IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 10 May 2024, accepted 12 June 2024, date of publication 19 June 2024, date of current version 28 June 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3416741

RESEARCH ARTICLE

A Comparative Investigation of Cutaneous Rabbit and Funneling Tactile Illusions for Implementation in Vibrotactile Displays

BYRON REMACHE-VINUEZA[1,2], (Member, IEEE), ANDRÉS TRUJILLO-LEÓN[1,3], AND FERNANDO VIDAL-VERDÚ[1,3]

[1]Departamento de Electrónica, Universidad de Málaga, 29071 Málaga, Spain
[2]Facultad de Ingeniería, Industria y Producción, Universidad Indoamérica, Ambato 180103, Ecuador
[3]Instituto Universitario de Investigación en Ingeniería Mecatrónica y Sistemas Ciberfísicos (IMECH.UMA), 29590 Málaga, Spain

Corresponding author: Byron Remache-Vinueza (paulremache@uma.es)

This work was supported in part by Spanish Ministerio de Ciencia, Innovacion y Universidades; and in part by European Regional Development Fund (ERDF) under Contract PID2021-125091OB-I00.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Comité Ético de Experimentación of the Universidad de Málaga under Register No. CEUMA 58-2022-H in July 12, 2022.

ABSTRACT We designed two psychophysical experiments to compare the cutaneous rabbit tactile illusion with a cutaneous rabbit recreated using sequential funneling tactile illusions. These illusions were rendered between a pair of actuators held with the hands. A tactile illusion is a psychophysical phenomenon that arises when the real stimulus does not match the perceived sensation. Designers exploit tactile illusions to efficiently increase the resolution of vibrotactile displays for human-computer interaction applications. Initially, participants qualitatively compared both rendering methods. Subsequently, individuals reported the upper threshold of the Inter-Stimulus Onset Interval (ISOI) for the cutaneous rabbit and the Time Between Funneling (TBF) illusions of the recreated cutaneous rabbit using funneling, when the illusion broke apart. The primary differences reported between both methods for rendering the cutaneous rabbit illusion were related to the perceived amount of jumps and duration. Overall, funneling performed better at evoking the illusion of a hopping rabbit, while both methods effectively conveyed direction sensations. Finally, the upper ISOI threshold we found for the cutaneous rabbit was consistent with the value reported in the literature, approximately 190 milliseconds, and was surpassed by the TBF of the recreated cutaneous rabbit using funneling.

INDEX TERMS Cutaneous rabbit, funneling, haptic illusion, haptic interface, phantom sensation, tactile illusion, vibrotactile feedback, vibrotactile interface.

I. INTRODUCTION

Nowadays, Human-Computer Interaction (HCI) technologies incorporate vibrotactile feedback to enable multi-modal communication. By controlling the duration, frequency, intensity, or signal type of vibrations, users can differentiate between, for instance, incoming calls or notifications on a cellphone, skidding or crashing in a driving game, or smooth or wrinkled textures in virtual/augmented reality [1]. To enhance the resolution of a tactile display, increasing the number of actuators is common. This expansion is necessary for conveying additional information related to motion, direction or location. However, when the display resolution is limited to a pair of actuators, such as in the DualSense^{TM} game

The associate editor coordinating the review of this manuscript and approving it for publication was Lei Wei.

© 2024 The Authors. This work is licensed under a Creative Commons Attribution 4.0 License.
For more information, see https://creativecommons.org/licenses/by/4.0/

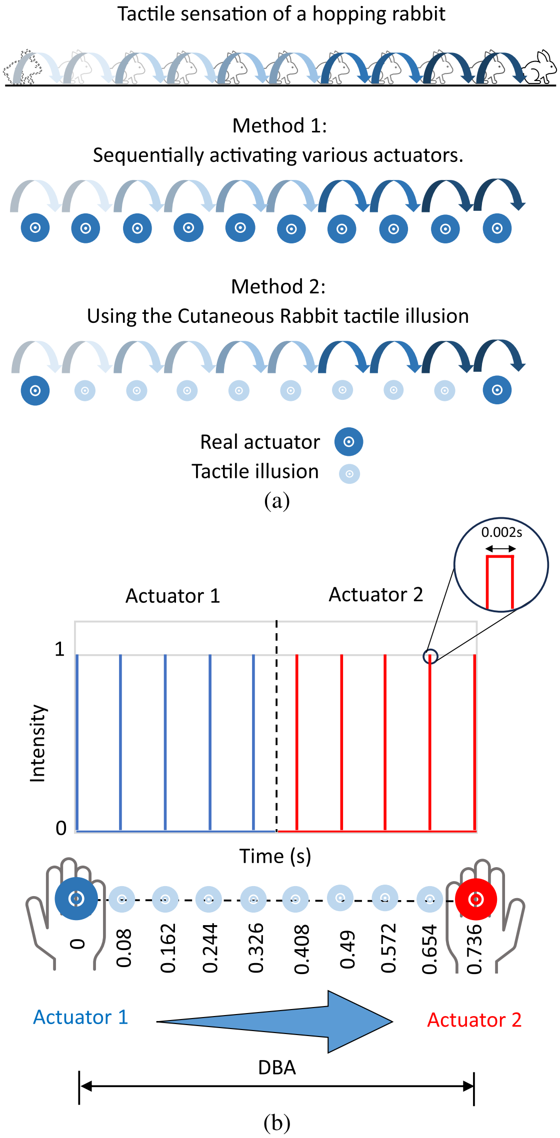


FIGURE 1. **This figure shows (a) an example of enhancing the resolution of a vibrotactile display by increasing the number of actuators (Method 1) and utilizing the Cutaneous Rabbit (CR) illusion (Method 2), and (b) a schematic representation of the rendering method to evoke the out-of-the-body CR illusion in midair between the hands. The Distance Between Actuators (DBA) remains fixed. The signals sent to actuators 1 and 2 are represented in blue and red, respectively.**

controller [2] for PlayStation 5, it becomes possible to create what are known as tactile illusions. A tactile illusion refers to the discrepancy between real stimulation and perceived sensations. Researchers have harnessed these illusions to develop applications for sensory substitution, such as assisting paraplegic patients to perceive their lower extremities within virtual environments [3], or conveying music through touch [4]. Since conveying this spatio-temporal information does not require additional visual or auditory stimuli, vision and audition can focus on other multi-modal activities, such as surgical procedures [5] or navigation [6].This paper focuses on the Cutaneous Rabbit (CR) [7] and the Funneling (FUN) [8] tactile illusions.

