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# Phantom sensation: Threshold and quality indicators of a tactile illusion of motion[☆], [☆☆]

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## ABSTRACT

Utilizing a randomized, blind, controlled experiment, and the ascending method of limits, we determined the minimum amplitude of motion at which individuals perceive a tactile illusion called moving phantom sensation, the perceived level of clarity and continuity of motion. Implementing tactile illusions in virtual/augmented reality, sensory substitution systems, and other human–computer interaction technologies results in interfaces with improved resolution, using two vibrating actuators only. The actuators are attached to the skin in different locations to render a moving phantom sensation. The intensity of vibrations increases in one actuator while decreases in the other according to the envelope of the voltage supply signals. This intensity variation creates the illusion of a vibrating point moving between the actuators. We gradually increased the amplitude of motion until the participant reported perceiving the illusion, for eight values of duration of the stimulus from 0.1 to 6.0 s. Participants perceived the illusion at a minimum amplitude of motion of 20%; being 100% the motion from one actuator to the other. The median level of clarity of the perceived illusion at the minimum amplitude of motion was 2 (not so clear). Finally, we found a positive correlation between duration and continuity of motion.

## 1. Introduction

Interaction between human beings and computer based technologies have evolved and become multi-modal. Accordingly, new tools and methods to communicate information through the sense of touch have emerged in a well established research field known as haptics [1]. Haptic communication is enabled by somatosensory receptors embedded in the human body. Kinesthetic information is sensed via proprioceptors in bones, muscles, and ligaments, whereas tactile information is sensed through mechanoreceptors in the skin [2]. Understanding the information flow through the sense of touch has allowed researchers to develop technologies to aid people with disabilities, such as sensory substitution systems to convey information to visually-impaired people [3]. Haptic feedback also plays an important role in gaming. For example, the DualSense™ controller for PlayStation 5 [4] is a commercial device that incorporates vibrotactile stimulation to make video games more immersive.

Furthermore, the sensed tactile information does not always agree with the perceptual response. In other words, there may be differences between the physical stimulus and what is perceived by our nervous system. This discrepancy is known as tactile illusion, which is analogous to visual and auditory illusions [5]. Tactile illusions communicate substantial information with a reduced number of actuators, thus allowing to optimize the size of tactile interfaces [6]. Indeed, the spatiotemporal information that tactile illusions may convey makes them suitable for implementation in several human–computer interaction (HCI) technologies. For instance, the investigators in [7] implemented tactile illusions to enable multi-modal communication between a mobile phone and the user. Tactile illusions can be implemented in virtual

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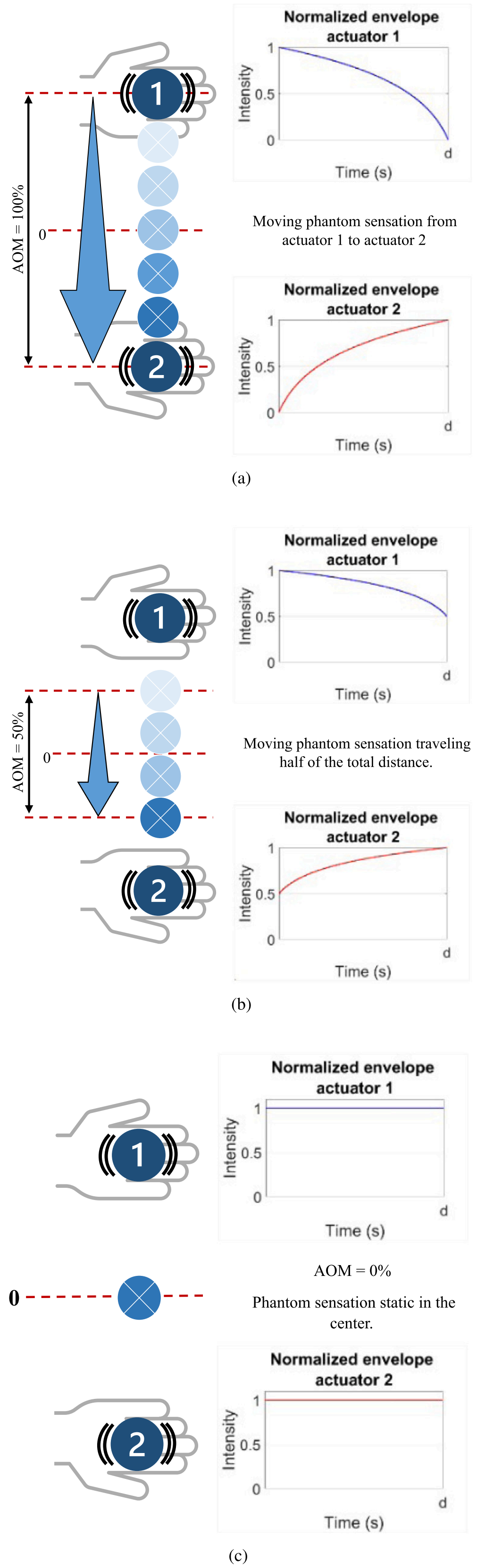
and augmented reality to create more immersive environments. The authors in [8] published a survey where tactile illusions are implemented in the context of multi-modal displays for virtual reality. Researchers also implement tactile illusions in sensory substitution systems to, for instance, guide blind walkers [9] or to transmit music to the hearing impaired [10]. In rehabilitation, tactile illusions enrich the embodiment of prosthetic limb users [11]. Nevertheless, tactile illusions arise just under certain conditions, hence comprehension of the technical and psychophysical implications is an indispensable first step for successful implementation.

