159.93,\ p = 6.13 \cdot 10^{-32}$. The effect size was estimated by calculating the Kendall's W concordance coefficient. A substantial agreement between the participants was found, with $W = 0.666$, so the significance of the differences found is of high relevance. For post hoc comparison between durations, Wilcoxon Signed-Rank tests for repeated measures was performed for every possible combination of conditions to compare the median perceived end-point of PM by duration. Then, the Bonferroni-Holm method was used to calculate the corrected *p*-values. The results, summarized in Table 7, show statistically significant differences in all pairwise comparisons. Figure 11 shows a plot of the median perceived end-point location versus duration. Using a Spearman correlation test, a strong positive correlation was found between the median perceived end-point of PM and illusion duration, with $\rho = 1.0,\ p = 3.97 \cdot 10^{-4}$.

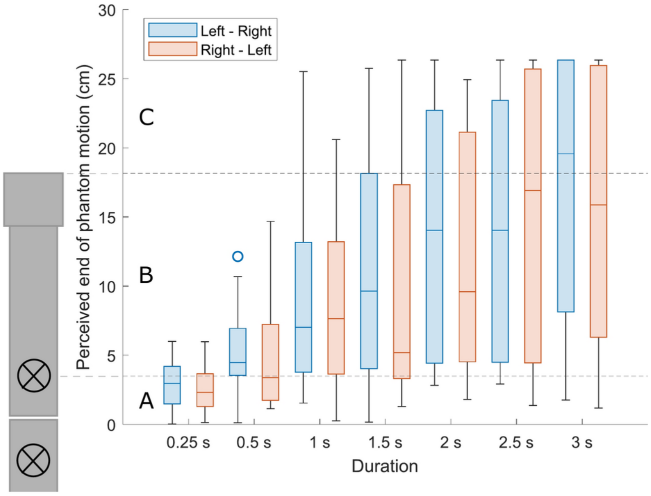
The heat map of Fig. 12 shows the proportion of reports by region where the end of phantom motion was perceived. Region *A* corresponds to the hand, region *B* corresponds to out of the hand but still inside the interface, and region *C* corresponds to out of the interface. Here one can see that, for durations below $1\ s$, no reports of PM end-point locations out of the interface (region *C*) are provided. On the other hand, as duration increases, end-points start being reported further from the hand, with only 10 % of the reports laying in region *A* and 48 % laying in region *C* when the duration is 3 *s*.

In the case of CR, using a Friedman test for repeated measures, no statistically significant differences were found between the median perceived end-point by duration, with $\chi^2 = 0.8,\ p = 0.669$. Then, a Wilcoxon Signed-Rank test for repeated measures was used to compare the median perceived end-point of the CR motion by direction. According to the results, there are statistically significant differences between the median perceived end of cutaneous rabbit motion by direction, with $W = 1227,\ z = 2.3,\ p = 0.022$. According to Fig. 13, when the motion was presented from left to right the perceived CR ended significantly further than when presented from right to left. Regarding these differences, a medium effect was found, with $r = 0.3$, so that although there are significant differences these are of moderate relevance. In the same manner of Fig. 12, the heat map of Fig. 14 shows the propotion of reports by region (*A*, *B* or *C*) where the end-point of CR motion was perceived. Note that for all durations most of the reports lay on region *B*, out of the hand but still inside the interface.

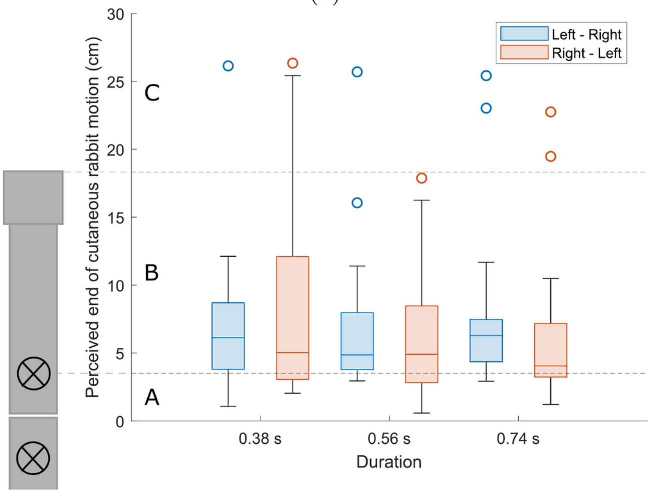
Experiment 1: discussion

In this experiment, the influence of the duration of PM and CR tactile illusions on the distance covered by the moving points was studied. A preliminary experiment from a previous work was redesigned to overcome its limitations and produce more reliable results. The new setup allowed to collect accurate data whereas the new haptic device delivered quality and clear tactile illusions. Besides, the previous sample was almost doubled.