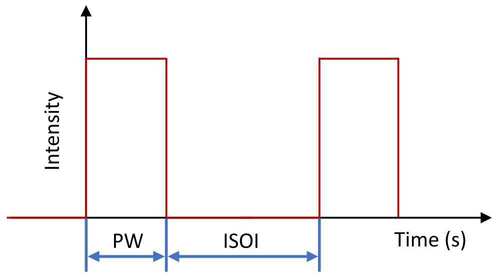


FIGURE 2. **This figure schematizes two pulses from a Cutaneous Rabbit (CR) signal with their temporal elements: Pulse Width (PW) and Inter-Stimulus Onset Interval (ISOI); not-to-scale.**

Regarding the Cutaneous Rabbit (CR) tactile illusion, Fig. 1a shows the recreation of a hopping rabbit using two methods. Method 1 employs ten actuators that activate sequentially to create the sensation of jumps. In contrast, Method 2 (depicted in the same figure) demonstrates how real actuators are replaced by the CR illusion. This substitution conveys a similar sensation while significantly reducing the required number of actuators to just two. Fig. 1b provides a schematic representation of the method used to evoke a ten-jump CR illusion out of the body in midair between the hands. The process involves presenting five short pulses with temporal regularity in actuator 1 (held with the left hand), followed by another five pulses with identical characteristics in actuator 2 (held with the right hand), with a certain Distance Between Actuators (DBA). The evoked sensation is a point progressively hopping from one real actuator to the other [7].

Two variables that determine important thresholds in CR are the number of pulses (i.e. the amount of hops) and the Inter-Stimulus Onset Interval (ISOI), which is the time between pulses. Fig. 2, which is not-to-scale, illustrates two pulses with their Pulse Width (PW) and the ISOI.

With respect to the Phantom Sensation or Funneling (FUN) illusion, Fig 3a shows how a real actuator, initially used to recreate the localized hit number two with Method 1, is replaced by this illusion in Method 2. Fig 3b shows a scheme for rendering the FUN illusion. In this method, a pair of actuators located in different areas of the skin vibrate synchronously, creating an illusory or virtual actuator positioned between the two real actuators. The location of these virtual actuators depends on the intensity of vibrations from each real actuator and varies according to a specific envelope. In a study by David Alles in 1970 [8], it was suggested that if the intensity of actuator vibrations changes according to a logarithmic envelope, the perceived vibrotactile loudness of FUN remains approximately constant regardless of the evoked location.

In theory, and in contrast to CR, FUN could be sequentially evoked at any location between the real actuators, as deduced from Fig. 3b. Consequently, an illusion similar to CR can be achieved using sequential arrangements of FUN or virtual actuators. If the duration of the virtual actuator rendered with FUN matches the duration of the pulses in CR, and the FUN illusions are presented with the same regularity and in the

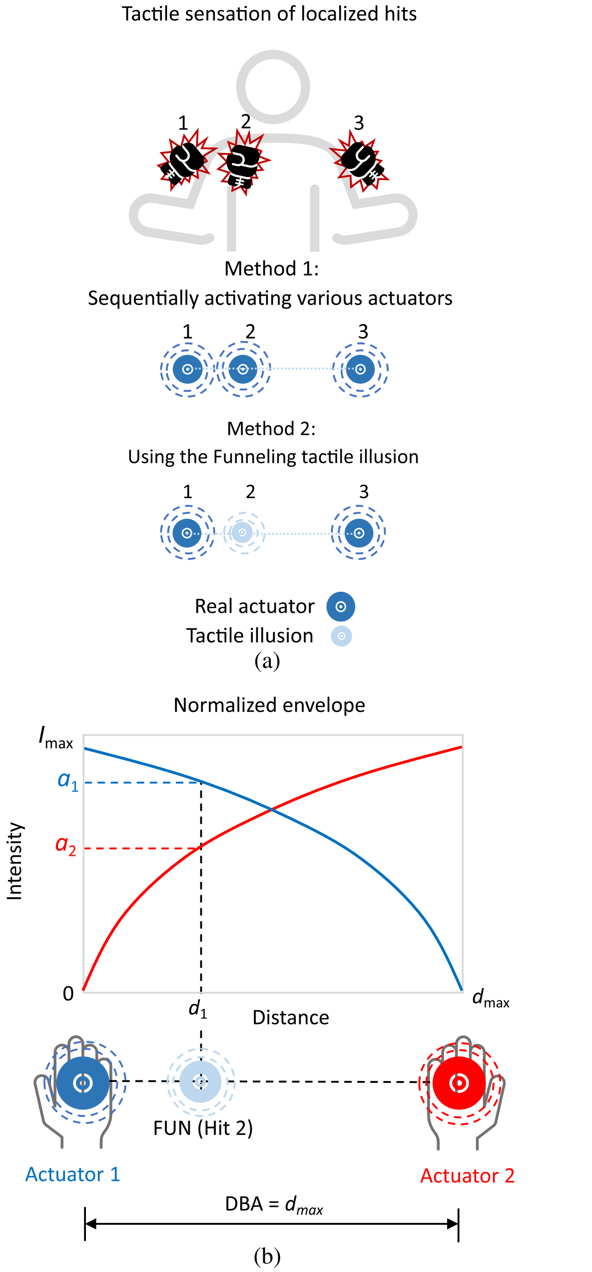


FIGURE 3. **This figure shows: (a) an example of 3 localized hits recreated with 3 real actuators in a vibrotactile display (Method 1) and using two real actuators for hits 1 and 3 and the Funneling (FUN) illusion for hit number 2 (Method 2), and (b) a schematic representation of the rendering method to evoke an out-of-the-body FUN in midair between the hands, to recreate hit number 2 with a fixed Distance Between Actuators (DBA), which corresponds to d_{max}. In blue and red are the logarithmic envelopes that determine the intensity of actuators 1 and 2, respectively.**

same quantity as the jumps in CR, this sequential change in the location of a virtual actuator may closely recreate the sensation evoked by the CR illusion. The resulting signals are contrasted in Figure 4, where CR generates a sensation of a point jumping ten times from actuator 1 to actuator 2, while FUN recreates a similar sensation with a virtual actuator sequentially changing location ten times from actuator 1 to actuator 2. We will refer to this combined illusion as the CR-FUN illusion. Notably, the Time Between Funneling

