Basic Properties of Phantom Sensation for Practical Haptic Applications

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Abstract. Phantom sensation (PhS) is a pseudo-tactile sensation that occurs when two or more mechanical or electrical stimuli are presented simultaneously to the skin. PhS has two well-known characteristics. First, the location of PhS can be changed by changing the strength of stimuli. Second, the intensity of stimulation can influence the resulting PhS. This illusion has the potential to greatly reduce the number of stimulators required in wearable tactile interfaces. Although it has been shown that PhS is perceived more clearly with shorter pulses, currently only rough quantitative evaluation has been performed. In addition, the subjective qualities of the sensation have not previously been examined. We first summarize the basic characteristics of PhS, including the relationship between the duration of stimuli and the clarity of the illusion.

Keywords: Phantom sensation, funneling illusion, tactile illusion, haptic I/O and tactile display

1 Introduction

Two major problems are inherent in the development of tactile displays. First, tactile receptors are distributed over the entire body. Second, it is difficult to stimulate tactile receptors from remote locations, typically requiring physical contact. As such, most tactile displays designed to present spatially specific tactile stimulation have been composed of dense pin arrays activated by small actuators.

However, apparatus involving numerous actuators directly contacting the skin are typically bulky and complex. Moreover, these systems are generally costly, making them inappropriate for many research settings. The necessity of numerous actuators directly contacting the skin requires a large array of wire harnesses, further reducing the practicality of these systems.

One potential solution to this problem involves the use of a tactile illusion called 'phantom sensation' (PhS). PhS was initially discovered by von Bekesy as a form of 'funneling' illusion [1] (Fig.1), and is an illusory tactile sensation that arises between two points of simultaneous vibration or electric stimulation [2] [3]

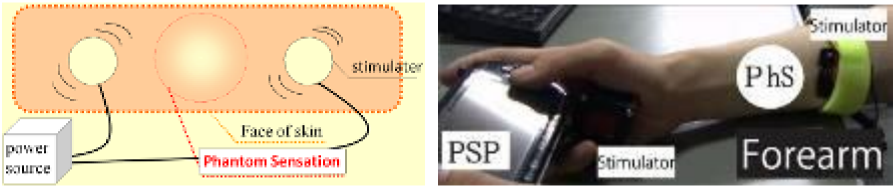

Fig. 1. PhS is induced by tactile stimuli in two locations. The location in which PhS is experienced is determined by the ratio between the strength of the two stimuli. The image on the right shows an example of one potential application of PhS. This system stimulates the palm and forearm, in conjunction with a handheld videogame. PhS can be elicited at any location of the forearm with a very simple setup, and could be used to produce tactile sensations as part of a videogame.

The subjective strength and clarity of the illusory sensation in comparison to the sensation of the two actual stimuli, is dependent on the duration of the actual stimuli. If constant stimulation is applied, PhS becomes relatively weak compared with the actual stimuli. Stimuli of a short duration, on the other hand, produce a stronger PhS and a weaker perception of the two actual stimuli.

Following von Bekesy's initial report, many studies have examined the basic properties of PhS. Several studies have shown that the position and strength of the illusory sensation can be controlled by changing the strength ratio of the actual stimuli [2] [3] [4] [5] [6] [7] [8] (Fig.1 (left)).

Fig.1 (right) shows our exploratory study of a novel application of PhS, aiming to test the use of PhS in conjunction with portable gaming devices including PSP and iPhone.

We used tactile stimulators on the palm and forearm to generate PhS at an arbitrary position on the forearm. This method enabled the subjective sensation of game characters and objects 'dancing' on the arm of the gamer. The ability to adjust and quantify the position, strength, and 'clarity' of the PhS are necessary elements of such a system. We defined the 'clarity' of the PhS as the ratio between the strength of the sensation of the experienced PhS, and the sensation of the two real stimuli.

(clarity) = (PhS strength) / (real stimuli strength)

We adjusted two stimulation parameters and examined their effects. The first parameter was the duration of stimulus presentation. It has been previously established that stimuli of shorter durations generate clearer sensations[1]. However, no previous research has examined the effects of the duration of the resting period between the stimulus pulses on the clarity of repeated stimulation. The present study evaluated the effects of rest-period duration on PhS, allowing the selection of appropriate stimulus durations.

The second parameter in question was the spatial location of stimuli. It was previously established that a large distance between the stimuli could cause the location of the experienced PhS to become ambiguous. Therefore, we tested the effects of an additional third stimulator between the original two stimulators. Previous work has shown that two-dimensional arrangements of three or more identical stimuli can generate a PhS in the center of the array[4]. However, it is unclear how PhS is affected by differences in the stimuli. In addition, the effect of a single stimulus on the PhS generated by the other two is not well understood. This knowledge will enable the design of systems with an appropriate spatial distribution for producing a PhS with the desired properties.

