FOREHEAD PHANTOM SENSATION SUGGESTS THAT PHANTOM SENSATION IS AFFECTED BY VISUAL FEEDBACK AND PERCEIVED RISK AND ACCOMPANIES INCREASE IN TACTILE SENSITIVITY

A Thesis

by

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ABSTRACT

Phantom sensations are frequently seen in amputees, and occur in some mental disorders like Alzheimer's and Parkinson's disease. Despite their common occurrence, there are several complicating factors that make it difficult to elucidate the underlying cause of the phantom sensation. The brain often undergoes complex neural reorganization after limb damage, and some neurological diseases like Parkinson's degenerate and destroy the nerves themselves. In addition, the symptoms often appear sporadically and present differently among different patients, making it difficult to work with in a clinical environment and presenting challenges for data collection. All of these factors make it difficult to derive a robust theoretical model to explain the phantom sensation. A way to easily evoke the phantom sensation in a healthy-bodied subject would make it much easier to determine its mechanism, which would help lead us towards developing a cure. In this work, we propose a simple test to evoke the phantom sensation. A sharp pencil moving towards a subject's forehead, but not touching it, can create a tactile hallucination. The tactile hallucination can also be created entirely through virtual reality, with no physical contact. In our experiments, we found that this sensation is created by visual feedback, is directly correlated to the perceived risk of the moving object, and even measurably influences the subject's tactile sensitivity. We use this information to propose an addition to the standard sensorimotor model that can explain these phantom sensations.

DEDICATION

To my mother and father.

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Contributors

This work was supervised by a thesis committee consisting of Dr. Hangue Park, Dr. Yang Shen, and Dr. Paul Gratz of the Department of Electrical and Computer Engineering and Dr. Jeongehee Kim of the Department of Engineering Technology and Industrial Distribution.

The initial experiment design and IRB proposal was written by Ziqi Zhao. The virtual reality environment used in the experimental tests was created by Dr. Jeonghee Kim.

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CHAPTER I

INTRODUCTION

Phantom sensations often accompany an extreme level of physical and psychological distress and are hard to overcome even with intense physical and psychological therapy, as in the example of phantom limb sensation or phantom pain after amputation of the limbs [1]. The issues of phantom sensations are not limited to the cases of limb amputation. Neurodegenerative diseases often create phantom sensations. For example, people with Alzheimer's disease often feel like they are floating in the air [2], and more than half of the people with Parkinson's experience visual, auditory, olfactory, or tactile hallucinations [3]. Fig. 1 describes the known cases of phantom sensations. Although these kinds of phantom sensations significantly lower people's quality of life, available solutions to this problem are fairly limited. For example, drugs and anesthetics are only temporarily effective in treating the phantom pain [4,5]. A novel treatment method currently being tested is mirror therapy - showing amputee patients a reflection of an intact limb where their amputated limb used to be, in order to provide them with a visual scene of original body organization [6]. While this treatment has shown promise in certain trials, its effectiveness on a wide spectrum of patients is still inconclusive [7]. In general, there is no proven effective treatment yet for uncomfortable phantom sensation or phantom pain.

The biggest reason for the lack of effective treatment is perhaps the lack of an analytical model that can interpret the formation of the phantom sensation. The current interpretation of the phantom sensation is mostly qualitative. Most of the investigations of the phantom sensations have been built on self-reported data from subjects [4]. While the subjective rating can provide insight, it can be difficult to elucidate the underlying cause creating the sensation because the patients can only see its end results. Brain-imaging studies such as fMRI have been used to explore the origin of the problem, and show that sensory areas corresponding to amputated limbs are often transferred to different areas of the brain after the limb is removed [8]. The most popular current theory, at least for phantom pain in amputees, is the “remapping hypothesis” - the brain wants to preserve its internal proprioceptive mapping of the body, and when one part of the body is removed, the brain rearranges itself via neuroplasticity to re-map that proprioception to a different part of the body - such as re-mapping the feeling in a subject’s thumb onto his cheek [9]. Such a subject might then experience phantom limb pain originating on his cheek. But another proposed explanation that is consistent with the brain-imaging data is that the brain wishes to preserve its full functional ability - it is not seeking to have a complete body map, but to have a full sensory ability [10]. Brain-imagery studies are thus useful, but cannot still elucidate the origin of phantom sensations because it cannot cover the whole sensorimotor loop of the phantom sensation. To design a therapeutic solution to overcome the phantom sensation, understanding its underlying principle is necessary. Without clarifying the principle of generation of phantom sensation, the promise of addressing those undesirable phantom sensations will remain uncertain.