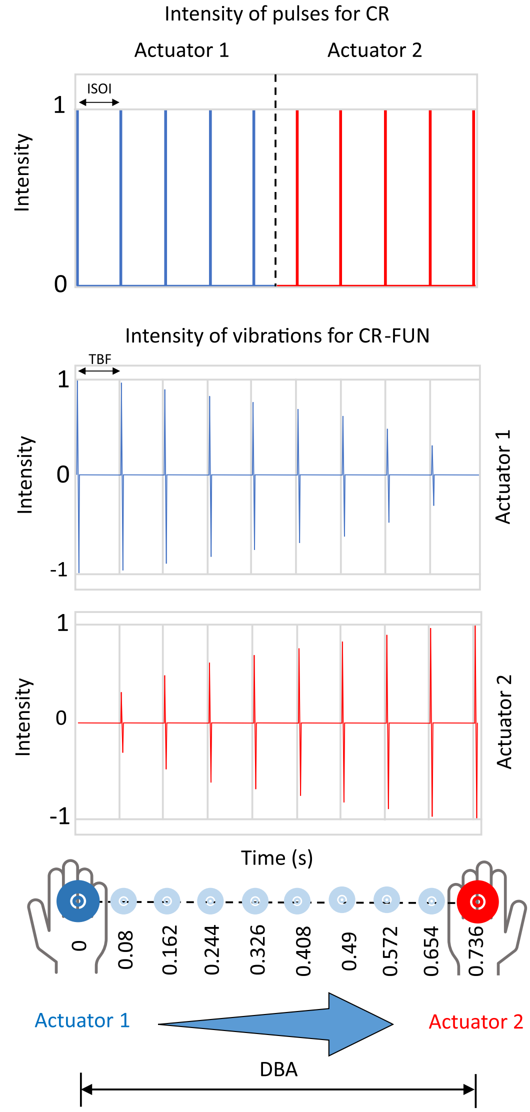


FIGURE 4. **This figure shows a schematic representation of a spatio-temporal tactile illusion perceived as ten jumps from actuator 1 to actuator 2. The illusion is rendered using the Cutaneous Rabbit (CR) illusion (in the upper section of the figure) and the recreated CR using Funneling illusions (CR-FUN) (bellow the CR illusion), with the recommendations extracted from [7]. The Inter-Stimulus Onset Interval (ISOI) of CR could be interpreted as the Time Between Funneling (TBF) illusions of CR-FUN.**

illusions (TBF) in the CR-FUN signals could be interpreted as the ISOI observed in the CR signals.

For this CR-FUN illusion we address the following research questions:

- We are uncertain whether individuals can distinguish between CR or CR-FUN illusions. Additionally, we do not know if one performs better than the other. In experiment 1, a systematic experimental procedure was designed to qualitatively compare CR with CR-FUN.
- As the ISOI of CR increases, there is a possibility that the CR illusion may break apart. In experiment 2, we investigated the maximum ISOI and compared it with the results reported by Geldard and Sherrick [7]. Furthermore, we determined the maximum

TBF threshold of CR-FUN and contrasted it with the maximum ISOI threshold of CR.

Moreover, while some researchers have successfully evoked the FUN illusion in midair between two fingers [9], we did not find any reports of CR being perceived out of the body in midair. This information could be valuable if the goal is to implement CR or FUN in vibrotactile interfaces for virtual/augmented reality such as the Meta Quest Touch Pro controllers [10], which users hold with their hands.

These contributions may signify opportunities for a more efficient implementation of CR and FUN in multi-modal displays. In Section II we briefly review some related work. In Section III we describe the experimental design. In Section IV we present the results of our investigation and discuss about the results obtained. Finally, in Section V we summarize the main findings of our research.

II. RELATED WORK

FUN and CR may evoke similar spatio-temporal sensations, such as motion, direction, and location. For instance, Sungjae Hwang and Jung-hee Ryu [11] compared the perception of direction information between CR and FUN. The results showed better performance of CR for direction recognition and also yielded faster responses in a steering wheel turning task. However, the CR and FUN illusions did not have the same spatio-temporal characteristics. In contrast, Topon Visarrea et al. [12] designed a low-cost vibrotactile interface and compared its performance in conveying direction using three tactile illusions: CR, FUN, and phantom motion (a continuous moving phantom sensation). The results showed better overall performance of sequential FUN illusions. According to the authors, the perception of direction was similar for all the tactile illusions. Unfortunately, detailed methods and statistical information were not provided to support this conclusion. In this investigation the spatio-temporal characteristics of FUN and CR were also different.

Furthermore, it is critical to consider the operating limits when deciding whether to use FUN, CR, or both. Evaluating the advantages and limitations of various tactile illusions to enhance the resolution of a vibrotactile interface is a common practice [13], [14], [15]. Geldard and Sherick studied the CR variables and reported some thresholds in [7]. For instance, they found that the maximum number of pulses to render a CR illusion is eighteen pulses by actuator; beyond this value, the illusion may break apart. The minimum number of pulses is three, known as reduced CR [16]. In this case, the first pulse (reference) and the third pulse (attractor) are felt in actuator 1 and actuator 2, respectively, while the second pulse (attractee) may be perceived as a single point between the two real actuators; a single pulse alone would not generate the tactile illusion. Additionally, the speed of the moving points in the CR illusion is limited by the ISOI thresholds. Geldard and Sherrick suggested that, for a fixed number of five pulses per actuator, the ISOI threshold at which the CR illusion breaks apart is approximately 200 milliseconds. Moreover, Gi-Hun Yang et al. successfully conveyed direction information using a variable ISOI with CR [13]: 24 milliseconds between the pulses presented in each actuator and 30 milliseconds between the last pulse of actuator 1 and the first pulse of actuator 2. These direction changes allowed the researchers to create different moving patterns that were easily recognized by the participants (achieving 92% performance).

In previous works, CR has been compared with sequential arrangements of FUN, or virtual actuators, but under different temporal and spatial conditions. In this work, we suggest matching the spatio-temporal conditions of both tactile illusions and compare the CR illusion with the CR-FUN illusion resulting from this alignment.

III. TOOLS AND METHODS

We designed two randomized, blind, controlled experiments based on methods extracted from relevant literature (see Sections III-F3 and III-G1). These experiments were conducted under the legislation recommended by the Comité Ético de Experimentación of the Universidad de Málaga for *Experimentation Projects with Humans and its Tissues*, available at https://www.uma.es/ceuma/info/123048/proyecto-de-experimentacion-con-humanos-y-sus-tejidos-legislacion/. All procedures were approved by the Comité Ético de Experimentación of the Universidad de Málaga, with register number CEUMA 58-2022-H in July 12, 2022. The Ethics Committee of the Universidad Indoamérica validated our experimental design based on the approval given by the Universidad de Málaga. We adjusted the intensity of FUN vibrations or CR pulses until we achieved a clear and comfortable perception of the stimuli based on participant feedback. Importantly, tactile stimulation did not reach or exceed the pain threshold in any case.

A. MODEL TO RENDER THE CUTANEOUS RABBIT ILLUSION

The stimuli to render the CR illusions were designed according to the recommendations of Geldard and Sherrick [7]. Figure 1b shows a schematic representation of the rendered CR tactile illusion, along with the signals sent to the actuators. These signals generate a CR illusion from actuator 1 to actuator 2, or from the left hand to the right hand (LR). Specifically, five pulses are first presented in actuator 1 with an ISOI of 0.078 seconds, a PW of 0.002 seconds, and maximum relative intensity (see also Fig. 2). Subsequently, the other five pulses with the same characteristics are presented in actuator 2. Note that in Fig. 1b, the ISOI between the last pulse of actuator 1 and the first pulse of actuator 2 remains the same.

