Short Papers

Snake Effect: A Novel Haptic Illusion

Frederico M. Severgnini, Juan S. Martinez, *Member, IEEE*,
Hong Z. Tan, *Fellow, IEEE*, and Charlotte M. Reed

***Abstract*—We present a novel, movement-based haptic illusion called the "snake effect." Unlike apparent motion or sensory saltation, the snake effect feels wavy and creepy as though the belly of a slithering snake is making and breaking contact with the skin. This illusion is achieved by modulating the amplitudes of vibrotactile pulses sent successively to an array of tactors. Pilot testing established the following signal parameters for creating the snake effect: a minimal pulse duration of 1.69 s, carrier frequency in the range of 200-300 Hz, amplitude modulation of the carrier with a sine, sine-squared or Gaussian waveform (shown to be more effective than a linear up-and-down ramp), and a peak amplitude of 30 dB above detection threshold. The main experiment examined the most effective signal onset asynchrony (SOA) ranges by estimating the upper and lower SOA thresholds using a one-up one-down adaptive procedure with interleaved ascending and descending series. The results indicate an optimal SOA range from 271.5 ms to 798 ms with a midpoint of 535 ms. The snake effect is a vivid illusion that can be used as a distinctive signal for encoding information and to enhance immersion and engagement in gaming and entertainment.**

Index Terms—Haptic illusion, movement illusion, SOA, snake effect.

I. INTRODUCTION

The present study was motivated by the need for vivid and distinct sensations that can effectively encode information through haptic devices. In a literature survey by Tan *et al.* (2020), it was found that illusory movement sensations delivered by multiple tactors can significantly increase the number of distinct vibrotactile stimulation patterns that are quickly learned and recognized, thereby effectively increasing the information transmission capacity of haptic displays [1]. Lederman & Jones (2011) provide a comprehensive review of tactile and haptic illusions, including movement illusions that result from a series of vibrotactile pulses presented successively on multiple tactors across the skin [2]. The two best-known movement illusions are *tactile apparent motion* that feels like a single stimulus moving smoothly on the skin [3], [4] and *sensory saltation* that feels more like a sequence of discrete taps "as if a tiny rabbit were hopping" across the skin [5], [6]. Cholewiak & Collins (2000) investigated the parameters for well-defined "dotted lines" drawn with either a veritical presentation (sequential activation of an array of tactors) or sensory saltation, and found the sensations to be equivalent in a discrimination task [7]. These movement illusions have been studied using two-dimensional tactor arrays for applications such as navigation guidance and entertainment [8], [9], [10], [11].

Movement illusions have been successfully incorporated into a tactile speech communication system consisting of a 4-by-6 tactor array worn on the forearm. Taking a phonemic-based encoding approach, Reed *et al.* (2019) detail the design of 39 haptic symbols representing the 39 phonemes of spoken English, with 24 position-based symbols representing the 24 consonants and 15 movement-based symbols for the 15 vowels [12]. In addition to using many "stimulus dimensions" such as spatial location, frequency, amplitude modulation and duration to increase information transmission, the vowel symbols were all based on illusory movements and employed additional dimensions such as movement direction and spatial extent to increase their distinctiveness. Phoneme identification results with ten young adults indicated a mean recognition rate of 86% correct with few confusions between consonants and vowels [12]. Tan *et al.* (2020) report the acquisition of 500 English words encoded with the haptic phonemic symbols with 21 participants. While individual results varied, the best participants achieved an average word acquisition rate of 1.3 words per minute [13]. A follow-up study by Martinez *et al.* (2020) improved the 39 phonemic symbols by assigning the shortest duration to the 10 most frequently-occurring phonemes and created 10 additional symbols for the 10 most frequently co-occuring phoneme pairs. Ten new participants were able to achieve an average identification accuracy of 83% correct with the 49 phonemic symbols [14]. Encouraged by the high level of phoneme recognition achieved by the participants in these studies after only several hours of training, we set out to investigate new types of movement illusions that can be added to the haptic symbol set to encode additional speech information, such as punctuation and even emojis, without significantly affecting the recognition accuracy.

Other applications such as virtual or mixed reality for gaming and entertainment can also benefit from new movement illusions on the skin due to the vivid and rich sensations arising

---

Manuscript received August 18, 2020; revised January 13, 2021 and February 15, 2021; accepted March 26, 2021. Date of publication March 31, 2021; date of current version December 16, 2021. This work was supported in part by a research grant funded by Facebook Inc., and by the National Science Foundation under Grant 1954842-IIS and Grant 1954886-IIS. This article was recommended for publication by Associate Editor Dr. Gionata Salvietti and Editor-in-Chief Prof. Domenico Prattichizzo upon evaluation of the reviewers' comments. *(Corresponding author: Hong Z. Tan.)*

Frederico M. Severgnini, Juan S. Martinez, and Hong Z. Tan are with the Haptic Interface Research Laboratory, School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907 USA (e-mail: fredericomqs@gmail.com; mart1304@purdue.edu; hongtan@purdue.edu).