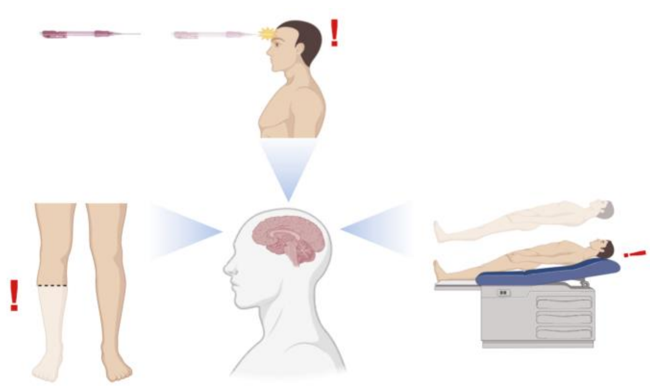


Figure 1: Phantom sensation in amputated limbs, forehead sensation, and floating hallucination in Alzheimer's.

The question then is to find a model that can be used to explain the phantom sensation theoretically. One of the best candidates for this is the well-tested comparator model for sensorimotor behavior. The comparator model explains the creation of perception as the difference of two inputs - sensory signals from the body, and the internal model stored in the cerebellum [11-13]. The internal model is a predicted or anticipated sensorimotor outcome, built over years of the body's experience with similar actions [14]. When a sensorimotor action seems imminent, the brain recalls the summation of its prior experiences with similar phenomena, saved as an internal model, and creates a copy of it (known as an efference copy). The body compares the efference copy to the real-world sensory feedback it is receiving, and the error between the two is used to update the next prediction. In this way, the error term should ideally converge towards zero in a Bayesian fashion, each prior situation informing the next, as the body's prediction eventually matches the reality of the situation.

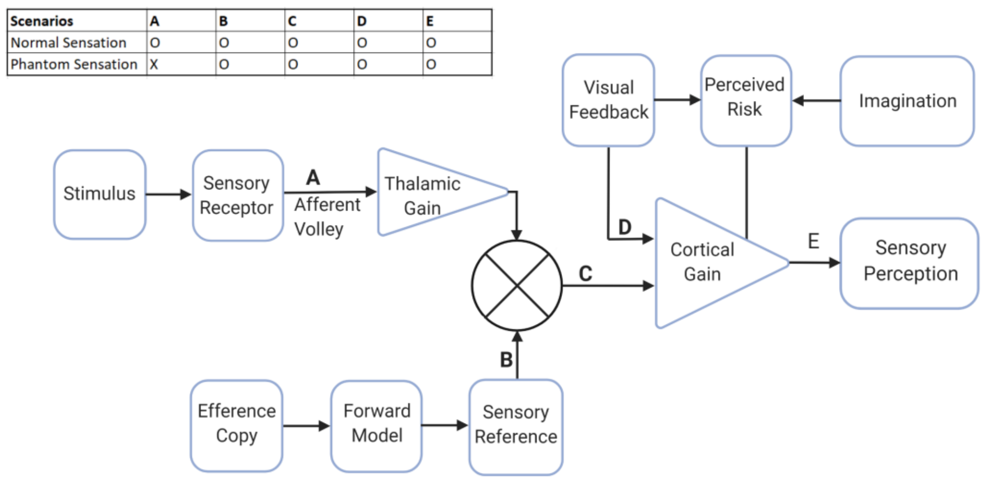
This sensorimotor model has been advanced as a possible explanation for phantom sensations in the case of missing limbs. The theory is that a subject may try to move their limbs, sending a motor signal and generating an efference copy to predict its outcome. However, there is no real-world feedback coming from the missing limb. The subject then just feels the sensory reference signal alone as a phantom sensation [15].

The sensory reference is updated based on the error between the sensory reference and the actual sensory feedback. Based on the comparator model, the phantom sensation can potentially be explained by the change of the sensory reference, as the actual sensory feedback is inactive without physical interaction [16]. However, considering that the sensory reference is known to change slowly by accumulation of experience [17-19], the concept of changing sensory reference needs to be tested very carefully in multiple conditions.