B. MODEL TO RENDER THE FUNNELING ILLUSION

The model to create the FUN illusion was obtained from that proposed by Lee et al. [9]. In their work, the relative intensity of the vibrations for actuators 1 and 2 is calculated according to equations 1 and 2.

$$a_1(d) = I_{max}(\frac{log(d+1)}{log(d_{max}+1)})^r. \quad (1)$$

$$a_2(d) = I_{max}(\frac{log((d_{max}-d)+1)}{log(d_{max}+1)})^r. \quad (2)$$

where:

- a_1, a_2: are the intensity of vibrations of actuators 1 and 2, respectively, to generate FUN at the relative distance d.
- I_{max}: is the maximum intensity of vibrations.
- d: is the relative distance at which the FUN is located from actuator 1.
- d_{max}: is the relative distance from actuator 1 to actuator 2.
- r: is a constant value.

Fig. 3b illustrates the output of equations 1 and 2. In the example of the figure, we show the relative location of a rendered FUN at a distance d_1 from actuator 1, while a participant holds the actuators with their hands.

In the model, we set I_{max} to 1. Additionally, we set r to 1 to generate a smooth logarithmic envelope, following the suggestion by Alles [8]. The maximum distance d_{max} was set to 10. This allowed us to control relative variations of d rather than actual distances, as proposed by Lee et al. [9]. For example, if the DBA is 5cm, it corresponds to $d_{max} = 10$ in the model. In this case, choosing a value of $d = 5$ represents 50% of d_{max} or 2.5cm. Consecuently, this configuration generates a FUN illusion at the relative location 5 (i.e. at the center) or at 2.5cm from actuator 1. With these considerations, the model used in our experiments is described by equations 3 and 4.

$$a_1(d) = (\frac{log(d+1)}{log(11)}). \quad (3)$$

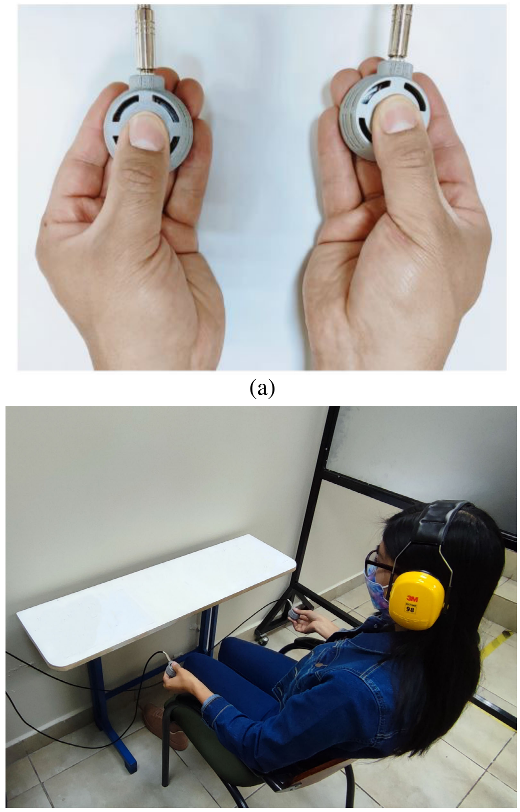
$$a_2(d) = (\frac{log(11-d)}{log(11)}). \quad (4)$$

Using this model, we can generate as many sequential FUN illusions as required, with any duration, and at any location between the real actuators.

C. APPARATUS

The signals to render CR and FUN illusions were exported as waveform audio files (WAV) using the models implemented in Matlab (See Sections III-A and III-B). We used the open digital audio workstation (DAW) Audacity to arrange the WAV files exported from Matlab according to the corresponding experimental procedure requirements (see Sections III-F3 and III-G1). Subsequently, the stereo signal from Audacity was sent to an audio amplifier using the compuiter's audio output. The intensity of the vibrations was controlled using the volume knob available on the amplifier. Finally, the stereo output of the amplifier was routed to a pair of voice coil actuators. Figure 5a shows the actuators built by the authors, following the design proposed by Yao and Hayward [17].

We measured the frequency response of the actuators using a vibrometer. The difference between the acceleration of actuators 1 and 2 was approximately 0.7g at the peak frequency of 250Hz.



(a)

(b)

FIGURE 5. This figure shows (a) the actuators built by the authors held, by a participant, (b) the way participants were required to hold the actuators in both experiments.

D. PILOT STUDY

The purpose of the pilot study was to establish proper guidelines for the experimental design. Several volunteers, including the authors, were asked to hold the actuators with their hands, as shown in Fig. 5a. The high concentration of mechanoreceptors in the fingertips facilitated adequate perception of vibrations. Participants wore earmuffs and were seated in a chair with armrests to maintain a natural and relaxed position. Both tactile illusions were presented in a loop, moving from one hand to the other (as shown in Fig. 4), while participants provided feedback to the experimenter.

From this pilot study we established the following guidelines:

- It is feasible to render the CR illusion out of the body in midair between the hands. According to the participants' feedback, the CR illusion was consistently perceived.
- Some practice and good concentration is required to properly perceive the FUN and CR tactile illusions.
- Features that may be perceived differently when rendering CR using FUN include perceived direction, perceived amount of jumps, and perceived duration.
- The difference between frequency responses of the actuators did not affect the perception of either FUN

or CR illusions. Similar results were found by Shirin Kasaei and Vincent Levesque for a moving phantom sensation in [18]. Other researchers also reached the same conclusion when using different tactile displays (such as a tablet and a smartwatch) to evoke tactile illusions [19].

E. QUALITY INDICATOR: LEVEL OF CLARITY

We established a quality indicator to evaluate the clarity of the perceived sensations in the practice session. This indicator, named Level of Clarity (LOC), can take values from 0 to 4, where 0 represents *imperceptible*, 1 represents *almost imperceptible*, 2 represents *not so clear*, 3 represents *clear*, and 4 represents *very clear*.

F. EXPERIMENT 1

The purpose of this experiment was to qualitatively compare CR with CR recreated using FUN (CR-FUN). Participants were seated in a chair with armrests, holding the actuators with their hands. To minimize cross-modal interference, participants closed their eyes and wore earmuffs (as shown in Fig. 5).

1) PARTICIPANTS

A total of 24 participants were recruited from Universidad Indoamerca in Quito - Ecuador. Among them, 16 were male and 8 were female, aged between 16 and 59 years old ($M = 29.6, SD = 14$). These participants took part in both experiments, voluntarily agreeing to participate, signing informed consent letters, and providing general information through a questionnaire.

2) PRACTICE SESSION

The practice session aimed to familiarize participants with the CR and CR-FUN illusions. The tactile illusions were presented in random order. Each illusion was presented in a loop, initially moving from actuator 1 to actuator 2 (left to righ direction, LR), as explained in Section III-A and exemplified in Fig. 4. Then, the illusion was presented in reverse, from actuator 2 to actuator 1 (right to left direction, RL). Rest periods of 0.5 seconds separated changes in direction. Stimulation continued until participants reported perceiving the illusion of "a smooth progression of jumps from one hand to the other". Participants successfully recognized both CR and CR-FUN during the practice session. CR was perceived with an LOC of 3 *clear* ($Md = 3, IQR = 1$), while CR-FUN was perceived with an LOC of 4 *very clear* ($Md = 4, IQR = 1$).