### 1.1. Related work

The opportunities to implement tactile illusions in HCI technologies keep expanding thanks to continuous investigation on haptics [12,13]. In this novel but growing field of research, a widely studied and implemented spatiotemporal tactile illusion is the apparent motion, an illusory point moving between two real stimuli. The study of tactile illusions of motion began about a century ago [14]. One of the first investigations on apparent tactile motion presenting time-delayed vibrotactile stimuli on the skin was published in 1966 by the researchers Carl E. Sherrick and R. Rogers [15]. However, D. Alles in 1970 [16] would suggest that there is a difference between the spatiotemporal tactile illusion obtained with synchronous and asynchronous stimuli. According to Alles, the perception of a tactile illusion of motion evoked by presenting two asynchronous vibrotactile stimuli in different locations on the skin, such as in the work of Sherrick and Rogers, depends on two fundamental variables: duration of the stimuli and the inter-stimulus onset interval (ISOI).

On the other hand, Alles referred to the spatiotemporal tactile illusion obtained with synchronous stimuli as phantom sensation, a denomination already introduced by Von G. Bekesy in 1967 in his work *Sensory Inhibition* [17]. With this approach it is possible to generate static or dynamic phantom sensations. The former is perceived as an illusory/virtual actuator vibrating between the real actuators and is also known as funneling effect [18]. The difference in intensity of vibrations between the actuators determines the location of the phantom sensation, which depends on the shape of a specific envelope. To generate a moving phantom sensation the vibration intensity of each actuator varies in time according to the envelope shape. The illusory motion is commonly rendered with 100% amplitude of motion (AOM); meaning the motion from one actuator to the other, as shown in Fig. 1a. Fig. 1b and c show different envelope configurations to render a moving phantom sensation with 50% of AOM and a static phantom sensation with 0% AOM, respectively. According to Alles, a logarithmic envelope, shown in Fig. 1a and b creates a moving phantom sensation with constant vibrotactile loudness.

Researchers may use these illusions to build large vibrotactile displays with improved resolution thanks to the sort of virtual actuators created between the real ones by the illusions. For instance, in [19] the authors designed an algorithm and a vibrotactile display with 12 actuators to render moving phantom sensations with different directions and lengths, combining synchronous and asynchronous stimulation. In this case, virtual actuators are created by static phantom sensation while moving virtual actuators are created by changing the ISOI between the excitation signals of the static, real, or virtual, actuators. However, the determination of the ISOI to generate the tactile illusion of motion is not direct and depends on other variables such as stimuli duration [20] or the number of actuators [21]. In this context, and considering a broad range of possible applications, it is easier to generate and sustain the moving illusion with synchronous stimuli varying the intensity of the actuators' excitation signals. According to Alles, this method evokes a more robust moving phantom sensation than the one with asynchronous stimuli. Our contribution focuses on this approach.



Moving phantom sensation from actuator 1 to actuator 2

(a)

Moving phantom sensation traveling half of the total distance.

(b)

AOM = 0%

Phantom sensation static in the center.

(c)

**Fig. 1.** Examples of moving phantom sensations with duration equals to *d* for (a) 100% amplitude of motion (AOM), (b) 50% AOM, and (c) 0% AOM. The traveled distance is measured symmetrically from the center between the actuators to the sides.

### 1.2. Research questions

An open question remains related to the limits of the created illusion. Specifically, what is the minimum distance the virtual moving actuator can travel while still being perceived by the user? Moreover, we can wonder about the quality of this perception. In [16] the researcher recommends rendering moving phantom sensations with durations no shorter than 0.25 s to keep accuracy in the perception of apparent motion in prosthetic limb applications. Moreover, the researchers in [22] evaluated the quality of a moving phantom sensation using continuity of motion (COM) and consistency indicators. They evaluated the apparent motion with 3 stimuli durations: 0.75, 1.5, and 2.0 s. The results show that the COM and consistency of the perceived moving phantom sensation enhances as the duration increases. The authors in [23] found that the subjective quality of a penetrating moving phantom sensation from the palm to the back of the hand improves as the duration increases; for stimuli durations of 0.5 and 1.0 s. However, these results are in contrast with what was reported in [24], where the authors found a statistically significant decay on the perceived COM as duration of stimuli increases for values from 0.11 to 1.0 s. In addition, in [25] the authors tested moving phantom sensations with two stimuli durations: 4.0 and 8.0 s, and found that a longer duration is perceived to travel a longer distance.