We conducted three experiments. The first was conducted to confirm that our system generated a PhS, and to evaluate the basic properties of the illusion induced by our setup. The second experiment evaluated the relationship between the duration of the rest interval of the stimuli and the clarity of PhS induced. The third experiment evaluated three stimulus paradigms.

2 Methods

2.1 Set up

We presented PhS induction stimuli to the left forearm. Mechanical vibration was used as tactile stimulation. We asked participants to place their forearm onto two stimulators. (Fig. 2)

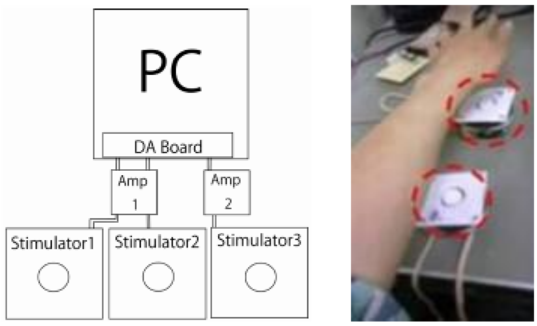

Fig. 2. System setup: PhS was generated by using two stimulators (audio speakers). In the third experiment, we used three stimulators.

The distance between two stimulation points was 130 mm (based on previous work [2])

We used audio speakers as vibrating stimulators (ES-06603/8Ω MAX14W, S.J). A contactor (ABS plastic, Φ20 mm) was attached to each speaker. As the maximum amplitude of vibration was 2 mm, the contactor was set 2 mm higher than the edge of the speaker, so that it continuously contacted the skin during stimulation.

Our system output tactile stimulation controlled by a waveform generated by a D/A board (PCI-3523A, Interface Corp.; Fig. 2). We used headphones to play white noise to mask the sound of the vibration stimulators.

2.2 Waveforms for Stimulation

Because PhS is not generated by static pressure, and constant vibration induces only very weak PhS, we used pulse wave stimulation like that shown in Fig. 3 to maintain a clear PhS. The pulse width was fixed to 5 ms (based on preliminary testing), while the amplitude and cycle were varied as experimental manipulations.

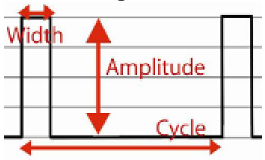

Fig. 3. Waveform for stimulation. The width was fixed to 5 ms; amplitude and cycle were manipulated experimentally.

3 Experiments

3.1 Experiment 1: Basic properties of PhS with different types of pulse stimulation

Experiment 1 was conducted to confirm that our experimental setup could generate PhS on the forearm. We measured basic aspects of the experience of PhS, including location and strength. In addition, we tested the effects of varying spatial and temporal aspects of the tactile induction stimuli.

An LCD monitor was located on the right side of the left forearm and a visual representation of the PhS was displayed, in the form of square (a 'PhS image'; Fig. 4) Participants could move and resize three squares using horizontal scroll bars on the right side of the screen.

Participants were asked to indicate the position and size of any PhS experienced, by moving and resizing the white square on screen for PhS, and purple squares for real stimulations. They submitted responses pressing a button. Participants were also asked to indicate the strength of experienced PhS from 0 to 100 using a moving scale bar. A rating of 100 represents the subjective strength of the sensation of a single stimulator driven with 100% amplitude. A rating of 0 indicates that no tactile stimulation was perceived. Pulse cycle and width were fixed to 1,000 ms and 5 ms respectively.

In the first test, the amplitude of the two stimuli was changed from 12.5% to 100% of the maximum stimulation strength, while the PhS size and strength were measured separately. In the second test, the ratio of the amplitude of the two stimuli was changed from 0.125 to 8, and PhS position was measured. Each participant completed five trials. The 100% amplitude was set by each participant so that they could perceive PhS easily and reliably. In the second test, the larger amplitude was set to 100%. For example, if the ratio of two amplitudes was 8.0 or 0.125, the larger amplitude was set to 100%, while the smaller amplitude was set to 12.5%. Participants were three adults familiar with PhS. (22-23 years old, all males)