3) PROCEDURE OF THE MAIN EXPERIMENT

We designed four CR illusions with LR direction and four with RL direction, following the characteristics described in Section III-A and shown in Fig. 4. Additionally, using similar characteristics and the approach described in Section I, we designed four CR-FUN illusions with LR direction and four with RL direction. CR illusions with LR direction were paired with CR-FUN illusions with LR direction, and

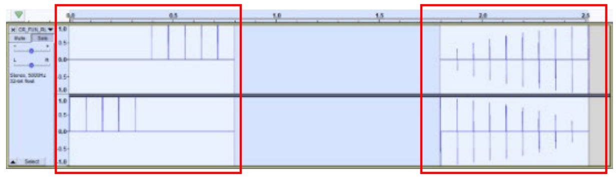


FIGURE 6. **This figure shows a stereo strip from Audacity showing a sequence of Cutaneous Rabbit (CR) on the left and CR recreated using Funneling (CR-FUN) on the right with 1-second pause, both with right to left (RL) direction. The name used to refer to the tactile illusions when asking the questions to the participants is labeled above each tactile illusion: first group and second group of stimuli.**

CR illusions with RL direction were paired with CR-FUN illusions with RL direction. Each pair was sequentially arranged in stereo strips in Audacity, with 1-second pauses (as exemplified in Fig. 6). Four pairs started with CR and the other four started with CR-FUN, to avoid order effects. In total, we conducted eight trials. Initially, we presented the stimuli once, and participants were allowed to repeat them as many times as necessary to ensure reliable responses. When asking the questions, we referred to the first tactile illusion of every trial as the *First group of stimuli* and the second tactile illusion as the *Second Group of stimuli*, to not prime the participant about the type of tactile illusion that was presented first or second (See Fig. 6).

We gathered qualitative data based on the following indicators:

- *Perception of the illusion*. Participants answered a two-alternative forced-choice question: "Did you perceive a successive progression of jumps traveling from one actuator to the other with both groups of stimuli?" Possible answers: "Yes" or "No". If the answer was "No", we asked a second question: "Which group did not evoke the illusion?" Possible answers: "First group" or "Second group". Note that although all participants reported perceiving the illusions in the practice session, tactile illusions can be fragile and may not always be elicited or may suddenly break apart.
- *Perceived direction*. Participants answered two two-alternative forced-choice questions: "What was the direction of the jumps in the first group of stimuli?" and "What was the direction in the second group of stimuli?" Possible answers for either question: "Left to Right (LR)" or "Right to Left (RL)". Even if the illusion was not perceived, participants might still have perceived a sensation of direction, especially with CR where the actuators are activated asynchronously (i.e., actuator 1 first and then actuator 2, or vice-versa).
- *Perceived amount of jumps*. Participants answered a three-alternative forced-choice question: "How would you compare the amount of jumps in each group of stimuli?" Possible answers: "the same", "the first group had more", or "the second group had more".
- *Perceived duration*. Participants answered a three-alternative forced-choice question: "How would you compare the duration of each group of stimuli?"

Possible answers: "the same", "the first group lasted more", or "the second group lasted more".

- *Similarity*. Participants answered a four-alternative forced-choice question: "How similar the first and second group of stimuli were?" Possible options were in a scale from 0 to 3: 0 (*completely different*), 1 (*different*), 2 (*similar*), and 3 (*exactly the same*).
- *Overall feedback*. At the end of experiment 1, we presented a single trial containing CR and CR-FUN illusions (in random order and direction). Participants were asked an open-ended question: "Could you describe in your own words the differences that you perceived between the groups of stimuli?" to obtain a richer overall qualitative evaluation of both CR and CR-FUN. We gathered, grouped, and summarized the most relevant information from their responses.

Once the participants gave their overall feedback about the experience in experiment 1, they proceeded with experiment 2.

G. EXPERIMENT 2

In this experiment we determined the upper threshold of the Inter-Stimulus Onset Interval (ISOI) for CR and the Time Between Funneling illusions (TBF) for CR-FUN when the illusions break apart. We used a chair with armrests, as in experiment 1, and asked the participants to close their eyes and wear earmuffs to avoid cross-modal interference, as shown in Fig. 5.

1) PROCEDURE OF THE MAIN EXPERIMENT

We designed twelve CR and twelve CR-FUN illusions with the following ascending ISOI and TBF values, respectively: 80, 100, 120, 140, 160, 180, 200, 240, 280, 320, 360, and 400 milliseconds. One session in Audacity contained the twelve CR illusions arranged in independent stereo channel strips to easily switch from one ISOI to the next using the *Solo* function. Another session in Audacity contained the twelve CR-FUN illusions, also arranged in independent stereo channel strips, facilitating switching from one TBF to the next. Participants evaluated the ISOI and TBF thresholds separately; the order of this evaluation was randomized. Initially, we presented the participants the CR (or CR-FUN) illusion with an ISOI (or TBF) of 80 milliseconds looping as in the practice session; from left to right (LR) and backwards from right to left (RL), with pauses of 0.5 seconds between changes of direction. We gradually increased the ISOI (or TBF) until the participant reported that the illusion broke apart. The value of ISOI (or TBF) just before the illusion disappeared was recorded. We repeated the procedure for CR-FUN (or CR).

IV. RESULTS AND DISCUSSIONS

Before processing the data gathered in each experiment, we verified its distribution using two methods: visual and mathematical. We employed q-q plots to visually assess the distribution of the data. For statistical analysis, we used the Shapiro-Wilk test. All data samples exhibited a non-normal distribution. Therefore, we used appropriate non-parametric statistical methods for further data processing.

A. RESULTS OF EXPERIMENT 1

1) PERCEPTION OF THE ILLUSION

To process the data, we first added up the number of times each participant reported successful recognition of CR and CR-FUN. We then calculated the corresponding percentage and computed the median performance across all participants. We used a non-parametric Wilcoxon (W) signed ranks test for matched pairs to compare the medians of perceived CR and CR-FUN. We found that participants performed significantly better at recognizing CR-FUN ($Md = 100\%, IQR = 0$) than CR ($Md = 100\%, IQR = 50$), with $W = 67, z = 2.2, p < 0.05$. Fig. 7a shows a box plot of successful perception of CR and CR-FUN.

2) PERCEIVED DIRECTION

Before processing the data, we added up the number of times each participant reported successful recognition of direction, as in the previous point. We then calculated the median performance across all participants. We used a non-parametric Wilcoxon (W) signed ranks test for matched pairs to compare the medians of perceived direction of CR and CR-FUN. We found that participants performed significantly better at recognizing the direction of CR ($Md = 100\%, IQR = 0$) than the direction of CR-FUN ($Md = 100\%, IQR = 12.5$), with $W = 3, z = -2.35, p < 0.05$. Fig. 7b shows a box plot of successful perception of the direction of CR and CR-FUN.