The primary finding concerning PM is that the duration of the illusion exerts a substantial influence on the distance traversed by the phantom moving point, which is in alignment with the exploratory results reported in[50]. Moreover, the motion direction seems not to affect the perceived end-point, what would be in contradiction with that reported in[58], whose authors found a difference in distance perception related to the direction. On the other hand, the end-point was not only perceived out of the hand and inside the vibrotactile interface, but also beyond this device. Hence the out-of-the-object perception is present in a more significant way, since in this case the haptic interface is considerably longer than that used in[50].



(a)



(b)

Fig. 10. Reports of perceived end-point locations for **(a)** phantom motion and for **(b)** cutaneous rabbit illusions. In *y*-axis, the distance covered by the moving point with respect to the interface center. In *x*-axis, the illusion duration. The region *A*, from $0\ cm$ (interface center) to the dashed line at $3.5\ cm$ represents the grasping hand area (half of the distance between actuators). The region *B*, from the dashed line at $3.5\ cm$ to the dashed line at $18.32\ cm$ represents the area out of the hand but still inside the interface. The region *C* above the dashed line at $18.32\ cm$ represents the area out of the interface. Note: in this figure, the haptic interface is shown from a top view and 90° counterclockwise turned to fit it with the plot. $\otimes$ symbol is used to represent actuators.

Duration (s)	0.25	0.5	1	1.5	2	2.5	3
z-value	1.892	0.56	0.542	1.248	1.568	-0.828	0
Signed ranks	142	120	119.5	126	147	59	97
p-value	0.059	0.575	0.588	0.212	0.117	0.407	0.035
Corr. *p*-value	0.351	1.222	1.151	0.8488	0.584	1.222	0.247
$h\ (\alpha = 0.05)$	0	0	0	0	0	0	0

Table 6. Results of Wilcoxon Signed Rank tests for comparing the median perceived end-point of phantom motion by direction for each duration, and the corrected *p*-values calculated using the Bonferroni-Holm method.

Duration (s)	0.5	1	1.5	2	2.5	3
0.25	$3.16 \cdot 10^{-6}$	$1.11 \cdot 10^{-6}$	$1.11 \cdot 10^{-6}$	$8.09 \cdot 10^{-7}$	$8.96 \cdot 10^{-7}$	$9.19 \cdot 10^{-7}$
0.5		$3.63 \cdot 10^{-6}$	$1.54 \cdot 10^{-6}$	$1.54 \cdot 10^{-6}$	$1.26 \cdot 10^{-6}$	$1.01 \cdot 10^{-6}$
1			0.003	$3.16 \cdot 10^{-4}$	$2.79 \cdot 10^{-5}$	$3.59 \cdot 10^{-6}$
1.5				0.01	$8.95 \cdot 10^{-4}$	$1.77 \cdot 10^{-4}$
2					0.046	0.003
2.5						0.046

Table 7. Corrected *p*-values from pairwise comparison between perceived end-point of phantom motion by duration, using the Wilcoxon Signed-Rank test and the Bonferroni-Holm correction method.

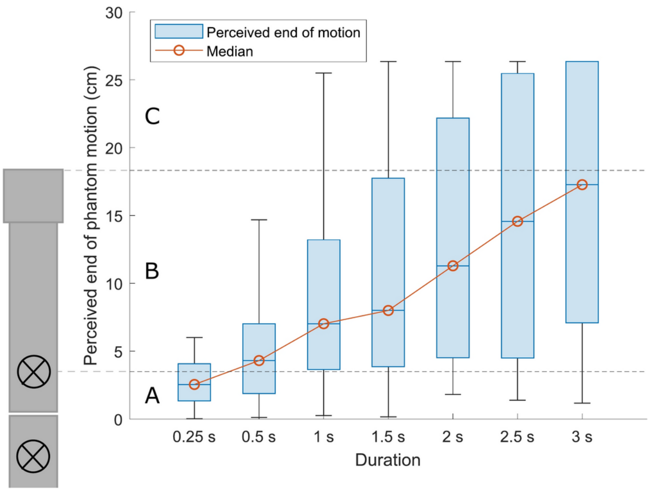


Fig. 11. Reports of perceived end-point of PM by duration. Note: in this figure, the haptic interface is shown from a top view and 90° counterclockwise turned to fit it with the plot. ⊗ symbol is used to represent actuators.

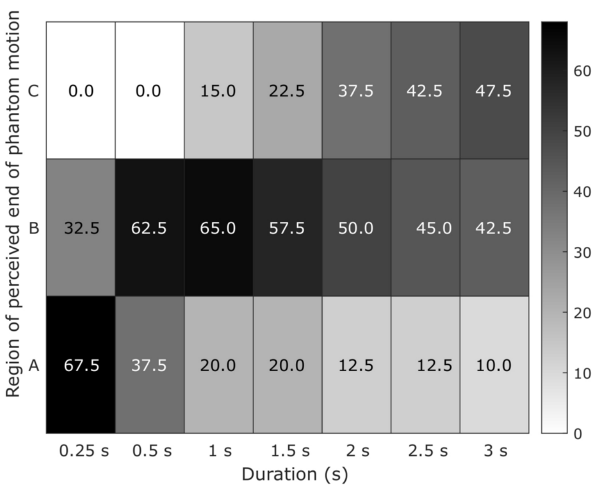


Fig. 12. Heat map of proportion of reports of perceived end of phantom motion in percentage (%) by region. Region *A* refers to the hand, region *B* corresponds to out of the hand in the interface, and region *C* to out of the interface.