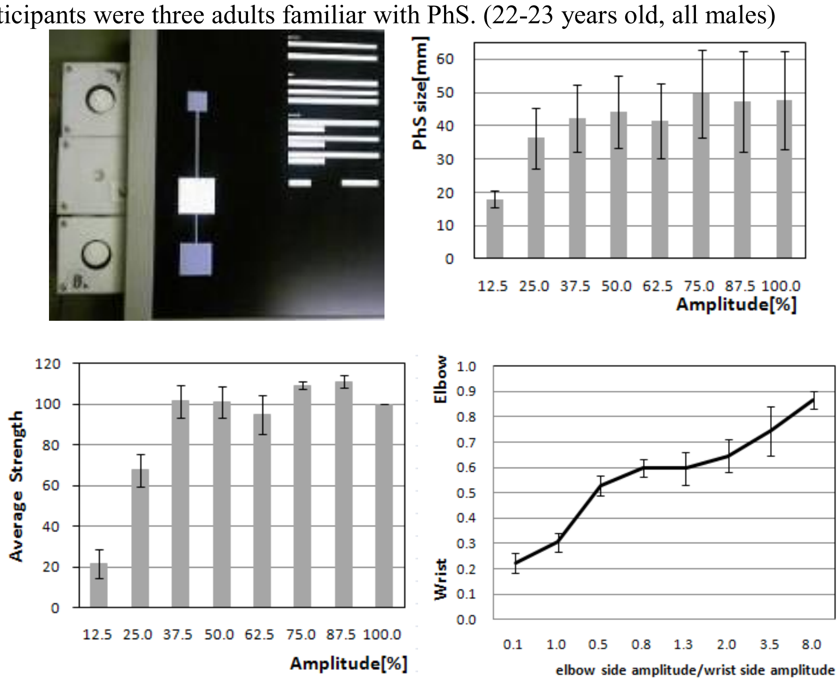

Fig. 4. Upper left: Experimental setup. Upper right and lower left: PhS size and strength as a function of amplitude. Lower right: PhS location as a function of the ratio of the two actual stimuli strength. Each vertical bar represents the standard error. All participants gave similar answers in all three experiments.

As shown in Fig. 4, the location and strength of PhS indicated by tactile image adjustments changed in response to changes in the ratio and amplitude of the stimuli, which are well known from previous researches.

Interestingly, we found that the 'size' of the experienced PhS was altered by changes in stimulus strength (Fig. 4, top right). To the best of our knowledge, this change in the subjective size of PhS has not been reported in any previous studies. We instructed participants to distinguish size and clarity. However, the upper right and lower left graphs are similar in shape, indicating that participants might not be able to distinguish between size and clarity.

3.2 Experiment 2: Change in PhS clarity with change in Pulse Cycle

It has been previously shown that constant stimulation can generate a constant PhS, but because actual input stimuli are also perceived, this can result in a relatively ambiguous PhS experience. The trade-off between continuity and clarity has not yet been explored quantitatively.

To this end, we changed continuity by using different cycles. We used stimulation of 100, 50, 5, 2, and 1 pps (pulses per second). The pulse width was fixed to 5 ms. We calibrated and fixed amplitudes for each participant so they could perceive PhS easily and reliably.

Participants responded according to the strength of the PhS they experienced, and the strength of the two real stimuli, using the same setup as in Experiment 1.

Participants were three adults familiar with PhS. (22-23 years old, all males). Five trials were conducted for each stimulation type. The results are shown in Fig. 5.

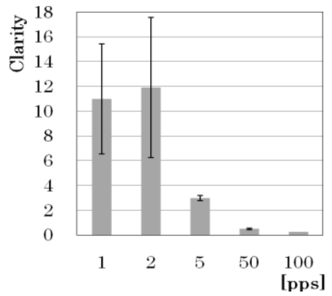

Fig. 5. Clarity of experienced PhS as a function of pulse cycle. Vertical bars represent standard error. All participants gave similar answers in this experiment. There is a statistically significant difference between 2pps and 5pps ($p<0.05$).

Our results clearly showed that stimulation over 5 pps produced an ambiguous PhS. To the best of our knowledge, this is the first quantitative report of a relationship between continuity and clarity in the PhS. This result indicates that stimulation under 5 pps should be used in systems designed to induce PhS.

3.3 Experiment 3: PhS induced by three stimulators.

Previous work has shown that three or more stimulators arranged in a two-dimensional space can generate a single PhS at the center of the stimulator set, and enable it to move in the triangular area formed by three stimuli [3] [4] [7]. However, no study has examined the generation of PhS with three or more stimulators in a straight line.