3) PERCEIVED DURATION

We calculated the number of pairs of CR and CR-FUN that were perceived with equal duration (Eq), with longer duration in CR-FUN (CR-FUN+), and with longer duration in CR (CR+) for each participant. Then we expressed these results as a proportion of the eight pairs that were presented and calculated the proportions for the whole sample. We can see in the stacked bar graph on the left of Fig. 8a that most of the participants perceived longer duration in CR-FUN (54%) than equal duration (39%) and than longer duration in CR (8%).

4) PERCEIVED AMOUNT OF JUMPS

For each participant, we calculated the number of pairs of CR and CR-FUN that were perceived with equal amount of jumps (Eq), with more jumps in CR-FUN (CR-FUN+), and with more jumps in CR (CR+). We expressed these results as a proportion of the eight pairs that were presented to each participant and then calculated the proportions for the whole sample. We can see in the stacked bar graph on the right of Fig. 8a that most of the participants perceived more jumps in CR-FUN (65%) than equal amount of jumps (32%) and than more jumps in CR (3%).

5) SIMILARITY

Each pair of CR and CR-FUN was evaluated using the similarity scale. For each participant, we added up all the

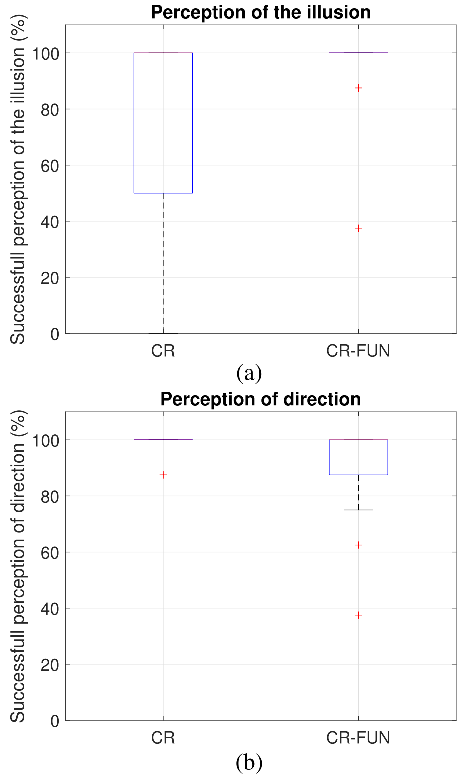


FIGURE 7. **This figure shows box plots of data gathered in experiment 1 for (a) successful perception of Cutaneous Rabbit (CR) and CR recreated using Funneling (CR-FUN), and (b) successful recognition of the direction of jumps for CR and CR-FUN.**

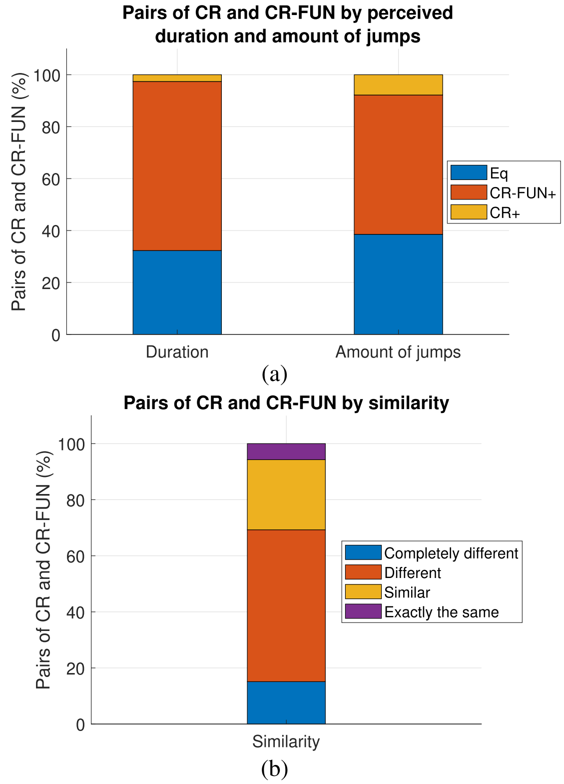


FIGURE 8. **This figure shows stacked bar graphs of data gathered in experiment 2 for (a) pairs of Cutaneous Rabbit (CR) and CR recreated using Funneling (CR-FUN) by perceived duration and amount of jumps, and (b) pairs of CR and CR-FUN by similarity.**

qualifications and calculated the proportion from the eight trials presented and then for the whole sample. Fig. 8b shows a stacked bar graph with the results. According to these calculations, most of the participants perceived the pairs of CR and CR-FUN as different (54%), followed by similar (25%), then completely different (15%), and finally exactly the same (6%).

6) OVERALL FEEDBACK

To complement these results, we classified the overall feedback obtained from the final open question. We summarize the following:

- Participants P1, P5, P6, P9, P10, P13, P14, P15, P17, and P24 reported that in some CR the illusions, there was a space in the middle, either like a larger jump or a pause.
- Participants P4, P8, P12, and P24 reported that some CR illusions went directly to the other hand without jumps transferring between the actuators.
- Participants P1, P13, P14, P15, and P17 reported that the CR-FUN illusions were more continuous than the CR illusions.
- Participant P8 reported that only the CR-FUN illusions accomplished the whole trajectory.
- Participant P24 reported that some CR-FUNs were felt in both hands at once, not in midair.
- Participant P3 reported that some CR-FUN illusions did not indicate a direction, so he/she could not perceive that the points reached the other hand.
- Participant P11 reported that in some CR-FUN illusions, the jumps were felt in the same place.
- Participants P5, P6, P7, P17 reported that the main differences between both CR and CR-FUN were the number of jumps and the duration. They considered that CR-FUN had more jumps and therefore lasted longer.
- Participant P12 described the difference between CR and CR-FUN as the "speed of the jumps"; CR was perceived as faster than CR-FUN.
- Participant P18 perceived that CR had less intensity than CR-FUN.

7) DISCUSSION

In experiment 1, we recreated the cutaneous rabbit (CR) illusion using the funneling (FUN) illusion, which we referred to as the CR-FUN illusion. In a practice session, we presented both CR and CR-FUN to the participants, who successfully recognized both illusions. Then, to compare the rendering methods proposed in this experiment, we presented the participants with pairs of CR and CR-FUN and asked five forced-choice questions. We also asked a final open question, which we used as complementary feedback to reinforce the results of Experiment 1.

According to our results, the CR-FUN illusion was better perceived than the CR illusion. This result aligns with that reported by Topon Visarrea et al. [12], where even with spatio-temporal differences between CR and the arranged FUN illusions, FUN was better perceived. Participants reported that an important reason for this difference was that CR was perceived with an empty space in between the jumps, like a larger jump or a pause in the middle of the motion. Moreover, some participants considered that the CR-FUN illusion created a more continuous sensation. If the purpose of a vibrotactile interface is to evoke a robust illusion of jumps progressively moving between the hands, a recreated CR using FUN might be a more reliable option.