It is well known that the neural stimuli generated by the physical interaction is not the only way to evoke or modulate perception. For example, people sometimes feel sensation just by watching others and being assimilated to others' situations, which is currently understood as a process of mirror neurons replicating the conditions using visual information [20]. The most general example of modulating sensory perception is perhaps the sensory modulation by the cognitive involvement. Multiple human studies suggest that the sensitivity in human sensory modalities (*e.g.*, visual feedback, tactile feedback) changes according to the cognitive involvement (*i.e.*, concentration or distraction) on that sensory modality [16,21]. In case of the hand reaching movement, hands become more sensitive when they reach towards the object than when their hands are approaching to the object [22]. Distraction using the virtual reality environment can decrease tactile sensitivity [16]. As every form of sensory feedback except olfactory is delivered to the somatosensory cortex via the thalamus, the cognitively-driven synaptic gain at the thalamus can change the sensory perception [23,24]. However, the change in interstage gain at the thalamus may not be proper to explain the phantom sensation, because the source of the phantom sensation is still vague with the lack of physical interaction between the body and the external world.

Therefore, we propose an addition to the traditional sensorimotor model to explain phantom sensations. Our model replaces the comparator of the model with a mixer, and adds in an additional cortical gain stage to the output of that mixer. The mixer allows us to explain perception output from a single sensory reference input, instead of requiring two inputs to make a sensical output with a comparator. Although the comparator model is more common, some existing sensorimotor models do incorporate a mixer [15]. Also, the growing body of evidence exploring and verifying cortical gain [25] merits its inclusion into the model. While the thalamic gain alone does not adequately explain the creation of the phantom sensation, the inclusion of the cortical gain block can provide an explanation. Small changes in the sensory reference can be magnified into a very noticeable perception by the cortical gain.

As the generation of the phantom sensation is a heavily psychological process and there are even cases of purely psychological phantom sensations [26], we also employed a psychological factor on the formation of the phantom sensation. We especially focus on the effect of the perception of risk, as the risk notification would be one of the most important tasks for sensory signaling. Some amputee patients have reported that they have phantom sensations as if their missing limb is positioned with the posture at the event of limb damage, and the phantom pain grows stronger when the other limb is positioned with a similar posture. It has been hypothesized that this is a way for the body to avoid repeating whatever "risky" behavior it believes, to minimize the possibility of losing the other limb [27]. Fig. 2 shows a conceptual model to explain the generation of the phantom sensation. As shown in the model, we will take the perception of risk into account, along with the change in sensory reference, in interpretation of the resulting phantom sensation.



Scenarios	A	B	C	D	E
Normal Sensation	O	O	O	O	O
Phantom Sensation	X	O	O	O	O

Figure 2: Sensorimotor model of phantom sensation

To investigate the principles of the forehead phantom sensation, we tested three hypotheses in this study. *The first hypothesis* of this study is that visual feedback of an object approaching the forehead will evoke the phantom sensation on the forehead without any physical interaction. As physical objects close to the forehead may have a tiny physical effect from air flow or touching the hair on the forehead, we employed virtual reality that is completely free from physical interaction. *The second hypothesis* of this study is that the forehead phantom sensation will be augmented by the perceived risk. We intend to identify the effect of perceived risk on the phantom sensation. The rationale is that, since the sensation is generated via psychological process, creating a stronger psychological factor will amplify this feeling. *The third hypothesis* of this study is that the phantom sensation evoked on the forehead will change tactile sensitivity on the forehead. As suggested by the block diagram in Fig. 2, the actual sensory feedback and the phantom sensation will interact with each other at the central nervous system (CNS), and therefore we expect the reciprocal effect between each other.

CHAPTER II

EXPERIMENTAL DESIGN

Unfortunately, the experimental investigations of the principles of phantom sensation has been limited, and it is hard to test the hypotheses over the phantom sensation. For example, even though the amputation of the limbs often evokes the phantom sensation, it is hard to consistently and repeatedly evoke it. Also, complex neural reorganization occurs after the limb amputation, which further hampers the investigation of the principle of the phantom sensation [28]. Hallucination or illusory perception in people with neurodegenerative diseases, which is another circumstance of the phantom sensation, is also difficult to be consistently evoked in a research environment, because the on-going neural changes and following symptoms of neurodegenerative diseases complicate the generation of the phantom sensation. Heavily psychological phantom sensations, such as strong tactile feedback caused by specific visual scenes and innate fear, depend too much on psychological factors and do not work consistently in a research environment [29].