For the longest duration tested (3 *s*), 90% of the end-points were sensed out of the hand, either inside or out of the haptic interface (regions *B* and *C*, respectively). Note that half of the 3 *s* stimuli were reported out-of-the-object (see Fig. 12, region *C*). For shorter durations, 0.25 *s* and 0.5 *s*, all of the reports laid either in the hand or in the interface (regions *A* and *B*, respectively). Most of them inside the hand in the first case and most inside the

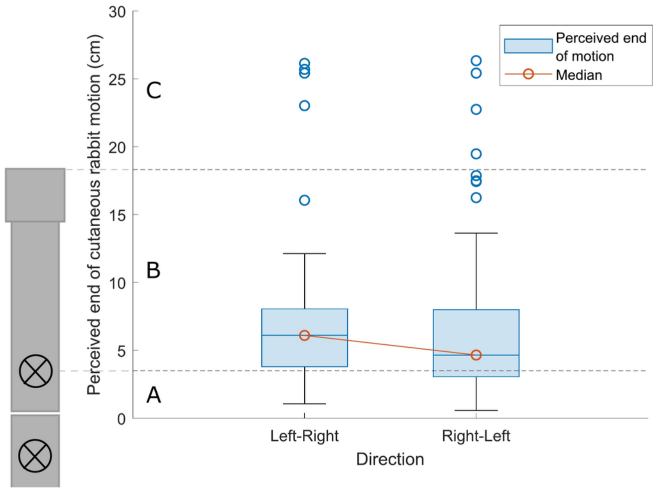


Fig. 13. Reports of perceived end of cutaneous rabbit motion by direction. Note: in this figure, the haptic interface is shown from a top view and 90° counterclockwise turned to fit it with the plot. ⊗ symbol is used to represent actuators.

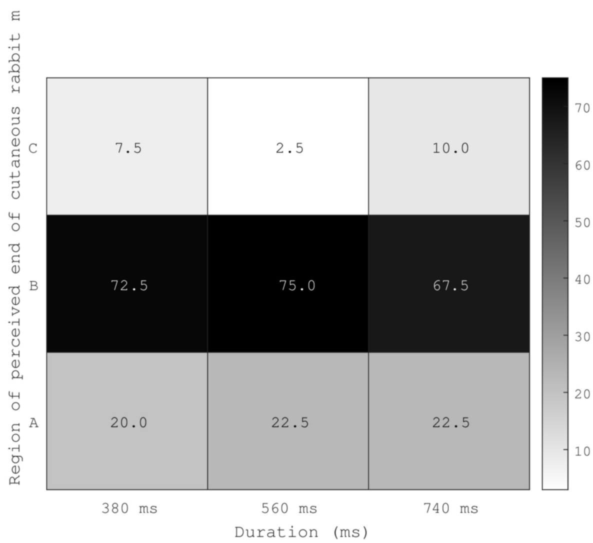


Fig. 14. Heat map of proportion of reports of perceived end-point of CR motion in percentage (%) by region. Region *A* corresponds to the hand, region *B* refers to out of the hand but still inside the interface, and region *C* to out of the interface.

haptic device in the second. For durations equal and longer than 0.5 *s* most of the reports (at least 62.5 %) laid out of the hand (regions *B* and *C*). Although the effect seems to be robust, it is to be noted that the dispersion of reports is not negligible and increases with the illusion duration. Even in the case of a 3 *s* PM, there is a 10% of end-points perceived in the inter-actuator area. It reflects the fact that a few number of participants told to sense the point always inside the hand but moving with different velocities. Consequently, in these instances, the illusion duration exerted a stronger influence on the velocity of movement compared to the covered distance.

In the case of cutaneous rabbit, no relationship was found between the duration of the illusion and the perceived end-point. Moreover, the motion direction appeared to influence the distance. This time, the finding is in line with the results in[58], maybe due to the fact that the illusory motion its authors elicited was closer to CR than to PM. According to our results, when CR was presented from left to right the end-point was perceived further than when presented from right to left. However, the level of significance of this difference was low so the effect should be prudently considered. When looking at Fig. 14, one can observe that the end-point location is consistent across the three regions, no matter the illusion duration. Most of the reports were out the hand but inside the object.

Experiment 2: visuo-haptic stimulation

The results of Experiment 2 are shown and discussed below.

Experiment 2: results
Data from Experiment 2 were first pre-processed in the same way as with Experiment 1. It showed that data from both visuo-haptic PM and CR are not normally distributed. Therefore non-parametric statistical methods were used.

<u>Coherence between haptic and visual stimuli</u> Reports of perceived level of coherence between vibrotactile and visual stimuli for PM and CR are plotted in Fig. 15a,b, respectively.