Charlotte M. Reed is with the Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, MA 02139 USA (e-mail: cmreed@mit.edu).

Digital Object Identifier 10.1109/TOH.2021.3070277

from movement direction, spatial extent and trajectory. Besides information transmission, haptic stimulation can be a powerful tool in addition to vision and audition for enhanced immersion and enjoyment. For example, Fröhner *et al.* (2019) reported improved subjective embodiment of a virtual hand with feedback to the thumb and index finger via a haptic glove [15]. Haans & IJsselsteijn (2009) provided empirical evidence that touch mediated with actuators may lead to similar altruistic behavior as unmediated touch by a stranger [16]. There is also a growing body of research on affective haptics. Bianchi *et al.* (2014) developed a fabric-based wrist display that simulated human caress. Subjective valence and arousal ratings were shown to be correlated with the velocity and force of caress, respectively [17]. Culbertson *et al.* (2018) used slow (<5 Hz) up-down motions of tactors in an array to simulate stroking on the forearm and succeeded in creating a continuous and pleasant sensation [18]. Research on affective haptics has grown significantly in recent years and has permeated other fields such as human robot interaction [19], [20], [21], [22]. Interestingly, saltatory movements can feel either delightful or frightening depending on an individual's reaction to the imagery of a "tiny rabbit" hopping on the skin. Regardless, the hedonic property of haptic movement illusions, whether positive or negative, can be an effective way to attract attention and amplify immersion. Therefore, new movement illusions can contribute to the growing body of haptic effects for delivery through wearable array displays in a wide range of applications.

The "snake effect" investigated in the present study evokes the imagery of a slithering python with its heaving belly making and breaking contact with one's forearm. The signal pattern for the snake effect is similar to that of apparent motion, with one important difference. Like the apparent motion illusion, the snake effect is elicited with a single pulse sent to a tactor followed by another pulse sent to a second tactor with the two pulses overlapping in time. However, the snake effect uses amplitude modulation to create the oscillatory or wavy sensation with the perceived contact area expanding and contracting periodically over time. In comparison, apparent motion uses a constant amplitude for a smooth and continuous illusory motion. Based on the definition in Lederman & Jones (2011) that "... an illusion is the marked and often surprising discrepancy between a physical stimulus and its corresponding percept," we maintain that the snake effect, like apparent motion, is a tactile illusion. An earlier study by Israr & Poupyrev (2010) used overlapping vibratory pulses with an initial full onset and a gradual decrease of amplitude for a blur effect, but provided no specific parameters [23]. Our pilot study indicated that it was more effective to have both a gradual increase and decrease of the amplitude envelope to create a vividly creepy sensation. The snake effect is also characteristically different from sensory saltation in that the snake effect delivers a continuous and oscillatory movement illusion. In terms of signal generation, the snake effect is created differently from sensory saltation where a typical stimulus for sensory saltation consists of three vibratory pulses sent to a tactor, another three to a second tactor, and one terminating pulse sent to a third tactor (cf. Tan *et al.* 2003 [8]).

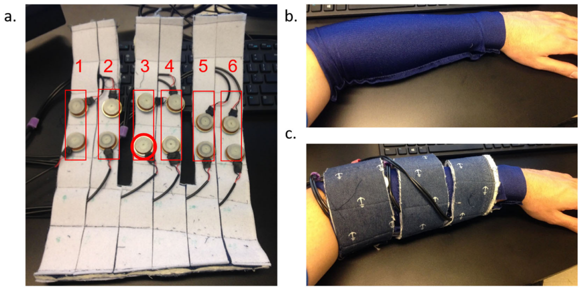


Fig. 1. The "snake" display: (a) the tactor array, (b) the protective sleeve, and (c) the gauntlet that holds the tactor array on the forearm. The red circle in (a) indicates the tactor used for detection threshold estimation. The rectangles indicate the 6 activation positions in the tactor array, as the two tactors in each rectangle were driven with identical waveforms.

The present study reports on the results of perceptual studies designed to specify the optimal signal parameters for eliciting the snake effect.

II. METHODS

A. *Participants*

A total of ten participants (5 females; 22 to 31 years old) participated in the experiment. Nine of the participants were right-handed and one was left-handed by self-report. Of the ten participants, two (the first two authors) had felt the snake effect before in a pilot study, and the rest were naive. All participants gave their informed consent and were paid for their time.