In our third experiment, we tested the effects of three stimulators arranged in a straight line. We hypothesized that this setup would either generate two PhSs, or would produce a single PhS. We investigated this issue because such an ambiguous situation is likely to arise in practical applications of PhS involving the use of multiple stimulators simultaneously. As demonstrated by the second experiment, the clarity of PhS can be changed by the continuity of the stimuli. Therefore, we used two types of stimuli: a continuous 120 Hz sine wave (referred to as 'sine mode'), and a 5 ms pulse with 1,000 ms cycle (referred to as 'pulse mode'). We calibrated amplitudes for each participant so they could perceive PhS easily and robustly. We prepared four combinations as follows.

(1) All stimulators driven by sine mode. (mode: sin-sin)
(2) Two terminal stimulators driven by sine mode, and one central stimulator driven by pulse mode.(mode:sin-pul)

(3) Two terminal stimulators driven by pulse mode, one central stimulator driven by sine mode.(mode:pul-sin)
(4) All stimulators driven by pulse mode.(mode:pul-pul)

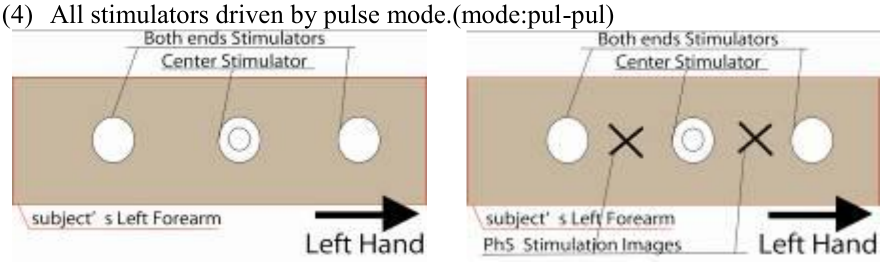

Fig. 6. Experiment 3 setup. Right figure shows a 'divided' tactile image.

Initial testing revealed that participants reported four types of tactile sensation:

Augmented: Augmented PhS felt at the central stimulator.

Blended: PhS sensation and real sensation of central stimulator mixed at the central stimulator.

Divided: Two PhSs perceived between the two pairs of stimulators.

Lost: No PhS elicited.

Participants were three adults familiar with PhS (22-23 years old, all male). The trials were conducted ten times for each combination. Participants were asked to categorize the sensation they experienced as Augmented, Blended, Divided, or Lost for each trial. The results are shown in Fig. 7.

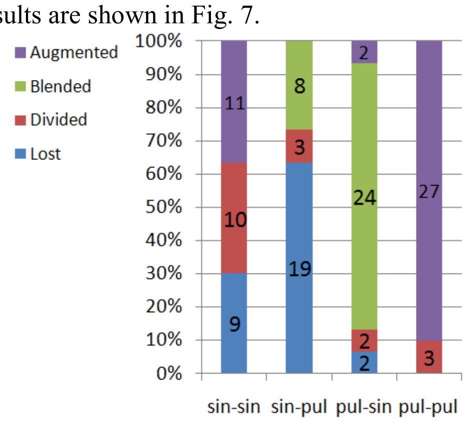

Fig. 7. Percentage of reported sensation types, sorted into combinations. The number on each column indicates the total number of answers. All participants experiments. The number on each column The results showed statistically significant differences (χ^2 test, $p<0.01$).

When the two terminal stimulators were driven in sine mode (sin-sin and sin-pul), responses were highly variable and inconsistent, implying that PhS generated by terminal stimulators was vague and difficult for participants to categorize.

When the two terminal stimulators were driven by pulse mode (pul-sin and pul-pul), responses were more consistent. This was likely due to pulse stimuli inducing stable PhS. Interestingly, the central stimulator in sine mode clearly induced a 'blended' sensation of sine wave and pulse stimuli.

4 Conclusion

This study examined the effects of temporal and spatial properties of stimulation on the clarity of subjectively experienced PhS, in an attempt to aid the development of practical applications for the tactile illusion.

In terms of the temporal aspects of PhS, we revealed that the clarity of PhS is drastically reduced when pulse stimuli are presented at a frequency higher than 5 pps. Clarity in our paradigm was defined as a ratio of subjective strength between the sensation of PhS and the sensation of actual tactile stimuli.

Regarding the spatial aspects of PhS, the fusion of the experience of real stimuli and PhS occurred only when two terminal stimuli were presented as pulses. This finding is consistent with previous research. However, we also reported a novel way of 'blending' PhS pulses and sinusoidal stimuli (pul-sin). We propose that the development of a tactile display composed of a central 'shape' display and a peripheral 'impulse' display may have practical applications.

Having summarized the temporal and spatial features of PhS, we now hope to apply our findings in the development of a portable tactile stimulation device.

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