For the case of PM, Friedman test for repeated measures showed statistically significant differences between the median perceived levels of coherence and location/direction of the moving visual points, with $\chi^2 = 17.73,\ p = 0.003$. However, there was only a slight agreement between participants about these differences, with a Kendall coefficient of $W = 0.056$, so the significance of the differences found are of low relevance. Figure 16a illustrates the results. Overall, the median perceived LoC between the vibrotactile and the visual stimuli in visuo-haptic PM ranges from 4 (*Very similar*) to 5 (*Identical*). Furthermore, Friedman test for repeated measures was used to compare the median perceived levels of coherence according to the duration of PM. No statistically significant differences were found, with $\chi^2 = 2.41,\ p = 0.3$.

Regarding CR, Friedman test for repeated measures was again used to compare the median perceived levels of coherence according to the location/direction of visual stimuli. Significant differences were found, with $\chi^2 = 11.35,\ p = 0.023$. However, there is only a slight agreement between participant reports, with a Kendall coefficient $W = 0.045$, that is to say, the significance of the differences found is of low relevance. Figure 16b shows the results.

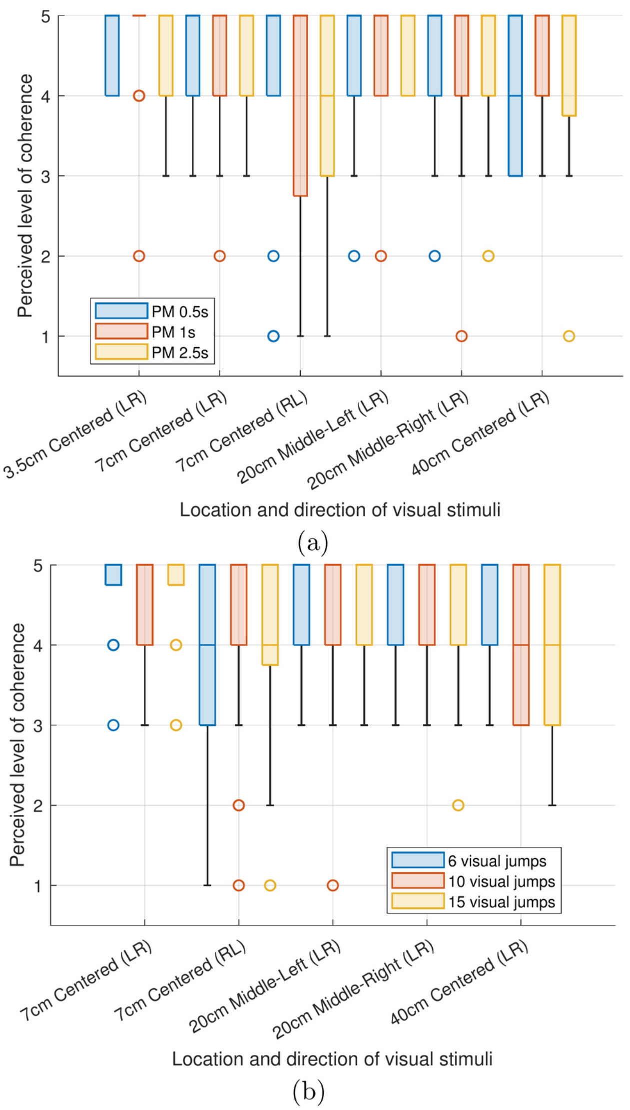


Fig. 15. Reports of perceived level of coherence between vibrotactile and visual stimuli for **(a)** visuo-haptic PM and **(b)** visuo-haptic CR. Remember that numbers in *y*-axis have the following meaning: *Completely different* (1), *Different* (2), *Similar* (3), *Very similar* (4) and *Identical* (5).