B. *Apparatus*

The experimental device was composed of a 2-by-6 tactor array that formed six pairs along the longitudinal (elbow to wrist) direction (see Fig. 1). The tactors were wide-bandwidth exciters (Tectonic Elements, Model TEAX13C02-8/RH, Part No. 297-214) sourced from Parts Express. A 3D-printed circular cap (2.172 cm diameter, 2 mm thick) was press-fit to each actuator to provide a comfortable contact area with the skin. As shown in Fig. 1, the 12 tactors were arranged in three groups of 4 on a gauntlet via Velcro attachment which allowed their spacing to be adjustable for accommodating different arm lengths. The gauntlet was then wrapped around the forearm with Velcro strips. A MATLAB program generated 12 independent waveforms that were synchronously converted to 12 analog audio signals by a MOTU 24Ao device. The signals were then amplified to drive the 12 tactors, respectively. We verified with an accelerometer (Kistler 8794A500) that the tactor responses followed the signal waveforms.

C. *Stimuli*

The vibrotactile signals consisted of amplitude-modulated 300-Hz sinusoidal waveforms delivered to consecutive tactor pairs (marked 1 to 6 in Fig. 1 a) with a constant SOA (signal onset asynchrony). The same waveform was sent to the two tactors at each of the 6 positions to increase the perceived signal intensity (cf. [24]). Fig. 2 illustrates the timing sequence of the waveforms used to create the snake effect, using a

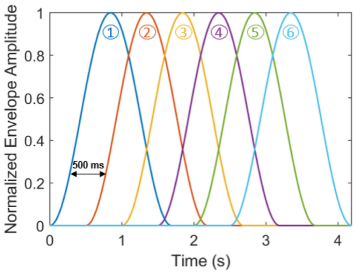


Fig. 2. Tactor activation sequence as shown by the sine-modulated envelopes of 300 Hz pulses. Each pulse is 1.69 s long, and successive pulses are delayed by an SOA of 500 ms. The six pulses were sent sequentially to the six pairs of tactors shown in Fig. 1 a.

sine-shaped amplitude envelope as an example. Due to the “funneling illusion” (where the simultaneous activation of two tactors on the skin with equal intensity leads to the perception of being stimulated at the midpoint between the two tactors), the amplitude-modulated pulses were perceived at the six midpoints between each of the six tactor pairs [25] [2].

Four modulation envelopes were investigated: sine, sine-squared, linear and Gaussian. All envelopes started from 0 (except for Gaussian which started at a low value), reached the maximum amplitude at half the duration, and went back to 0 (except for Gaussian). Fig. 3 shows the waveforms of the four types of envelopes.

The first two authors performed a pilot study using the method of adjustment to choose the appropriate parameters for signal duration, peak amplitude, modulation type and SOA range for the most salient snake effects. Using the Gaussian modulation, it was found that the signal duration needed to be at least 1.69 s for the stimulus to feel “creepy.” Consequently, all subsequent signal durations were fixed at 1.69 s. In terms of signal amplitude, it was found that a peak amplitude of 30 dB SL (sensation level; dB above detection threshold of a 300-Hz vibration) ensured a clearly perceivable snake effect. The use of a high-frequency carrier signal (i.e., 300 Hz) led to a penetrating sensation that enhanced the perceived creepiness, although the exact frequency did not matter as long as it was in the 200-300 Hz range. Among the different modulations, it was clear that the linear modulation did not lead to a wavy, crawling sensation on the skin over an SOA range of 0 to 1.69 s. The linear modulation was therefore eliminated from further tests. Due to the similarity in their waveforms, the signals modulated by Gaussian and sine-squared envelopes were indistinguishable. Sine-squared envelope was chosen over Gaussian envelope because it started and ended at exactly zero. As a result, only the sine and sine-squared modulations were investigated further. The measured acceleration profiles for a 300-Hz vibration modulated by the sine and sine-squared envelopes are shown in Fig. 4.

There appeared to be an SOA range within which the snake effect was most apparent. The upper and lower SOA bounds for snake effect were estimated in the main experiment.

D. Calibration Procedure

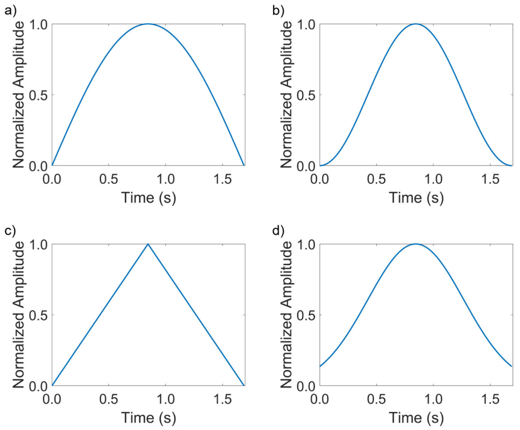


Fig. 3. Normalized amplitude envelopes used to modulate a 300 Hz vibration: (a) sine, (b) sine-squared, (c) linear, and (d) Gaussian.