To address the limitations in investigating the principles of the phantom sensation, we propose to use the forehead sensation, which is a visually-evoked phantom sensation on the forehead by an object approaching towards the forehead. There have been intense discussions about this kind of 'weird feeling' on the forehead in several different online forums, such as Quora, Reddit-ELI5, and AboveTopSecret. This sensation is generally described as a tingling sensation in the middle of the forehead when a pointed object, such as a pencil, is approaching the forehead [30]. This sensation is also known to be evoked very consistently and repetitively with minimal adaptation. Therefore, we can test multiple interventions in evoking the phantom sensation. This forehead phantom sensation cannot fully explain the phantom sensation, as the principles of the phantom sensation varies. However, it would be important to learn insight to the phantom sensation, using the experiment-friendly phantom sensation.

The experiments in this study were performed in accordance with relevant guidelines and regulations, according to the procedure described in the protocol approved by the Institutional Review Board of Texas A&M University (IRB2018-1497D). Informed consent was collected from all subjects. Nine healthy human subjects with no history of neurological disorders participated in the experiments in this study. The subject group consisted of two females and seven males. All subjects were over the age of 18, and the age of subjects was ranged from 20 to 40.

To determine the efficacy of each intervention, Welch's Anova test was performed at the 95% confidence level, to conduct a robust statistical test not to be affected by any small difference in variances. To verify that the data satisfies the prerequisites for Welch's Anova, we tested normality of data distribution using the Kolmogorov-Smirnov test of normality. All datasets satisfied the condition of $p>0.05$ and normality could be assumed. We also applied Bonferroni correction, and then used $p<0.05$ as the condition for statistical significance.

The pencil we used for the test was a standard mechanical pencil with a thin lead. It was made of steel and was 14.3 cm long. The sharp lead for the pencil was 0.7mm in diameter and extended to 30mm from the tip of the sharp pencil. The eraser stick used were standard ones with a refillable eraser lead. It was made with plastic and was 12.7mm long. The eraser lead was 9mm in diameter and their rubber portion was extended to 30mm long from the tip of the eraser stick.

The virtual reality (VR) headset used was an Oculus Rift, which was connected to a Dell XPS 15 7590 laptop, and the VR program was launched through the laptop. The VR program used was created in Unity, modeling both a pencil and an eraser that could move in an empty room. The pencil and eraser were designed to sit at the subject's eye level and point roughly at the top of their nose. The pencil and eraser were modeled to look similar to the real-life pencil and eraser that we were using. In the experiment, the program was executed and ran on a Windows laptop PC. The operator could move the virtual eraser forward (where the subject would perceive it as coming closer towards their forehead) with speeds of 15 cm/s (slow speed) or 45 cm/s (fast speed).

The subjects were asked to take a seat in an office chair in the laboratory. The operator then turned the chair for the subjects to face against a white wall in the lab. They were asked to maintain good upright posture during the entire experiment. Before the experiments began, subjects were also introduced to the Likert scale that was being used to evaluate the subjects' perception. The grading standard was a level from one to ten, one being feeling nothing at all and five as clear sensation, while the sensation increases as the number becomes larger. If the sensation was too strong and disturbing, subjects were instructed to select a level from six to ten, with ten being extremely disturbing.

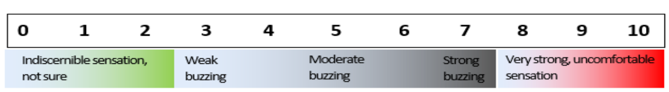


Figure 3: Likert scale used in the subject trials

The 1st experiment was designed to test the 1st and 2nd hypotheses that "visual feedback of the object approaching the forehead will evoke the phantom sensation on the forehead without any physical interaction" and "the forehead phantom sensation will be augmented by the perceived risk".

To test the 1st hypothesis, we compared subjects' subjective perception on the forehead for three different conditions of the object approaching the forehead: eyes open with an eraser stick approaching vertically, eyes closed with an eraser stick approaching vertically, and virtual reality with a virtual eraser stick approaching vertically, at fast speed. The operator or virtual reality program moved the object from a distance of approximately 45cm steadily over 1 second (~45 cm/s). The operator or virtual reality program then stopped the object at about 5mm distance from the forehead, clearly before physical contact was made, and took it away from the forehead. In open-eye or virtual reality conditions, subjects were asked to focus on the object moving towards them, as shown in Figs. 3a and 3b. In a closed-eye condition, subjects were asked to close their eyes when told by the experimenter, and the operator gave a verbal 3-second countdown before the tests ("3, 2, 1, go"), and asked to open their eyes after the object was taken away from the forehead. All subjects were asked to report the forehead sensation on a Likert scale right after the object was taken away from the forehead.