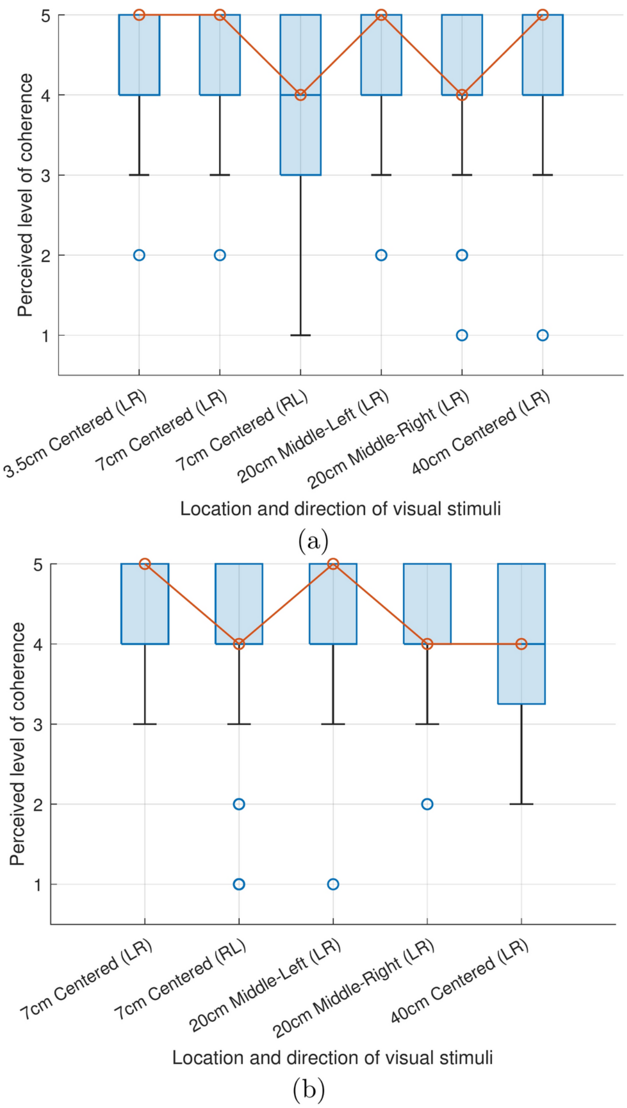


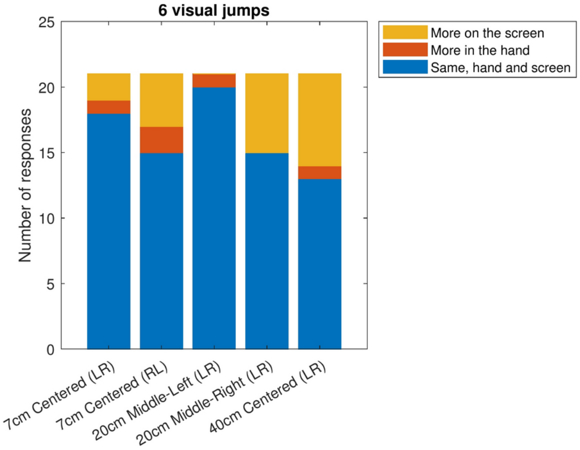
Fig. 16. Reports of perceived level of coherence by location and direction of visual stimuli for **(a)** visuo-haptic PM and **(b)** visuo-haptic CR. Note that numbers in *y*-axis mean: *Completely different* (1), *Different* (2), *Similar* (3), *Very similar* (4) and *Identical* (5).

In general, the median perceived LoC between the haptic cutaneous rabbit and the visual jumping cues goes from 4 (*Very similar*) to 5 (*Identical*). Finally, the median reported levels of coherence of CR by number of visual jumps were compared using a Friedman test for repeated measures. No significant effect of the number of visual jumps on the perceived level of coherence was found, with $\chi^2 = 0.57,\ p = 0.754$.

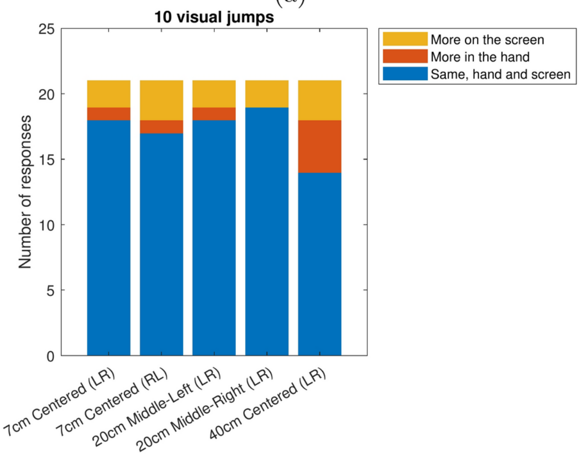
Perceived number of jumps and location of visuo-haptic cutaneous rabbit Regarding the number of jumps perceived with cutaneous rabbit, Fig. 17 shows the responses of the participants to whether they felt the same number of jumps in both modalities, more vibrotactile jumps or more visual jumps. The results indicate that, for all cases (6, 10, and 15 visual jumps), most of the participants reported perceiving the same amount of jumps in both haptic and visual modalities. Finally, according to the results in Fig. 18, most of the participants perceived that the location and direction of the CR illusion matched the visual motion of the jumping dot on the screen, for the three numbers of visual jumps.

Experiment 2: discussion
The second experiment provided insight into the impact of visual stimulation on the perception of phantom motion and cutaneous rabbit tactile illusions.