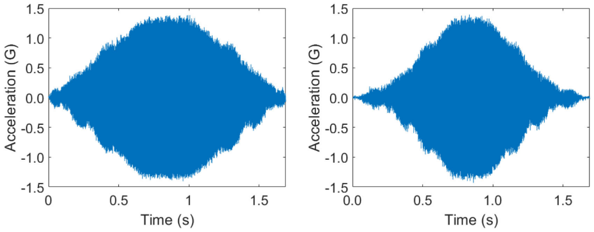
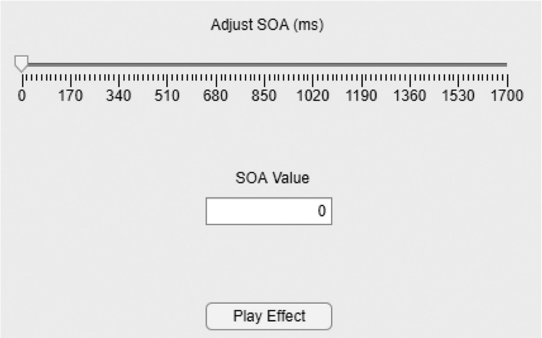


Fig. 4. Acceleration profiles corresponding to the amplitude envelopes shown in Fig. 3 a (sine) and Fig. 3 b (sine-squared), respectively, with a duration of 1.69 s and a carrier frequency of 300 Hz.

In order to ensure that each participant perceived the tactile stimulation at similar levels, a three-interval one-up two-down forced-choice adaptive procedure (see [26]) was used to estimate the individual detection thresholds of a 300-Hz vibration with duration of 400 ms and an inter-signal interval of 500 ms. The tactor circled in red in Fig. 1(a) was used for the calibration. Each trial consisted of three intervals, out of which only one contained the 300-Hz vibration and the other two contained no vibration. The participant’s task was to indicate the interval (1, 2, or 3) that was randomly selected to contain the vibratory signal on each trial. After one incorrect response, the vibration level was increased (hence “one-up”). After two consecutive correct responses, the vibration amplitude was decreased (“two-down”). This way, the level of the vibration was adjusted adaptively based on the participant’s responses. The signal amplitude was initially set at a relatively high level to ensure that it could be clearly felt. The step size for the first 4 reversals was 5 dB for faster convergence. The step size for the remaining 12 reversals was 2 dB for better resolution of the estimated threshold. A reversal was defined as a change in stimulus intensity from increasing to decreasing, or vice versa. Detection threshold was estimated by averaging the local maxima and minima of signal levels at the last 12 reversals. The threshold obtained this way corresponds to the 70.7% point on the psychometric function [27].

The perceived intensity of the 12 tactors was equalized using a method of adjustment [26]. An unmodulated 300-Hz vibration at 30 dB SL was delivered to the reference tactor marked in red in Fig. 1(a), followed by a vibration delivered to one of the remaining tactors. The level of each of the



SOA Value: 0

Fig. 5. User interface for adjusting SOA values.

remaining tactors was adjusted by the participant so that its perceived intensity matched that of the reference tactor. This procedure used a repeating sequence of three signals consisting of Reference-Test-Reference, where the signals were 400 ms with a 300 ms inter-stimulus interval. After each sequence, the participant judged whether the test signal was perceived to be stronger or weaker than the reference signal, and its level was then adjusted accordingly in 1-dB steps. This procedure continued until the participant was satisfied that the reference and test signals were felt to be equally strong. The adjustment procedure was conducted using the same reference tactor with each of the remaining 11 tactors. The results were then saved in a level-adjustment table for each participant. This step accounted for several factors that may affect the perceived intensity at each tactor: spatial variation of skin sensitivity to vibrations, unequal pressure applied to the tactors when attached to the skin, and differences in the mechanical response of the tactors. The equalization step was repeated if the participant removed the gauntlet during a break.

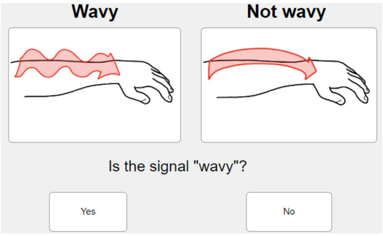
The results from the threshold and loudness-adjustment measurements described above were used to adjust the stimulation levels for individual participants during the main experiment to ensure that the perceived signal intensities were similar across participants.