On the other hand, the researchers in [26] tested the ability of individuals to determine the location of starting/ending point of a moving phantom sensation. The authors used 4 actuators arranged along the forearm from the elbow (actuator 1) to the wrist (actuator 4) to render 13 sequential static phantom sensations with 0.2 s of duration each, that create the illusion of motion. The researchers asked the participants to report the location of starting/ending point of the apparent motion. The results show better performance (around 75% accuracy) when the starting/ending point is in actuators 1 or 4. The performance for locations in-between these two actuators, including actuators 2 and 3, and virtual locations, does not reach 50%. The authors attribute these differences in accuracy to the location of actuators 1 and 4 near to the joints, were proprioceptors may aid the perception of the illusion. This results are aligned with reported acuity to detect the location of discrete vibrotactile stimuli [27]. In average the performance of individuals to locate the starting/ending point of the moving phantom sensation was 32.69% but is lower for virtual locations 25.13%, where the lower AOM tested between 2 actuators was 25%.

The knowledge of both aspects, the amplitude of motion and the quality of the moving phantom sensation, could allow building displays with increasing resolution, in the sense that the moving virtual actuators could not necessarily complete a displacement from one real actuator to the next, but could perform more complex motions in the 'space' between both real actuators. If this motion could be controlled effectively according to the user's perception, such as audio sources can in the auditory domain (*e.g.* stereo audio design for headphones [28]), it might signify new opportunities for efficient and cost-effective implementations in HCI. The specific goals of this work that intend to contribute to filling this gap are the following:

1. To determine the threshold of the shortest displacement of a moving phantom sensation between a pair of actuators that an individual can perceive. We define this threshold as the minimum amplitude of motion (AOM).
2. To report a qualitative measure of the perceived moving phantom sensation. We will identify suitable indicators to quantify the changes in the quality of a perceived moving phantom sensation.

## 2. Tools and methods

### 2.1. Apparatus

We developed an application in Matlab to synthesize and reproduce all the moving phantom sensations in waveform audio files format (WAV). The digital signal was converted to analog using a National Instruments data acquisition board (DAQ) model USB6002. A Fosi Audio stereo amplifier model TDA7498E was used to amplify the analog signals to finally reach a pair of voice coil actuators built by the authors according to [29] (See Fig. 3a). The architecture of the interface is shown in Fig. 2.

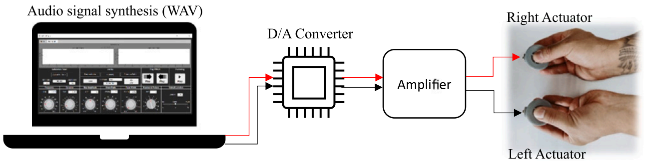


**Fig. 2.** This figure shows the architecture of the vibrotactile interface used in the practice session and main experiment.

In addition, audio files exported from Matlab were arranged and reproduced in Audacity to test the frequency response of the actuators. We used the volume sliders of a monophonic channel in Audacity to control the amplitude of the excitation signals. The amplitude for both actuators was +23 dB above the perception threshold. This amplitude was required to obtain confident lectures from the vibrometer for frequencies ranging from 180 Hz to 300 Hz. The temperature of the actuators was measured during the characterization experiment, averaging 21 °C. The actuators were set up in a flat surface of a plywood table of 1.0 inch thickness and metallic structure to measure the frequency response, as shown in Fig. 3b. The acceleration of the vibration of the actuators at 250 Hz differed in 0.7 g. This small mismatch does not affect the perception of the moving phantom sensation [30]. Moreover, the illusion can be elicited even with different actuators in different devices such as a tablet and a watch [31]. Furthermore, we guaranteed the perception of vibrations from both actuators according to the participant's feedback.

The carrier signal for every trial was a sine wave with a constant frequency of 250 Hz; meaning the frequency at which the actuators vibrate. This frequency corresponds not only to the peak frequency response of the actuators but it is also in the range of frequencies for lower perception thresholds to perceive the "vibration" sensation by means of the Pacinian channel [32]. The envelope selected was logarithmic to ensure the perception of constant vibrotactile loudness [16].

### 2.2. Qualitative evaluation of the moving phantom sensation

According to the authors in [15], a well-generated moving phantom sensation can be described as "*the longest uninterrupted feeling of movement between the first stimulus site and the second*". Various researchers have investigated the quality of a moving phantom sensation using different indicators to create an apparent motion aligned with this description. As explained in Section 1.2, in [22] the researchers evaluated the quality of a moving phantom sensation using COM and consistency indicators. Whereas the experimenters in [23] evaluated the quality of the moving phantom sensation with a level of clarity (LOC) indicator for the perceived direction of motion. However, we did not find a unified method. Based on this background we decided to evaluate the quality of the moving phantom sensation with two indicators: COM and LOC.