PM-related session Regarding the PM-related session, participants experienced simultaneously delivered pairs of stimuli: a visual moving dot and a PM tactile illusion. The PM illusions were 3 with different durations ($0.5\ s$, $1\ s$, and $2.5\ s$) and fixed direction (left-to-right). The visual stimuli included both directions (left-to-right and



(a)



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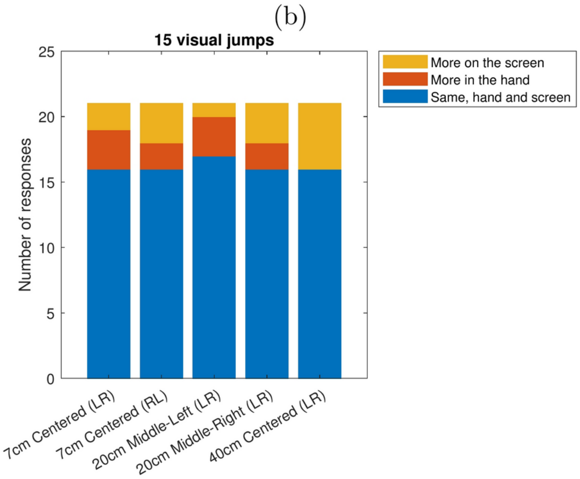

(c)

Fig. 17. Reports of perceived of number of visual points and vibrotactile points of cutaneous rabbit for **(a)** 6 visual points, **(b)** 10 visual points, and **(c)** 15 visual points.

right-to-left) and covered 4 distances (3.5, 7, 20, and 40 cm) across the three regions defined in the screen (*Middle-left*, *Centered*, and *Middle-right*).

For most of the combinations the level of coherence between the visual moving dot and the phantom motion is from 4 (*Very similar*) to 5 (*Identical*). These results suggest that participants perceived a similar or nearly identical motion perception in both modalities. Although the LoC is near the maximum (4–5), one may expect it to be higher for the case of the visuo-haptic stimuli inside the *congruent* group (see section "inlinkExperiment 2: visuo-haptic stimulationse4.2.2"), since both modalities were totally coherent. However, results of Fig. 15a

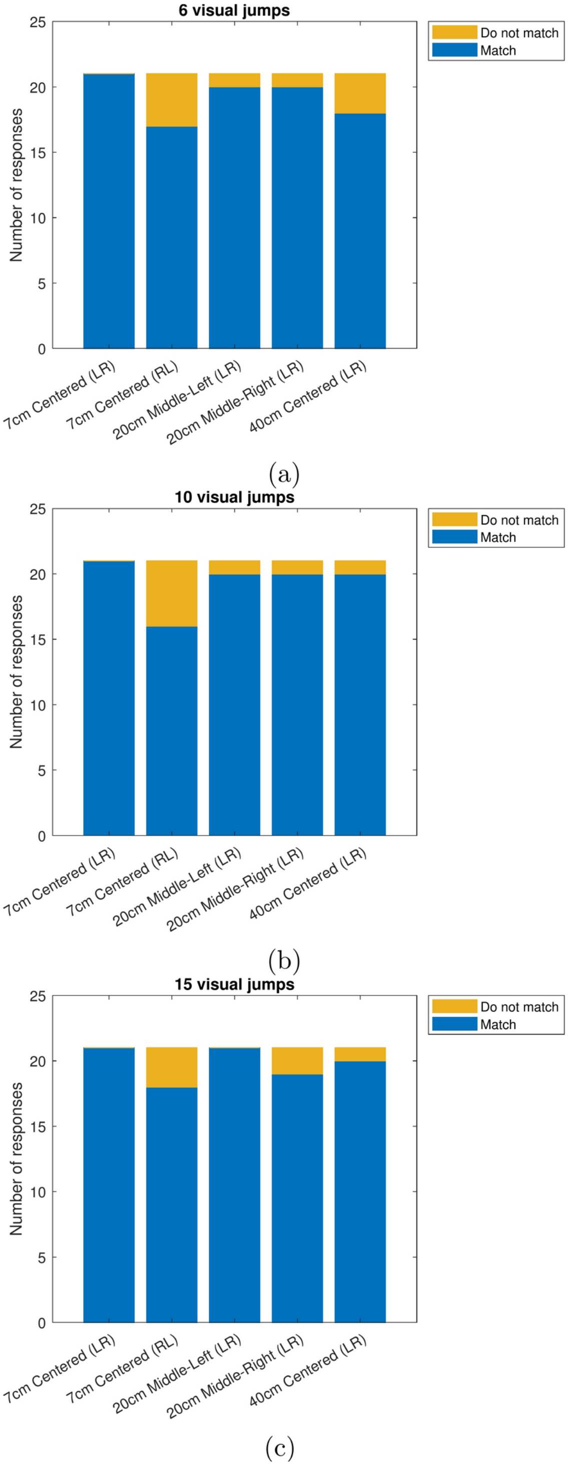

Fig. 18. Reports of perceived matching between the location and direction of visual points and vibrotactile points of cutaneous rabbit for **(a)** 6 visual points, **(b)** 10 visual points, and **(c)** 15 visual points.

appear to refute this hypothesis; LoCs reported for the case of *non-congruent* stimuli are comparable to those obtained for the *congruent* ones. The former group included:

- Visual stimuli located at the *Middle-left* and *Middle-right* screen areas, and thus out of the actuator inter-stimulus region.
- Visual dots covering distances different from the inter-actuator spacing (7 *cm*), with special attention to that moving 40 *cm*. In this case, some LoCs decrease to 3 (*Similar*) when pairing the stimulus with a PM of 0.5 *s* duration, maybe because it implies the visual dot traveling the longest distance in the shortest time.