E. Main Experiment

The main experiment was a 2 × 2 repeated-measure design. The two independent variables were modulation type (sine, sine-squared) and type of SOA threshold (upper, lower). The dependent measure was the SOA threshold.

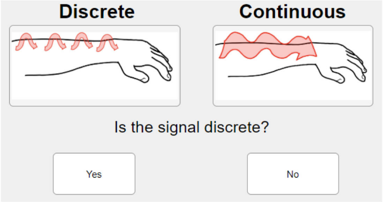
The participants sat comfortably in front of a computer monitor and placed the left forearm on the table. They wore noise-reduction earphones to mask any possible sounds arising from the tactors.

To familiarize the participants with the snake effect and the changing sensations as a function of SOA, they were asked to play with the vibrotactile stimuli freely by adjusting the SOA values using the interface shown in Fig. 5. A Gaussian modulation was used. The participants were asked to experience the vibrotactile stimuli at low, medium and high SOA values and notice the different characteristics. They could choose an SOA by either adjusting the slider or entering a value as shown in Fig. 5, then click on "Play Effect" to feel the signal.



Is the signal "wavy"?

(a) Lower SOA threshold



Is the signal discrete?

(b) Upper SOA threshold

Fig. 6. User interfaces for estimating (a) lower SOA threshold and (b) upper SOA threshold.

All participants described the snake effect as a wavy, continuous motion from the elbow to the wrist. At low SOA values, the effect was no longer wavy. At high SOA values, the effect became a sequence of discrete vibrotactile pulses. The snake effect was readily apparent, as each participant needed only 1-2 minutes to become familiar with the illusion.

Following this familiarization process, an interleaved one-up one-down adaptive procedure was employed to estimate the upper and lower values of SOA at which the snake effect was perceived. The value of SOA was adapted in real time based on the participant's responses. One ascending and one descending series were interleaved so the participant could not anticipate the change in SOA at the next trial [26]. On each trial, the ascending or descending series was selected with an equal *a priori* probability of 0.5. The SOA value was then determined based on the adaptive rule for all trials in that series only.

Measurements of upper and lower SOA thresholds were conducted as separate experimental conditions. To estimate the lower SOA threshold, the participant's task was to judge whether the tactile stimulus felt "wavy" using the interface shown in Fig. 6(a). Following the one-up one-down adaptive rule, if the participant responded "yes," the SOA value on the next trial was decreased; otherwise it was increased. All ascending and descending series started at an SOA of 50 ms and 350 ms, respectively, for the estimation of the lower SOA threshold. To estimate the upper SOA threshold, the participant was asked whether the tactile stimulus felt discrete using the interface shown in Fig. 6(b). If the answer was "yes," the SOA value was decreased on the next trial; otherwise it was increased. All ascending and descending series started at 600 ms and 900 ms, respectively, for the estimation of the upper SOA thresholds. The step size for SOA change for measuring both the upper and lower SOA thresholds was 45 ms for the initial three reversals for faster convergence, and decreased to 25 ms for the next ten reversals for better resolution of threshold estimates. These parameters were selected

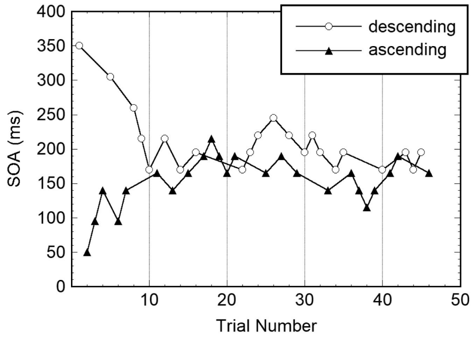


Fig. 7. An example of interleaved adaptive procedure for one participant, with sine-squared modulation, for the lower SOA threshold condition. The data points for the ascending and descending series are connected separately.

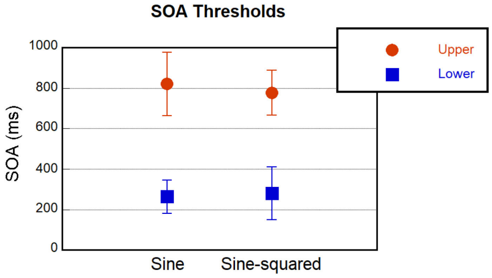


Fig. 8. Upper and lower SOA thresholds of snake effect for a 300 Hz carrier modulated with a sine or sine-squared amplitude envelope. Error bars denote standard deviations.

based on the pilot study conducted by the first two authors. A representative data plot of an interleaved one-up one-down adaptive procedure is shown in Fig. 7, for the condition of lower SOA threshold. The plot shows one descending series (unfilled circles) and one ascending series (filled triangles) interleaved, as a function of trial number, with the data points for each of the two series connected separately.