We will consider that a moving phantom sensation can be perceived as either continuous or discrete, regardless of the quality of the perceived sensation. Thus, the COM indicator will be a dichotomous variable. On the other hand, the LOC will be measured in a Likert scale to quantify the clarity of the perceived illusion. It means that the LOC does not directly depend on the COM. For instance, a participant can perceive either a continuous or discrete moving phantom sensation with different LOCs.

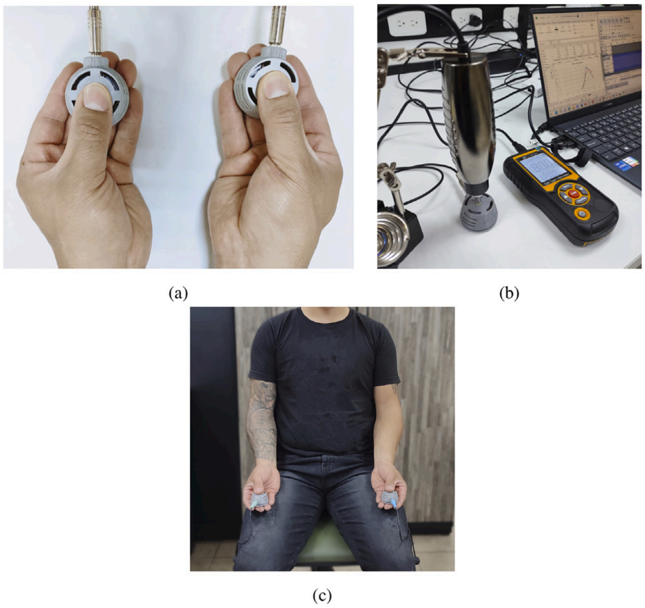


**Fig. 3.** This figure shows (a) the voice coil actuators and the way they were held with the hands during experimentation, (b) the set up for frequency response measurements, and (c) a participant sitting in a chair wearing earmuffs, closing the eyes, and holding the actuators ready for experimentation.

### 2.3. *Participants*

Participants were recruited from two universities, 18 from the University of Oslo and 29 from the University of Málaga. All participants voluntarily agreed to be part of the experiment, signed a consent form, and filled in general information in a questionnaire. From the sample, 68% (32) were male and 32% (15) were female. The participants were between 18 and 58 years old ($M = 29, SD = 11.05$).

### 2.4. *Procedure*

We investigated the moving phantom sensation employing randomized, blind, controlled experiments. The perception of tactile illusions requires the participants are focused on the task, so the duration of the experiment must be limited. Therefore, the ascending method of limits was used to keep the duration around 45 min, including a practice session. The analysis is then performed on a quite large set of responses from the 47 participants.

Each experimental design was approved by the Comité Ético de Experimentación of the Universidad de Málaga with register number CEUMA 58-2022-H, on July 12, 2022. The technical staff of the Centre for Interdisciplinary Studies Rhythm, Time, and Motion (RITMO) of the University of Oslo also validated the experimental design.

#### 2.4.1. *Location of the actuators*

The sensitivity of the skin to vibrations depends on the density of mechanoreceptors. Since the fingertips have a high concentration of mechanoreceptors and various current devices for gaming and virtual/augmented reality are designed to be held with the hands [4,33], we performed a pilot study asking some volunteers to sit in a chair, lay their hands over the legs closely aligned with the shoulders, and hold the actuators with the fingertips in a natural and relaxed way to keep an approximately constant holding force and separation between the actuators, as shown in Fig. 3a and c. Results of the pilot study showed a robust elicitation of moving phantom sensations. Therefore, we replicated this set up in the practice session and in the main experiment.

#### 2.4.2. *Duration of stimuli*

Duration of stimuli can affect the perception of a moving phantom sensation as follows:

- The longer the duration, the longer the perceived traveled distance, and vice versa [25].
- When the duration of stimulation is different for each actuator the perceived direction of motion can be biased [34].
- Duration of stimulation can affect the quality of the perceived moving phantom sensation [22,23].

Therefore, selecting the appropriate range of durations is critical for experimentation. We used the pilot study described in Section 2.4.1 to narrow our investigation towards an effective range of durations. We designed moving phantom sensations with durations no shorter than 0.1 s to avoid discrete stimuli sensations (*i.e.,* pulses) instead of vibrations to be aligned with the recommendations given in [16]. The volunteers reported a change in the sensation of COM and LOC according to the duration of stimuli. When the duration was short, from about 0.1 to 0.4 s, most participants reported discrete moving phantom sensations. When the duration of the moving phantom sensation was longer than 0.4 s most participants reported continuous motion. From about 1.0 s of duration and above some participants also reported sensations that were not in accordance with the definition of a moving phantom sensation. Reports included the perception of *"a curved moving phantom sensation"*, *"a moving phantom sensation that travels in circles around one hand or the other"*, and *"a moving phantom sensation that loops traveling from one actuator to the other"* when it was not looping.