- Haptic and visual stimuli moving in opposite directions. This could be the most striking result since, even if the LoC is slightly lower than for the other pairs of stimuli, it still ranges from 3 (*Similar*) to 5 (*Identical*) (see "7cm Centered (RL)" in Fig. 15a). Nevertheless, it should be noted that some participants perceived the mismatch, some of them reporting it to the experimenter, corresponding to the LoCs of 1 (*Completely different* stimuli) in the figure.

When comparing with Experiment 1, authors initially wondered if the visual mode would improve out-of-the-hand/out-of-the-object haptic perceptions, maybe reducing the dispersion of the distances reported as duration increased (see Fig. 11). However, the findings suggest that the distance covered by the tactile illusory point is exclusively modulated by the visual moving dot. Indeed, no significant differences appeared for the three durations involved (listed in Table 3) regarding the reported LoC of the visuo-haptic stimuli. It may indicate that a single fixed PM illusion is enough to elicit clear haptic motions with different end-points and in different areas of the screen if presented with the proper visual cue.

In the case of PM tactile illusions, results show that visual modality seems to override haptic inputs, and any inconsistency during the sensory integration is resolved in favour of the visual cues. Furthermore, this phenomenon appears to be robust.

CR-related session As mentioned above, the CR haptic stimulation involved only one tactile illusion with a point going from left to right in 10 jumps as described in[44]. The visual stimuli included left-to-right and right-to-left directions, covering several distances (7, 20, and 40 cm) in the available screen areas.

According to Fig. 15b, results are similar to those of the PM-related session. For most of the combinations, the level of coherence between the visual jumping dot and the CR perceived through the hand is from 4 (*Very similar*) to 5 (*Identical*), with almost no differences between the *congruent* and *non-congruent* group. Slightly lower LoC levels were again reported when motions in both modalities followed trajectories in opposite directions (see "7cm Centered (RL)" in Fig. 15b). Still, many volunteers sensed a high similarity between the stimuli despite this fact. It is worth noting that pairs involving the 10-jump visual stimuli did not reach higher LoCs than those using 6 and 15 visual jumps, although the number of jumps in both modes was the same only in the first case. Furthermore, no differences appeared when comparing reported LoCs for the three screen areas within the visual group of stimuli. Regarding the covered distance, some LoCs decrease again to 3 (*Similar*) for 40 *cm*, what suggests that shorter distances performs better in the visuo-haptic integration.

Figure 17 shows a comparison between the number of jumps perceived through each modality. It was perceived as the same for a majority of participants, regardless if this number actually matched in the visual and haptic stimuli as Fig. 15b already pointed. The lowest results in this aspect were obtained for the case of a centered motion of 40 cm, what is in line with above. On the other hand, most of the volunteers considered that the haptic and visual motions matched, regarding their location and direction (see Fig. 18). In the three cases, the larger number of "*Do not match*" responses are obtained for "7cm Centered (RL)" probably due to the opposite motion directions.

Although the results of Experiment 2 for CR are aligned with those of PM, both illusions should not be directly compared. PM and CR are robust tactile illusions but, unlike PM, CR is also quite rigid. It means that it breaks apart and stops being perceived easily if the conditions needed to make it appear change mildly[55,59]. This way, modifying its perceptual features becomes a challenge. Note that, for example, the traveled distance is not affected by the illusion duration, as Experiment 1 showed. The fact that adding a visual counterpart allows an eventual haptic designer to control the number of jumps, the covered distance and even the motion location, opens a new range a possibilities for its inclusion in A/VR experiences.

General discussion Predominance of vision over other sensory modalities have been reported in several studies when performing certain tasks. Hecht and Reiner explored its influence in speeded discrimination activities guided by visuo-haptic and visuo-auditory stimuli[60]. In both cases, vision dominated the sensory integration. As found in[61], visual information affects haptic exploratory tasks even when it is previously provided. Kassuba et al. studied this predominance using neuroimaging techniques in object recognition tasks[62]. Multisensory integration in visuo-haptic regions were found when haptic targets were preceded by visual cues. This directional asymmetry in crossmodal matching of visual and haptic object features suggests a functional primacy of vision in visuo-haptic object recognition. These works, together with those aforementioned such as[33], are aligned with the findings of the current investigation, in which vision practically overrides haptic inputs. Nevertheless, it should be noted that there are also authors whose findings point in the opposite course. Bresciani et al. studied the integration of visual and tactile events[63]. Volunteers were presented with sequences of visual flashes and taps simultaneously. They were instructed to count either the flashes or the taps. Results showed that touch had a stronger influence in vision than vision on touch, and touch was proved more reliable when modalities were presented alone. Other works such as[31,32], discussed in section "Introduction", or[64] also found a prevalence of the haptic mode in visuo-haptic integration.