The order of the four experimental conditions was randomized for each participant. Two interleaved adaptive series, one ascending and one descending, were conducted for each participant at each condition. The participant was asked to take a break between conditions. If the interleaved series did not converge or lasted longer than a total of 100 trials, it was repeated. An adaptive series was judged to have converged if the difference between the maximum and minimum SOAs during the last ten reversals at the 25-ms step size was within 250 ms. Of the ten participants, two had to repeat one condition once and another repeated two conditions, once per condition. The experiment was completed within one session which varied in time between 1 to 2 hours across participants.

F. *Data Analysis*

For each condition per participant, the local maxima (peaks) and minima (valleys) in SOA values obtained during the last ten reversals at the smaller step size were recorded for ascending and descending series, respectively. Each pair of peak and valley SOA values were averaged to obtain one threshold estimate. There were five estimates from ascending series and five estimates from descending series. The results with or without the first two authors (who were in the pilot study) were similar. Therefore, the mean and standard error of all 100 estimates (10 estimates per participant × 10 participants) were computed for each of the four experimental conditions. The upper and lower SOA thresholds for each amplitude envelope mark the SOA range within which snake effect can be clearly perceived.

III. RESULTS

Fig. 8 shows the estimated SOA thresholds for the four experimental conditions averaged across the ten participants. The SOA range for rendering the snake effect was 263 to 820 ms for sine modulation, and 280 to 776 ms for sine-squared modulation. It thus appears that sine modulation resulted in a slightly larger SOA range (557 ms) than sine-squared modulation (496 ms) for rendering the snake effect, although the difference (61 ms) is small. A two-way repeated measure ANOVA with the factors modulation (sine, sine-squared) and threshold type (lower-bound, upper-bound) revealed threshold type to be a significant factor ($F(1,19) = 225.91$; $p < .0005$), but not modulation ($F(1,19) = 0.42$; $p = .527$). There was no significant interaction of modulation and threshold type ($F(1,19) = 2.25$; $p = .125$). We therefore conclude that both the sine and sine-squared amplitude modulations resulted in a relatively large SOA range (about 500 ms) for rendering the snake effect effectively.

To summarize, we have experimented with the use of a linear array for creating the creepy sensation of a snake slithering from the elbow to the wrist. Each pair of tactors in the transversal direction was driven with the same waveform in order to increase the perceived signal intensity. The six columns of tactors in the longitudinal direction were driven by amplitude-modulated vibratory pulses that were successively delayed by the same SOA. In a pilot study, we found the minimum duration of vibratory pulses needed to produce the effect to be 1.69 s. In the main experiment, using a 300-Hz carrier frequency with a peak amplitude of 30 dB SL and a fixed pulse duration of 1.69 s, we found similar SOA ranges for sine and sine-squared amplitude modulations in order to elicit a vivid snake effect. On average, we recommend an SOA range from 271.5 ms to 798 ms with a midpoint SOA of 535 ms. As would be expected, a shorter (or longer) SOA gives the impression of a faster (or slower) creep of the "snake."

IV. DISCUSSION

Our findings can be compared with those in the literature on movement-based haptic illusions. Past research has shown that some signal parameters (e.g., duration, SOA) are more critical in eliciting an illusory movement than others (e.g., frequency, intensity). Compared to apparent motion and sensory saltation, it takes a relatively longer time to deliver the snake effect. The minimum duration needed for the snake effect, 1.69 s, is much longer than the pulse duration employed in eliciting the other two illusory movements. The average lower SOA threshold of 271.5 ms is on a par with the SOAs used in apparent motion and sensory saltation, but the upper threshold of 798 ms is much longer than those typically used in other movement illusions. Consequently, the speed at which the illusory snake crawls is much slower than that of the cutaneous rabbit or apparent motion. For example, Tan *et al.* (2003) used sensory saltation to draw straight lines on the back at a velocity of 67 cm/s (pulse duration = 26 ms, SOA = 50 ms, pulses per tactor =3, inter-tactor spacing = 10 cm) [8]. Sherrick & Rogers (1966) and Sherrick (1968) studied the optimal SOAs for apparent motion as a function of pulse durations on the thigh, and the illusory velocities estimated from their data range from 75 cm/s (maximum SOA = 265 ms for 400-ms pulses, minimum inter-tactor spacing = 20 cm) to 467 cm/s (minimum SOA = 75 ms for 25-ms pulses, maximum inter-tactor spacing = 35 cm) [28], [29]. More recently, Culbertson *et al.* (2018) used a much slower speed of 13.5 cm/s to simulate pleasant social touch [18]. In comparison, the fastest speed for the snake effect is 11 cm/s (minimum SOA = 271.5 ms, inter-tactor spacing ≈3 cm) and the slowest speed is 3.8 cm/s (maximum SOA = 798 ms). The slower movements that can be realized with the snake effect contribute towards a wider range of speed for movement-based illusions. Our original motivation was to find new movement illusions to expand the number of distinct haptic symbols that can be used in our tactile speech communication system. Given its vivid and creepy sensation, the snake effect can also be an effective way to enhance immersion and enjoyment in gaming, entertainment, and virtual and augmented reality systems. For example, the snake effect can be deployed to accompany image of a python slithering on a virtual arm, or to indicate an approaching enemy in a video game.