Furthermore, CR-FUN was perceived with more jumps than CR, which aligns with the reports of longer duration perceived in CR-FUN. In fact, participants indicated that the most relevant differences between CR and CR-FUN were the amount of jumps and the perceived duration. Some participants reported that CR went directly to the other hand without jumps transferring the hopping rabbit in the middle, implying that the motion was faster. However, this contradicts the reports of some participants that CR evoked a larger jump in the middle or a pause, which should be perceived as a longer illusion. We consider that more research is required to better understand this conflict.

Finally, we suggest that all the differences described above affect the perception of similarity, where about 54% of the sample considered that CR and CR-FUN were different, and only about 25% considered that they were similar. If CR and CR-FUN are implemented in a vibrotactile interface, the designer must be aware that combined sequences of CR and CR-FUN may provoke perceptual differences.

B. RESULTS OF EXPERIMENT 2

The results of experiment 2 show that the CR illusion was perceived up until an ISOI of 190 milliseconds ($Md = 190ms, IQR = 100ms$) and broke apart at an ISOI of 200 milliseconds ($Md = 200ms, IQR = 120ms$). Only for participants P2, P5, and P13, who represented 12.5% of the sample, the CR illusion did not break apart for any of the ISOI values explored in this experiment. In contrast, only for participants P1, P2, P6, P11, and P17, who represented 21% of the sample, the CR-FUN illusion broke apart at 280, 200, 320, 360, and 200 milliseconds, respectively. In general, CR-FUN was consistently perceived up to 400 milliseconds ($Md = 400ms, IQR = 0ms$), corresponding to the maximum TBF tested in this experiment. Due to experiment duration constrains, it was not possible to explore longer TBFs. Fig. 9 shows a box plot with the median ISOI and TBF values up until the illusions were perceived.

1) DISCUSSION

In experiment 2, we rendered the CR and CR-FUN illusions while increasing the ISOI and TBF, respectively. Participants reported when the illusion broke apart. In the case of CR, we found that the maximum ISOI for consistent perception of the illusion was 190 milliseconds, and the CR illusion broke apart at approximately 200 milliseconds. Our finding agrees with that reported by Geldard and Sherrick [7]. We suggest that, beyond this threshold, the neural system of individuals may not be able to integrate the stimuli due to the wide spaces between pulses. In contrast, we were unable to find the upper TBF threshold since the CR-FUN illusion, overall, did not break apart for any of the TBF values explored in this experiment. Since we do not know what would happen with longer TBF values, this upper threshold remains uncertain. Most of the participants reported consistent perception of the CR-FUN illusion even at a TBF of 400 milliseconds. Further investigation is required to ascertain what would happen to the CR-FUN illusion over a TFB value of 400 milliseconds. However, in the range from around 200 to 400 milliseconds, CR-FUN may reliably replace CR.

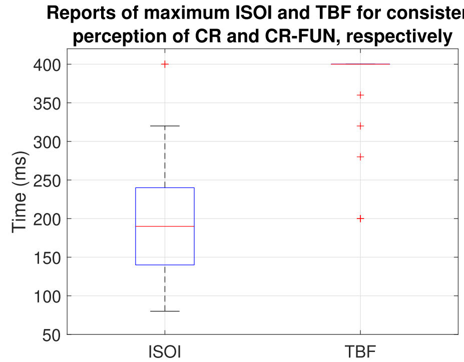


FIGURE 9. This figure shows a box plot of the reported Inter-Stimulus Onset Interval (ISOI) and Time Between Funneling (TBF) up until the Cutaneous Rabbit (CR) and CR recreated using Funneling (CR-FUN) illusions, respectively, were consistently perceived.

V. CONCLUSION

In this work, two experiments were performed to compare the Cuttaneous Rabbit (CR) illusion with the Funneling (FUN) illusion. We designed these experiments to aid developers in deciding when to use one or the other tactile illusion. Firstly, our results show that CR and FUN are spatio-temporal tactile illusions that can be evoked out of the body in midair between the hands. Most individuals perceived these tactile illusions as different. Participants highlighted the number of jumps and the duration as the most relevant differences between CR and CR-FUN. We consider that these differences arise mainly because in CR, the first five pulses are presented in actuator one and then the other five pulses are presented in actuator two, which sometimes evokes a pause or large jump in the middle of the jumping motion and may break the illusion apart. Furthermore, our results suggest that it may be possible to use CR-FUN instead of CR for Inter-Stimulus Onset Interval (ISOI) values longer than the upper threshold of CR, which is approximately 190 milliseconds. The maximum Time Between Funelling (TBF) we tested in our experiment was 400ms, which is more than twice the maximum ISOI for CR, and for which CR-FUN was robust. Nevertheless, it remains uncertain how long the TBF could be to keep a robust CR-FUN illusion. Overall, CR-FUN performed better than CR, suggesting that CR-FUN may successfully replace and even outperform, or be combined with, the CR illusion when required. Specifically, in scenarios where it is important to recognize the effect of a variable number of successive points transferring between the actuators at different speeds, i.e. applications that need flexibility, CR-FUN may work better. Conversely, in scenarios where the recognition of the direction of motion is more relevant, both CR and CR-FUN could be implemented. However, researchers and practitioners must be aware of the perceptual differences that may appear.

SUPPLEMENTARY MATERIAL

Find the data that supports this investigation in the following link: Click here to access data that supports this investigation.

ACKNOWLEDGMENT

The authors acknowledge the technical support of Prof. Fabián Sarmiento, who is a Researcher with Universidad Indoamérica, Quito, Ecuador.

REFERENCES

[1] S. Choi and K. J. Kuchenbecker, "Vibrotactile display: Perception, technology, and applications," *Proc. IEEE*, vol. 101, no. 9, pp. 2093–2104, Sep. 2013. [Online]. Available: http://ieeexplore.ieee.org/document/6353870/

[2] Actronika. (2021). *What's Under the Hood of the DualSense?*. [Online]. Available: https://www.actronika.com/post/whats-under-the-hood-of-the-dualsense#:~:text=%E2%80%8DOn%20each%20side%20of%20the,of%20buttons%20and%20a%20trackpad

[3] S. Shokur, S. Gallo, R. C. Moioli, A. R. C. Donati, E. Morya, H. Bleuler, and M. A. L. Nicolelis, "Assimilation of virtual legs and perception of floor texture by complete paraplegic patients receiving artificial tactile feedback," *Sci. Rep.*, vol. 6, no. 1, pp. 1–14, Sep. 2016. [Online]. Available: https://www.nature.com/articles/srep32293

[4] B. Remache-Vinueza, A. Trujillo-León, M.-A. Clim, F. Sarmiento-Ortiz, L. Topon-Visarrea, A. R. Jensenius, and F. Vidal-Verdù, "Mapping monophonic MIDI tracks to vibrotactile stimuli using tactile illusions," in *Lecture Notes in Computer Science (Including Subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)*. Deutschland: Springer, vol. 13417, 2022, pp. 115–124.