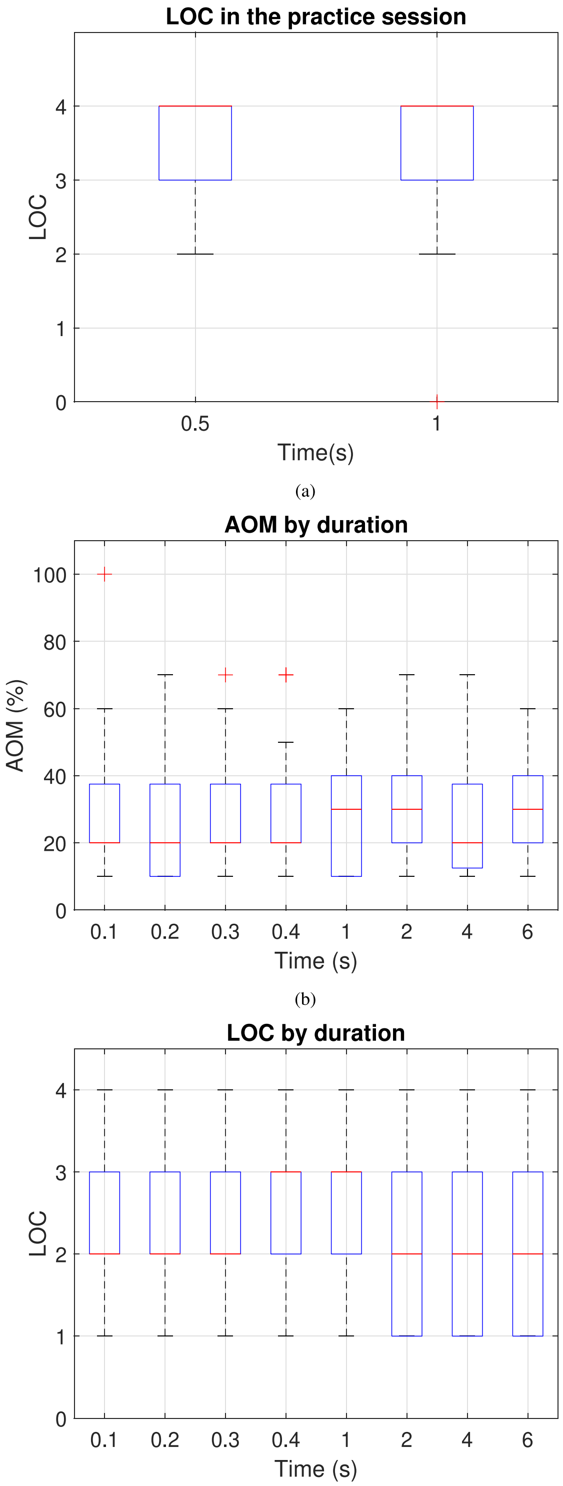
According to these results we selected the following durations for the main experiment: 0.1, 0.2, 0.3, 0.4, 1.0, 2.0, 4.0, and 6.0 s.

#### 2.4.3. *Control of the AOM*

The algorithm we used to change the AOM is based on the model proposed in [25]. We implemented the algorithm in Matlab so that the AOM can be modified while keeping the logarithmic shape of the envelope. The AOM corresponds to the relative distance traveled by the moving phantom sensation, measured symmetrically from the center between the actuators to the sides, as shown in Fig. 1. Half of the total AOM is from the center to the left and the other half is from the center to the right. Fig. 1a shows how the relative intensity of vibrations changes according to the shape of the envelope for an AOM of 100%. At time 0 actuator 1, held with the left hand, is activated at the maximum relative intensity and then decreases. Whereas actuator 2, held with the right hand, begins vibrating with the lowest intensity and increases according to the same but mirrored envelope. The AOM of 0% corresponds to no motion and may be perceived as a virtual actuator vibrating in the center (*i.e.*, a static phantom sensation or funneling effect [18]). The funneling illusion occurs since the vibrations intensity of both actuators is at a constant value during the whole duration of the phantom sensation, such as illustrated in Fig. 1c. The intermediate case of 50% AOM is shown in Fig. 1b. To avoid an extended experiment duration, for each stimulus duration defined in Section 2.4.2, the AOM changed in discrete steps of 10% from 0% up to 100%, as follows: 0%, 10%, 20%, 30%. 40%, 50%, 60%, 70%, 80%, 90%, and 100%.