To test the 2nd hypothesis, the experiment was repeated with eyes open and changing object sharpness and approaching speed. First, the eraser stick was changed to a sharp pencil with 30mm sharp lead, as a sharper physical object will augment the perceived risk. Second, the approaching speed was changed from fast to slow speed, as the slow speed will decrease the perceived risk. The speed was decreased to 1/3 of the fast speed, as moving the object from a distance of 45cm steadily over 3 seconds (~15 cm/s).

The conditions of the test are summarized in the table below. For data integrity, all conditions were applied in a random order using a random number generator and twice consecutively per condition. Between each test, subjects were told to wait and relax for 60 seconds, to minimize the habituation or adaptation of the nervous system to the forehead stimulus.

Test Name	Trial 1 Score	Trial 2 Score
Open Eyes - Nothing		
Open Eyes - Real Pencil - Fast speed		
Open Eyes - Real Eraser - Fast speed		
Open Eyes - Real Pencil - Slow speed		
Open Eyes - Real Eraser - Slow speed		
Closed Eyes - Real Eraser - Fast speed		
Virtual Reality - Eraser - Fast speed		
Sensitivity with VR - Pencil - Slow speed – measure the force threshold (g)		

Figure 4: The Likert-scale form used to evaluate subject's perception on the forehead

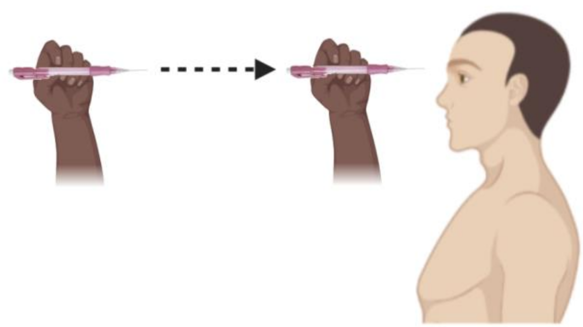


Figure 5: Mechanical pencil moving towards a subject's forehead

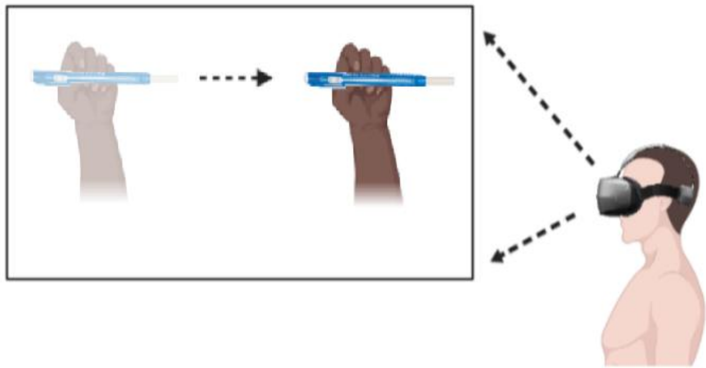


Figure 6: Virtual eraser stick moving towards a subject's forehead

The 2nd experiment was designed to test the 3rd hypotheses that "the phantom sensation evoked on the forehead will change tactile sensitivity on the forehead". Subjects were asked to wear the VR headset, and wear a hairband to pull the hair back and expose their forehead. While subjects were looking at a static image in the VR headset - just showing a wall - the operator conducted a standard Von Frey hair test to determine their tactile sensitivity on the forehead. The Von Frey hair test was conducted using 0.08g as a default force, increased the force step by step if subjects reported no hair touching their forehead, and decreased the force step by step if subjects reported a hair touching their forehead. The procedure was repeated until the operator found the minimum force evoking the tactile feedback on the forehead. The Von Frey hair was applied to the subject's forehead at random timing and was not applied sometimes, so that subjects could not report the hair touching their forehead by expectation. The experiment was then repeated with the virtual eraser approaching to the forehead. For data integrity, each test condition was repeated twice consecutively, with 60 second intervals in between.