In view of the above, sensory dominance seems to be somehow task-dependent, what makes it difficult to foresee. The modality appropriateness hypothesis, introduced by Welch and Warren[65], suggests that the mode with the greatest precision for an specific task will dominate perception. More elaborated approaches, like that described in the Introduction, based modality dominance on Bayesian statistic principles. They assume that each sensory input provides the CNS with noisy and variable information. Bayesian inference implies that an imperfect estimate from one sensory modality improves when taking into account the probabilities of other sensory signals. This way, the brain achieves an optimal estimate minimizing uncertainty and noise by combining probabilities of several sensory inputs[21]. Besides, optimal estimate also considers prior experiences when assigning more weight to the less variable modality[66–68], that will be eventually that dominating the integration.

Accordingly, a series of reasons could explain the visual dominance observed in this experiment. First, the tactile illusions of motion involved in this work are inherently noisy and demand a minimum of concentration. Phantom motion is generated using vibrotactile actuators, being the dynamic difference between the intensity of the vibrating signals that elicits the moving point. The underlying vibrating carrier signal contributes mainly to noise, and it is only its envelope that provides motion information (see Fig. 1). Furthermore, both PM and CR illusions are usually unknown and hardly present in day-to-day life, what makes prior experience with them unlikely or negligible. On the other hand, the experimental tests incorporated spatial tasks (an object moving following a trajectory in certain space), that are commonly dominated by vision due to its greater spatial acuity[41,69]. When looking at the visual stimulation, the presented cues were clear, and a vast prior experience of the volunteers with similar stimuli might be expected (e.g., in daily activities such as watching television or playing video games). All of this may justify the visual dominance, considering the previously described integration models.

Limitations of the study The main limitation of this experiment lies in use of the level of coherence to assess the visuo-haptic integration. This approach enables participants to evaluate visuo-haptic perception in an instinctive and holistic manner. This metric of general coherence is a valuable asset for designers of A/VR experiences, as it offers a straightforward method of identifying which visuo-haptic stimuli are well perceived and which are perceived with ambiguity. However, this parameter does not facilitate analysis of the specific nature of discrepancies when the level of coherence is low, e.g. whether the deviation is in the visual or haptic perception, and in what direction. New parameters should be used to explore and elucidate the source of the reported sensed incongruities.

Conclusions

This manuscript presents two experiments involving two tactile illusions of motion, namely, phantom motion and cutaneous rabbit. Using a haptic interface grasped with one hand, the first experiment investigated how the illusion duration affects the distance traveled by the illusory points. For phantom motion, a strong positive correlation was observed between the distance traveled and the duration of the illusion. Moreover, out-of-the-hand and out-of-the-object end-point perceptions were easily achieved by extending the duration. However, as the latter increased, the variability in individual reports also increased, indicating that the phenomenon was not uniformly perceived by all participants. In contrast, no significant influence of the duration was observed regarding CR. The end-point location remained consistent across all reports, no matter the illusion time. Cutaneous rabbit boundaries are predominantly perceived within the hand or just beyond it, in the interface.

The second experiment sought to ascertain the extent to which the visual modality affects the perception of tactile illusions. To this end, visuo-haptic stimuli were delivered to the volunteers. They consisted in a pair formed by a visual and a haptic stimulus with the same duration, presented at the same time. Visuo-haptic cues were divided into two categories, *congruent* and *non-congruent*. In the former, the visual and the haptic stimuli were coherent whereas in the latter both stimuli were contradictory (they differed in trajectory length, location or direction). Participants perceived a high level of coherence between the visual and the haptic modes in most of the visuo-haptic stimuli, no matter if they belonged to the *congruent* or *non-congruent* group. These results indicate that visual stimuli exert a substantial influence on the perception of the haptic illusions, determining aspects such as location, direction, traveled distance, and specific characteristics like the number of jumps in cutaneous rabbit. Participants sensed the same kind of motion through the visual and haptic sensory modes, even if the perception characteristics were those of the visual stimulus. Moreover, even if the visual cues almost overrided those haptic, volunteers reported a clear perception of the haptic motion.

These findings provide valuable information for the efficient and effective implementation of tactile illusions in virtual and augmented reality environments, and other multi-modal applications in the context of human-computer interaction. A simple haptic device equipped with two actuators is sufficient to elicit a clear and varied range of haptic motion experiences, provided that it is presented with the appropriate visual stimulus.

Data Availability

The data generated and analyzed during the current study are available in GitHub repository, https://github.com/PaulRemache/visuohaptic.

Received: 14 October 2024; Accepted: 21 March 2025
Published online: 31 March 2025

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Acknowledgements

A. Trujillo-León would like to thank W. Bachta and A. Bellicha for their valuable contribution in[50], publication that gave rise to the starting point of this paper.

This work was supported by the spanish Ministerio de Ciencia, Innovacion y Universidades and by the European ERDF program funds under contract PID2021-125091OB-I00.

Author contributions

I.G-M. implemented the experimental setup, conducted the experiments and performed a preliminary data analysis. B.R-V. carried out the data analysis. B.R-V. and A.T-L. designed the experiments, supervised the work and wrote the manuscript. A.T-L. proposed the experimental goals and the experimental setup concept. All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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