#### 2.4.4. *Practice session*

We designed a practice session to familiarize the participants with the moving phantom sensation. The stimuli of the practice session established a reference of "robust moving phantom sensation" to later evaluate the quality of the stimuli in the main experiment. The participants were seated in a chair holding the actuators in a natural and relaxed way with their hands, laid over the legs and aligned with the shoulders (*i.e.,* following the instructions stated in the pilot study; check Section 2.4.1), wearing earmuffs, and closing their eyes to avoid cross-modal interference and favor concentration (See Fig. 3a and c). We rendered 2 moving phantom sensations with 0.5 and 1.0 s of duration,



(a)

(b)

(c)

**Fig. 4.** The box plots show (a) results of reported LOC in the practice session for both 0.5 and 1.0 s duration, (b) the recorded minimum AOM when a moving phantom sensation was perceived for each duration, and (c) the LOC of the perceived moving phantom sensation for each duration. In all graphs the boxes contain 50% of the responses, the error bars represent minimum and maximum values, the red line corresponds to the median, and the red crosses are atypical data.

respectively. The moving phantom sensations looped from one actuator to the other (*i.e.,* from left to right and vice versa), with 1.0 s rests between direction changes, and 100% AOM. These two values of duration produced the best moving phantom sensations in the pilot study: very clear and continuous. The participants had to report their perception of the illusion answering the following one-option forced-choice question: do you perceive motion between the actuators? If the participant answered *yes* then the experimenter evaluated the LOC of the perceived moving phantom sensation by asking the following one-option forced choice question: how clear was the motion that you perceived? the options being on a scale from 1 to 4, with 1 *almost imperceptible*, 2 *not so clear*, 3 *clear*, and 4 *very clear*. If the participant failed to perceive the moving phantom sensation a value of 0 *imperceptible* was recorded. Only one participant reported not perceiving the illusion with a duration of 1.0 s but perceived it with 0.5 s duration with level 2 of clarity (not so clear). Results of the LOC for the practice session are in Fig. 4a. These suggest that all the participants perceived and recognized the moving phantom sensation for at least one duration (*i.e.,* they got familiar with the illusion and with a reference of "robust moving phantom sensation") with a median LOC of 4 (very clear). Once the practice session ended up the participant continued with the main experiment.

### 2.4.5. *Main experiment*

To avoid order effects we divided the participants into two groups according to the order of presentation of stimuli. In group 1 the stimuli started from long (6.0 s) to short (0.1 s). In group 2 the stimuli started from short (0.1 s) to long (6.0 s). The participants were assigned randomly to a group. In either case, and taking as a reference the ascending psychophysical method of limits, the first stimulus was the one with 0% AOM then was increased in steps of 10% as explained in Section 2.4.3 until the participant reported the perception of a moving phantom sensation. The moving phantom sensation kept looping from one actuator to the other with a pause of 1.0 s between direction changes, such as in the practice session. In every step the investigator asked the following two-options forced-choice question: do you perceive motion between the actuators? if the answer was *yes* we recorded the current AOM. If the answer was *not* the AOM was increased to the next value. We anticipated that the LOC of the perceived moving phantom sensation with the minimum AOM may decrease compared to that of the practice session, where the AOM was 100%. However, due to the illusory nature of the moving phantom sensation, which means complex neurological processes associated, the responses of the participants may unexpectedly change, probably because of a more robust or weaker elicitation or even a sudden disappearance of the illusion due to a lack of concentration. Therefore we decided to keep the same scale of LOC in case a participant fails to perceive the illusion, in case the illusion suddenly breaks apart, or, on the other hand, appears very clearly even with the minimum AOM. Thus, after recording the AOM the experimenter recorded the perceived LOC asking the following one-option forced-choice question: How clear was the motion that you perceived? the options being: 1 *almost imperceptible*, 2 *not so clear*, 3 *clear*, and 4 *very clear*. If the participant did not report the perception of the illusion with any AOM the LOC was 0 *imperceptible*. The participant then indicated the perceived COM, answering the following two-options forced-choice question: was the motion that you perceived continuous or discrete? Fig. 5 shows a flowchart of the main experimental procedure.

## 3. Results

Before presenting the results we tested the data to identify if the distribution was normal. We combined two strategies: visual and mathematical. We visualized the data distribution by performing a q–q test for every condition. All the plots showed a non-normal distribution of data. We confirmed these results by using Shapiro–Wilk tests. All the results rejected the null hypothesis that the data comes from a normal distribution. Therefore, we decided to use non-parametric statistical techniques.