The SOA experiments reported in this article were based on a linear snake effect in that the illusory movement was along a straight line from the elbow to the wrist on the dorsal forearm. We also conducted some preliminary work to explore more complex movement trajectories such as a spiral wrapped around the forearm. The tactor array was expanded from 12 to 16 by forming 4 rings spread out between the elbow and the wrist, with each ring consisting of 4 equally-spaced tactors around the forearm. A spiral trajectory was defined on the surface of the forearm and successive stimulation points were defined along the intended movement trajectory. When a stimulation point fell between two adjacent tactors, the funneling illusion was employed to create a phantom location [25] [2]. In exploratory experiments, 300-Hz vibrations were modulated with a sine-squared envelope, and delivered to successive veridical or phantom tactor locations. Observers were able to feel movement trajectory and direction of the spiral snake effect, but had difficulty determining the starting and ending points of the stimulus. Although requiring further study, these preliminary results with the spiral snake effect have demonstrated the feasibility of extending the snake effect to arbitrary trajectories on the body surface. Further details can be found in the first author's Master's thesis [30].

V. CONCLUSION

We have presented a novel haptic illusion that we call the snake effect in this study. It is created by sending a sequence of overlapping vibratory pulses to multiple tactors, using amplitude modulation that gradually increases and decreases stimulus intensities (e.g., sine, sine-squared). The percept was that of a continuous movement despite discrete tactor locations and expansion and contraction of contact area rather than intensity variation, indicating that the snake effect is a perceptual illusion [2]. The psychophysical experiments conducted in the present study examined the range of SOA that optimizes a linear snake effect. Future work will explore the use of longer durations and their effect on the optimal SOA values for the linear trajectory, as well as determining stimulus properties for eliciting the effect in novel movement trajectories and directions. The display configuration can be expanded from the one-dimensional tactor array used in the present study to two-dimensional arrays. Other parameters to be investigated include the effect of vibratory amplitude, frequency (Culbertson *et al.* 2018 reported a creepy sensation using very slow indentations on the skin [18]), number of tactors, inter-tactor spacing, and whether the "snake" can cross the body midline. A better understanding of the snake effect will contribute to the repertoire of haptic movement illusions, thus leading to an increase in the amount of information that can be effectively transmitted through haptic devices.

ACKNOWLEDGMENT

The authors would like to thank Ali Israr, Emily Fredette, and Yang Jiao for helpful discussion and assistance with this project.

REFERENCES

[1] H. Z. Tan, S. Choi, F. W. Y. Lau, and F. Abnousi, "Methodology for maximizing information transmission of haptic devices: A survey," *Proc. IEEE Proc. IRE*, vol. 108, no. 6, pp. 945–965, 2020.

[2] S. J. Lederman and L. A. Jones, "Tactile and haptic illusions," *IEEE Trans. Haptics*, vol. 4, no. 4, pp. 273–294, Oct.-Dec. 2011.

[3] J. H. Kirman, "Tactile apparent movement: The effects of interstimulus onset interval and stimulus duration," *Percept. Psychophys.*, vol. 15, no. 1, pp. 1–6, 1974.

[4] J. H. Kirman, "The effect of number of stimulators on the optimal interstimulus onset interval in tactile apparent movement," *Percept. Psychophys.*, vol. 17, no. 3, pp. 263–267, 1975.

[5] F. A. Geldard and C. E. Sherrick, "The cutaneous 'rabbit': A perceptual illusion," *Science*, vol. 178, no. 4057, pp. 178–179, 1972.

[6] F. A. Geldard, *Sensory Saltation: Metastability in the Perceptual World.* Hillsdale, New Jersey, USA: Lawrence Erlbaum Associates, 1975.

[7] R. W. Cholewiak and A. A. Collins, "The generation of vibrotactile patterns on a linear array: Influences of body site, time, and presentation mod," *Percept. Psychophys.*, vol. 62, no. 6, pp. 1220–1235, 2000.

[8] H. Z. Tan, R. Gray, J. J. Young, and R. Traylor, "A haptic back display for attentional and directional cueing," *Haptics-e: Electron. J. Haptics Res.*, vol. 3, no. 1, p. 20, 2003.