CHAPTER III

EXPERIMENTAL RESULTS

We compared the intensity of forehead sensation according to the conditions of visual feedback, among three different conditions: open-eyes with physical object, virtual-reality condition with virtual object, and closed-eyes with physical object. Intensity of forehead sensation was measured as 3.70±0.47 and 2.70±0.47 for physical object and virtual reality, respectively, with the eraser stick used for both conditions. The intensity of forehead sensation was not different between the cases of open eyes and virtual reality ($p=0.152$). For the same condition of physical object, intensity of forehead sensation was measured as 3.70±0.47 and 0.10±0.10 for open-eyes and closed-eyes, respectively, with the same eraser stick used for both conditions. The intensity of forehead sensation was significantly decreased by closing the eyes ($p<0.001$).

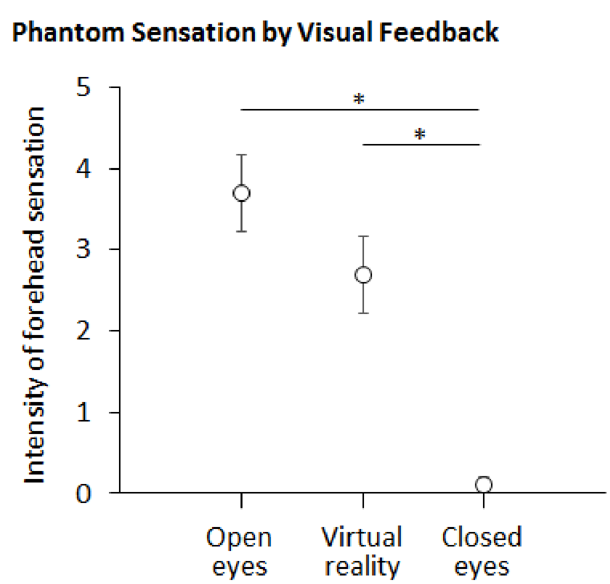


Figure 7: Phantom sensation evoked by the physical or virtual eraser stick approaching to the forehead. Three conditions of visual feedback were tested: open-eyes with physical object, virtual-reality condition with virtual object, and closed-eyes with physical object.

We compared the intensity of forehead sensation according to the perceived risk, which was controlled by the sharpness of the object and approaching speed to the forehead. The intensity of forehead sensation was measured as 2.69±0.29 and 4.08±0.42 for eraser stick and pencil, respectively, for a slow-approaching speed. The intensity of forehead sensation was larger with an approaching pencil than an approaching eraser stick, at slow approaching speed (p=0.012). The intensity of the forehead sensation was measured as 3.70±0.47 and 4.10±0.75 for the eraser stick and pencil, respectively, for fast approaching speed. The intensity of forehead sensation was not different between the pencil and the eraser stick at fast approaching speed (p=0.659). The intensity of forehead sensation was also compared between the speeds, with eraser sticks used, and the intensity was not different between fast speed (3.70±0.47) and slow speed (2.69±0.29) (p=0.088).

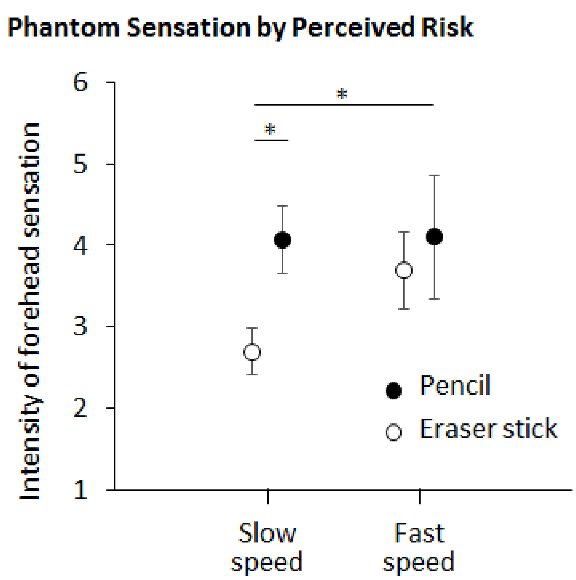


Figure 8: Phantom sensation evoked by the physical eraser stick or the physical pencil approaching to the forehead. Four conditions of perceived risk were tested: slow approaching speed with physical eraser stick, slow approaching speed with physical pencil, fast approaching speed with physical eraser stick, and fast approaching speed with physical pencil.