[5] M. Bergholz, M. Ferle, and B. M. Weber, "The benefits of haptic feedback in robot assisted surgery and their moderators: A meta-analysis," *Sci. Rep.*, vol. 13, no. 1, pp. 1–15, Nov. 2023. [Online]. Available: https://www.nature.com/articles/s41598-023-46641-8

[6] M. A. Plaisier, L. I. N. Sap, and A. M. L. Kappers, "Perception of vibrotactile distance on the back," *Sci. Rep.*, vol. 10, no. 1, pp. 1–7, Oct. 2020. [Online]. Available: https://www.nature.com/articles/s41598-020-74835-x

[7] F. A. Geldard and C. E. Sherrick, "The Cutaneous 'rabbit': A perceptual illusion," *Science*, vol. 178, no. 4057, pp. 178–179, Oct. 1972. [Online]. Available: https://www.science.org/doi/10.1126/science.178.4057.178

[8] D. Alles, "Information transmission by phantom sensations," *IEEE Trans. Man Mach. Syst.*, vol. MMS-11, no. 1, pp. 85–91, Mar. 1970. [Online]. Available: http://ieeexplore.ieee.org/document/4081935/

[9] J. Lee, Y. Kim, and G. Jounghyun Kim, "Rich pinch: Perception of object movement with tactile illusion," *IEEE Trans. Haptics*, vol. 9, no. 1, pp. 80–89, Jan. 2016. [Online]. Available: https://ieeexplore.ieee.org/document/7234937/

[10] Meta. (2023). *Controladores De VR Meta Quest Touch Pro*. [Online]. Available: https://www.meta.com/es/quest/accessories/

[11] S. Hwang and J.-h. Ryu, "The haptic steering wheel: Vibro-tactile based navigation for the driving environment," in *Proc. 8th IEEE Int. Conf. Pervasive Comput. Commun. Workshops (PERCOM Workshops)*, Mar. 2010, pp. 660–665. [Online]. Available: http://ieeexplore.ieee.org/document/5470517/

[12] B. T. Visarrea, C. Iza, G. Arteaga, and B. Remache, "Design of a portable interface for vibrotactile feedback applications," in *HCI International—Late Breaking Posters* (Communications in Computer and Information Science), vol. 1654, C. Stephanidis, M. Antona, S. Ntoa, and G. Salvendy, Eds. Cham, Switzerland: Springer, 2022, doi: 10.1007/978-3-031-19679-9_12.

[13] G.-H. Yang, M.-s. Jin, Y. Jin, and S. Kang, "T-mobile: Vibrotactile display pad with spatial and directional information for hand-held device," in *Proc. IEEE/RSJ Int. Conf. Intell. Robots Syst.*, Oct. 2010, pp. 5245–5250. [Online]. Available: http://ieeexplore.ieee.org/document/5651759/

[14] A. Israr and I. Poupyrev, "Tactile brush," in *Proc. SIGCHI Conf. Human Factors Comput. Syst.* New York, NY, USA: ACM, May 2011, pp. 2019–2028, doi: 10.1145/1978942.1979235.

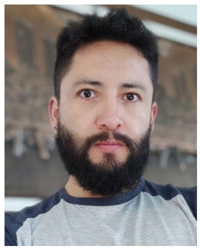
[15] J. Raisamo, R. Raisamo, and V. Surakka, "Comparison of saltation, amplitude modulation, and a hybrid method of vibrotactile stimulation," *IEEE Trans. Haptics*, vol. 6, no. 4, pp. 517–521, Oct. 2013. [Online]. Available: http://ieeexplore.ieee.org/document/6517847/

[16] R. Flach and P. Haggard, "The cutaneous rabbit revisited," *J. Experim. Psychology: Human Perception Perform.*, vol. 32, no. 3, pp. 717–732, 2006.

[17] H.-Y. Yao and V. Hayward, "Design and analysis of a recoil-type vibrotactile transducer," *J. Acoust. Soc. Amer.*, vol. 128, no. 2, pp. 619–627, Aug. 2010. [Online]. Available: http://asa.scitation.org/doi/10.1121/1.3458852

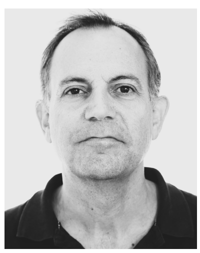
[18] S. Kasaei and V. Levesque, "Effect of vibration frequency mismatch on apparent tactile motion," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Mar. 2022, pp. 1–6.

[19] S. Hwang, J. Song, and J. Gim, "Harmonious haptics: Enhanced tactile feedback using a mobile and a wearable device," in *Proc. Conf. Human Factors Comput. Syst.*, vol. 18, 2015, pp. 295–298, doi: 10.1145/2702613.2725428.



BYRON REMACHE-VINUEZA (Member, IEEE) was born in Quito, Ecuador, in 1986. He received the bachelor's degree in mechanical engineering from Escuela Politécnica Nacional, Ecuador, in 2011, the master's degree in energy systems from The University of Melbourne, in 2014, and the Master of Arts degree in music technology from the University of Kent, in 2016. He is currently pursuing the Ph.D. degree in mechatronics with Universidad de Málaga. He is a full-time Lecturer/Researcher with Universidad Indoamérica, Quito. He has authored or coauthored 14 journal articles and presented his work at various international conferences. His current research interests include vibrotactile interfaces, assistive technologies, and music.

ANDRÉS TRUJILLO-LEÓN was born in Córdoba, Spain. He received the B.S. degree in telecommunication engineering, the M.S. degree in electronics engineering, and the Ph.D. degree in mechatronics engineering from the University of Málaga, Málaga, Spain, in 2008, 2011, and 2018, respectively. He was a Research Engineer with the Departamento de Electrónica, University of Málaga, until 2014, when he enrolled in a doctoral program. He was a Postdoctoral Researcher with the Institute for Intelligent Systems and Robotics (ISIR), Sorbonne University, Paris, France, where he was involved in haptics and assistive robotics. His current research interests include rehabilitation and biomedical engineering and sensors and instrumentation.



FERNANDO VIDAL-VERDÚ was born in San Fernando, Cádiz, Spain, in 1965. He received the M.Sc. degree in physics from Universidad de Seville, Seville, Spain, in 1988, and the Ph.D. degree in microelectronics from Universidad de Málaga (UMA), Màlaga, Spain, in 1996. Since 1991, he has been with the Departamento de Electrónica, Universidad de Málaga, where he is currently a Full Professor. He has authored or coauthored 35 international journal articles, seven chapters of books (edited by IEEE, Kluwer, CRC, Wiley, and Springer), and more than 60 conference papers. His current research interests include smart sensors, haptic and tactile interfaces, and assistive and healthcare applications and technologies.