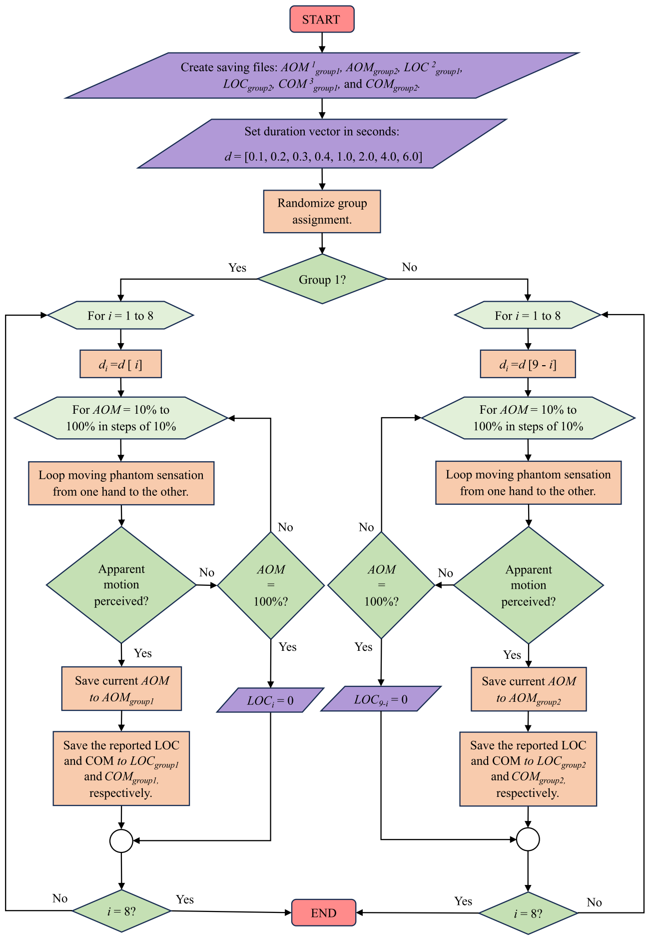


**Fig. 5.** This figure shows a flowchart of the main experiment. [1]AOM is the amplitude of motion, [2]LOC is the level of clarity of the perceived illusion, and [3]COM is the perceived continuity of motion.

### 3.1. Minimum AOM

We used a non-parametric Friedman test for correlated samples to compare the medians of AOM for the different durations. Differences across all durations were not statistically significant for AOM, with $\chi^2 = 7.9$, $p > 0.05$. Box plots of the minimum AOM at which the participants perceived a moving phantom sensation are in Fig. 4b.

### 3.2. Perceived LOC

We used a non-parametric Friedman test for correlated samples to compare the medians of LOC for the different durations. Differences across all durations were statistically significant, with $\chi^2 = 20.26$, $p < 0.05$. Box plots of the LOC reported by participants when perceived a moving phantom sensation are in Fig. 4c. For post hoc analysis we performed a multiple comparisons Dunn & Sidák's procedure. The results show that the only statistically significant difference is between the median LOC reported for 0.4 s of duration and the median LOC reported for 6.0 s of duration. No statistically significant differences were found between any of the other group combinations.

### 3.3. Order and the perceived LOC

We used a non-parametric Kruskal Wallis test for independent groups to verify the absence of an order effect. Indeed, differences across conditions were not statistically significant, with $\chi^2 = 0.07$, $p > 0.05$.

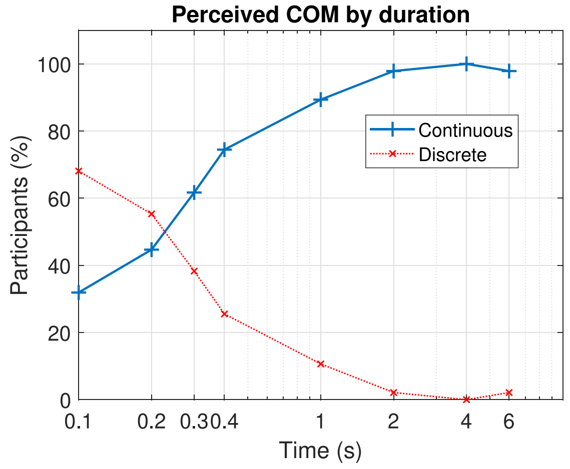


**Fig. 6.** This graph shows the amount of participants in % that reported COM, continuous in blue and discrete in red, by duration of stimuli.

### 3.4. Perceived COM

According to the goals of our investigation we now look for the transition from perceived discrete moving phantom sensation to continuous. Fig. 6 plots the percentage of participants that reported continuous moving phantom sensation in blue or a discrete moving phantom sensation in red. The results show that for durations between 0.1 and 0.2 s more than 50% of the participants (68% and 55% respectively) perceive the moving phantom sensation as discrete. On the other hand, for values of duration between 0.3 and 0.4 s more than 50% of the participants perceive a continuous moving phantom sensation (62% and 74% respectively); for values equal or greater than 1.0 s at least 90% of participants perceived a continuous moving phantom sensation. Using a Binomial parametric test we compared the observed proportion of participants reporting continuous moving phantom sensations against the expected proportion of 50%. We found that for a duration of 0.4 s the proportion of participants reporting continuous motion (74%) was significantly greater than the chance level (50%), with $p < 0.05$ (two tailed). In addition, we used a non-parametric correlation Spearman's test to identify if there is a correlation between COM and duration. Results show a strong positive correlation between COM and duration, with $\rho = 0.96$, $p < 0.05$; the longer the duration, the greater the number of participants that perceive continuous moving phantom sensations.