We compared the tactile sensitivity on the forehead at VR, according to the existence of the approaching object. The threshold value of the tactile sensitivity was measured as 0.04±0.02 (g) and 0.14±0.07 (g), with and without the virtual object approaching towards the forehead, respectively. The threshold value of the tactile sensitivity was not different when the virtual object is approaching to the forehead compared to the case when no virtual object is approaching to the forehead ($p=0.252$), which means that the tactile sensitivity does not change when the virtual object is approaching to the forehead.

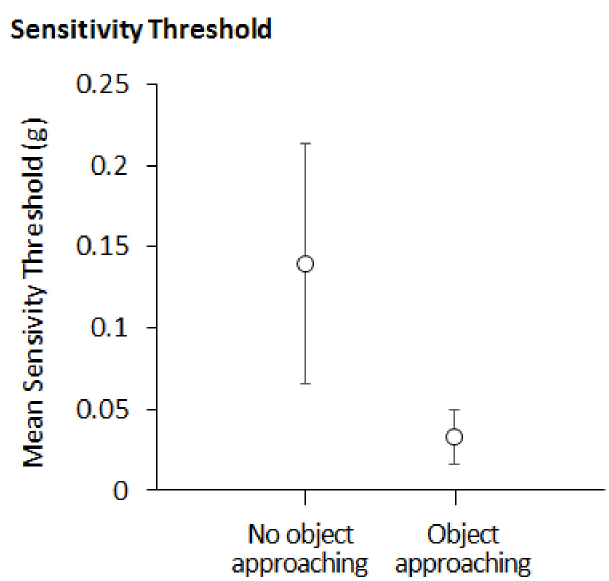


Figure 9: Sensitivity threshold on the forehead with and without the virtual eraser stick approaching to the forehead

CHAPTER IV

DISCUSSION

The conditions of the phantom sensation are unique and it is difficult to recruit the good number of subjects, which poses a hurdle in investigating its principles and test scientific hypotheses. Also, it is hard to control the conditions of the phantom sensation and evoke the phantom sensation consistently, as it is a multivariate function affected by psychological conditions as well as physical interactions. For example, phantom limb sensation is unique to the amputees and happens unexpectedly with random timing. In one study of phantom limb pain (n=183), 81% of the patients suffering from phantom sensations described their pain as “episodic”, and 50% reported one episode of phantom pain per week or less [31]. Therefore, the study of the phantom sensation has been extremely limited [32]. The forehead phantom sensation is a promising candidate to be used for the study of the phantom sensation, as it can be easily evoked by the pointed object approaching the forehead and observed in most people [33]. Through our experiment, we could also confirm that the forehead phantom sensation could be consistently evoked for subjects. The ability to evoke the sensation at any time among most healthy and able-bodied subjects, in a consistent manner simply by the approach of a pointed object to the forehead, makes this approach ideal for future use in investigation of the phantom sensation.

The experimental result confirms that visual feedback could evoke the sensation on the subject’s forehead without any physical interaction. A virtual object approaching the forehead could evoke the same level of intensity of phantom sensation on the forehead as a physical object approaching the forehead. It supports our first hypothesis that visual feedback of an object approaching the forehead will evoke the phantom sensation on the forehead without any physical interaction. Also, when subjects closed their eyes, the intensity of phantom sensation was clearly decreased and close to zero. Considering that the operator still provided a verbal signal before positioning the pointed object onto the forehead, this result suggests that imagination through the auditory feedback is not enough to evoke the forehead phantom sensation and visual feedback is necessary. Based on the fact that visual feedback has a strong effect on forehead phantom sensation, we expect that efference copy and following sensory reafference play an important role in evoking phantom sensation. The conventional comparator model of perception has two primary factors – actual stimulus and sensory reafference [34]. If the phantom sensation was perceived with no actual stimulus, the logical deduction is that it was being created by sensory reafference. Previous works have found that it is possible for visual feedback through virtual reality to alter tactile sensations, which suggest the link between visual feedback and sensory reafference [21].

As the object, approaching towards the forehead became sharper, subjects felt stronger forehead phantom sensations. As sharper approaching objects will be perceived as higher risk than dull approaching objects, this result suggests that the perceived risk is an important factor in augmenting the phantom sensation. It supports our second hypothesis that the forehead phantom sensation will be augmented by the perceived risk. We interpret this result as the nervous system providing a warning signal when faced with a threat. As tactile feedback is more intuitive sensation than visual feedback, with less processing needs and processing delay [35], the nervous system may activate tactile feedback for better preparation of the body to the potential threat. The prior studies on phantom limb pain for amputee patients also suggest that the nervous system provides a warning signal not to repeat the mistake to lose the limb [27]. This result also suggests that the nervous system does not always suppress the unpleasant sensations and rather uses them if needed.