[9] A. Israr and I. Poupyrev, "Tactile brush: Drawing on skin with a tactile grid display," *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, 2011, pp. 2019–2028.

[10] J. Park, J. Kim, Y. Oh, and H. Z. Tan, "The generation of vibrotactile patterns on a linear array: Influences of body site, time, and presentation mod," in *Proc. EuroHaptics*, 2016, pp. 47–56.

[11] G. Park, H. Cha, and S. Choi, "Haptic enchanters: Attachable and detachable vibrotactile modules and their advantages," *IEEE Trans. Haptics*, vol. 12, no. 1, pp. 43–55, Jan.-Mar. 2019.

[12] C. M. Reed *et al.*, "A phonemic-based tactile display for speech communication," *IEEE Trans. Haptics*, vol. 12, no. 1, pp. 2–17, Jan.-Mar. 2019.

[13] H. Z. Tan *et al.*, "Acquisition of 500 english words through a tactile phonemic sleeve (taps)," *IEEE Trans. Haptics*, vol. 13, no. 4, pp. 745–760, Oct.-Dec. 2020.

[14] J. S. Martinez, H. Z. Tan, and C. M. Reed, "Improving tactile codes for increased speech communication rates in a phonemic-based tactile display," *IEEE Trans. Haptics*, vol. 14, no. 1, pp. 200–211, Jan.-Mar. 2021.

[15] J. Fröhner, G. Salvietti, P. Beckerle, and D. Prattichizzo, "Can wearable haptic devices foster the embodiment of virtual limbs?," *IEEE Trans. Haptics*, vol. 12, no. 3, pp. 339–349, Jul.-Sep. 2018.

[16] A. Haans and W. A. IJsselsteijn, "The virtual midas touch: Helping behavior after a mediated social touch," *IEEE Trans. Haptics*, vol. 2, no. 3, pp. 136–140, Jul.-Sep. 2009.

[17] M. Bianchi *et al.*, "Design and preliminary affective characterization of a novel fabric-based tactile display," in *Proc. IEEE Haptics Symp.*, 2014, Art. no. 591596.

[18] H. Culbertson, C. M. Nunez, A. Israr, F. Lau, F. Abnousi, and A. M. Okamura, "A social haptic device to create continuous lateral motion using sequential normal indentation," in *Proc. IEEE Haptics Symp.*, 2018, pp. 32–39.

[19] H. Seifi and K. E. MacLean, "A first look at individuals' affective ratings of vibrations," in *Proc. IEEE World Haptics Conf.*, 2013, pp. 605–610.

[20] J. Mullenbach, C. Shultz, E. Colgate, and A. M. Piper, "Exploring affective communication through variable-friction surface haptics," in *Proc. SIGCHI Conf. Human Factors Comput. Syst.*, 2014, pp. 3963–3972.

[21] G. Huisman, "Social touch technology: A survey of haptic technology for social touch," *IEEE Trans. Haptics*, vol. 10, no. 3, pp. 391–408, Jul.-Sep. 2017.

[22] P. Beckerle *et al.*, "Feel-good robotics: Requirements on touch for embodiment in assistive robotics," *Front. Neurorobot.*, vol. 12, no. 84, 2018.

[23] A. Israr and I. Poupyrev, "Exploring surround haptics displays," *CHI'10 Extended Abstr. Hum. Factors Comput. Syst.*, 2010, pp. 4171–4176.

[24] S. Bensmaïa, M. Hollins, and J. Yau, "Vibrotactile intensity and frequency information in the pacinian system: A psychophysical model," *Percept. Psychophys.*, vol. 67, no. 5, pp. 828–841, 2005.

[25] G. von Békésy, "Funneling in the nervous system and its role in loudness and sensation intensity on the skin," *J. Acoustical Soc. Amer.*, vol. 30, no. 5, pp. 399–412, 1958.

[26] L. A. Jones and H. Z. Tan, "Application of psychophysical techniques to haptic research," *IEEE Trans. Haptics*, vol. 6, no. 3, pp. 268–284, Jul.-Sep. 2013.

[27] H. Levitt, "Transformed up-down methods in psychoacoustics," *J. Acoustical Soc. Amer.*, vol. 49, pp. 467–477, 1971.

[28] C. E. Sherrick and R. Rogers, "Apparent haptic movement," *Percept. Psychophys.*, vol. 1, no. 3, pp. 175–180, 1966.

[29] C. E. Sherrick, "Bilateral apparent haptic movement," *Percept. Psychophys.*, vol. 4, no. 3, pp. 159–160, 1968.

[30] F. M. Q. Severgnini, "Snake effect: Investigation of a novel haptic illusion," Master's thesis, School Elect. Comput. Eng., Purdue Univ., West Lafayette, IN, USA, May 2018.