## 4. Discussion

In this experiment we investigated the minimum AOM at which participants can perceive a moving phantom sensation and the perceived LOC and COM at that minimum value.

### 4.1. Minimum AOM and COM

Although some participants detected a moving phantom sensation with 10% AOM, on average, the median minimum AOM is about 20%. This minimum AOM is 5% lower than that tested in [26]. When the AOM reaches this minimum value individuals report the moving phantom sensation mostly as discrete for durations equal to or lower than 0.3 s. On the other hand, individuals reported the moving phantom sensation mostly as continuous for durations equal to or longer than 0.4 s. These results are aligned with what was reported in [22], where the authors found that a sensation of continuous apparent motion increases as duration increases. For vibrotactile interface design purposes researchers may consider extended durations; 1.0 s or more, to guarantee at least 90% of effectiveness in evoking continuous moving phantom sensations with minimum AOM.

### 4.2. Perceived LOC

When participants perceived the moving phantom sensation with the minimum AOM, the average LOC remained constant at 2 (not so clear). In the main experiment we expected these lower LOCs than those recorded in the practice session since the moving phantom sensations evoked with the minimum AOM are barely appearing. The best moving phantom sensation is rendered hypothetically with an AOM of 100%. Therefore, increasing the AOM from the threshold should also increase the median LOC. For durations longer than 2.0 s participants reported sensations in discrepancy with the definition of a moving phantom sensation which may be interpreted as a decay on the quality of the tactile illusion. However, we only found a statistically significant decay on LOC between the median for 0.4 s of duration and 6.0 s of duration, which makes it difficult to elucidate any conclusion. Our results are in contrast with the reported in [23] where the researchers found that the quality of the perceived moving phantom sensation enhanced as the duration increased. In any case, investigators and practitioners need to consider that shorter traveled distances (*i.e.,* AOM lower than 100%) evoke moving phantom sensations with lower LOCs than those moving from one actuator to the other (*i.e.,* AOM of 100%).

Stimulation for a long time affects perception and causes adaptation to the stimulus [35]. In our experiment the vibratory stimuli activate the Pacinian channel that rapidly adapts to the vibrations. We suggest that adaptation affects the perception of the changes in vibration intensity. Therefore, the tactile illusion may take other forms different from the reference moving phantom sensation, such as those described in Section 2.4.2.

These suggestions need to be confirmed by further research.

## 5. Conclusion

In this investigation we designed a randomized, blind, controlled experiment to identify the minimum value of amplitude of motion (AOM) at which individuals perceive a moving phantom sensation between a pair of vibrating actuators. We also assessed the quality of the perceived moving phantom sensation with two indicators: level of clarity (LOC) and continuity of motion (COM). The experimental design included a practice session where all the participants got familiar with a moving phantom sensation that was a reference for the main experiment. The participants perceived the moving phantom sensations of the practice session with an average LOC of 4 (very clear). In the main experiment, the moving phantom sensation was perceived at a median minimum AOM of 20%, where 100% represented the maximum AOM from one actuator to the other. An AOM of 0% represented no motion but a static phantom sensation in the center. The minimum AOM remained constant for every duration from 0.1 to 6.0 s. The LOC was measured on a subjective scale from 0 (imperceptible) to 4 (very clear). This qualitative indicator referred to recognizing a linearly moving phantom sensation between the actuators, like the reference moving phantom sensation perceived in the practice session, and not just the perception of the vibrations or any other tactile effect. For the minimum AOM the LOC remained at a median value of 2 (not so clear), a low value that was expected because the AOM was just in the limit; barely appearing, and would be expected to increase as the AOM increases. The COM was a dichotomous variable representing the continuity of the moving phantom sensation, with the values “discrete” for interrupted motion and “continuous” for uninterrupted motion. Although for a duration of 0.4 s a significant proportion (74% against the 50% chance) of the participants reported perceiving a continuous moving phantom sensation, a duration of at least 1.0 s was necessary to elicit a continuous moving phantom sensation in about 90% of participants, which may be required if implemented in vibrotactile interfaces. Finally, the correlation between COM and duration was strongly positive. This investigation contributes to establishing a methodology to evaluate the perception of moving phantom sensations. The results reported in this manuscript may represent a first step to developing a consistent method to control the traveling distance and location of a moving phantom sensation between a pair of actuators. Finding out if individuals can recognize the relative location of a moving phantom sensation as the AOM changes would be relevant to the research community on haptics to develop more efficient vibrotactile interfaces, multi-modal displays, and other HCI technologies.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Byron Paul Remache Vinueza reports financial support was provided by Spain Ministry of Science and Innovation. Byron Paul Remache Vinueza reports financial support was provided by European Regional Development Fund. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The data has been shared in an external link that redirects the reviewer to a personal Github folder. The data can be used to contrast the results reported in the manuscript only.

Phantom Sensation (Original data) (Github)

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## Appendix A. Supplementary material

Find the data that supports this investigation in the following link: https://github.com/PaulRemache/phantomsensation

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