As unpleasant sensations are usually suppressed by adaptation of sensory receptors and changed sensory pathway gain at thalamus or somatosensory cortex, this process of suppression may be inactivated by the generation of phantom sensation.

When the virtual object was approaching the subjects' forehead, subjects reported higher tactile sensitivity on their forehead (0.04±0.02 (g) with approaching object and 0.14±0.07 (g) without approaching object), although there was no statistical significance. We expect the difference will become statistically significant if we increase the number of subjects and number of sessions. If we assume that the difference will become significant with increasing number of subjects and sessions, it is similar to the case of the VR modulating the subjects' real-world tactile sensitivity. It supports our third hypothesis that the phantom sensation evoked on the forehead will change tactile sensitivity on the forehead. This suggests that actual sensory feedback and the phantom sensation closely interact with each other. If the two are closely intertwined, then it may be possible to modulate the phantom sensation with the physical sensory interaction too. Also, it would be helpful to advance the sensory feedback model integrating the phantom sensation. Building a theoretical model that explains the phantom sensation with the normal sensation by physical interaction will help us come to a deeper understanding of the phantom sensation.

We propose that the perception of the phantom sensation is governed by a combination of three different factors - the sensory stimulus, the sensory reference, and the perceived risk. To represent the effect of three different factors on the phantom sensation in generating the phantom sensation, we adopted a mixer in our model, as in Fig. 2. This model is an extended version of the conventional comparator model, to take the perceived risk into account [34]. The mixer model is consistent with the observed aspects of our experiment. In our proposed model, if there is no tactile stimulus and no perceived risk, there is no sensation created. This is suggested by the closed-eye experiments and is similar to our everyday experience - if we do not touch something and do not expect to touch something, we usually do not feel anything. If there is no tactile stimulus but there is a visual feedback that triggers a sensory reference, a phantom sensation could be created on the forehead. The strength of this sensation could be modulated by changing the perceived risk, as suggested by the proposed model [21].

While the model built in this study is assumed to be digital, it may be possible to ascertain some more certain "analog" values for some of the sensory gains through wider-scale trials. Further work would be required.

We also speculate that the occipital-cerebellar-cortical loop may be involved in generating the phantom sensation. Visual feedback from the occipital lobe would spur the creation of an efferent signal in the cerebellum, which would be delivered directly to the somatosensory cortex. This occipital-cerebellar-cortical loop would generate feelings of touch independently of the thalamus and the peripheral nervous system, in a manner that is consistent with our findings. We have demonstrated that the strength of the phantom sensation could be modulated by perceived risk without physical interaction. As there is growing evidence explaining how sensory gain can be modulated by the somatosensory cortex as well as the thalamus [25], which supports the existence of the occipital-cerebellar-cortical loop.

CHAPTER V

CONCLUSION

In this study, we investigated the principles of the forehead phantom sensation. We could trigger a forehead phantom sensation by visual feedback without any physical interaction, providing evidence that the phantom sensation can be solely triggered by the visual feedback. We also showed that perceived risk modulated the strength of the forehead phantom sensation, with sharper and faster-moving objects increasing the strength of perception. As an additional finding, we were able to connect this psychological phenomenon to a change in physical sensitivity, by observing the increase of subjects' tactile sensitivity on the forehead with the phantom sensation.

REFERENCES

[1] T. S. Jensen, B. Krebs, J. Nielsen, and P. Rasmussen, “Immediate and long-term phantom limb pain in amputees: Incidence, clinical characteristics and relationship to pre-amputation limb pain,” *Pain*, vol. 21, no. 3, pp. 267–278, 1985.

[2] P. S. Murray, S. Kumar, M. A. A. Demichele-Sweet, and R. A. Sweet, “Psychosis in Alzheimer’s Disease,” *Biological Psychiatry*, vol. 75, no. 7, pp. 542–552, 2014.

[3] R. C. Teeple, J. P. Caplan, and T. A. Stern, “Visual Hallucinations,” *The Primary Care Companion to The Journal of Clinical Psychiatry*, vol. 11, no. 1, pp. 26–32, 2009.

[4] Flor, Herta. "Phantom-limb pain: characteristics, causes, and treatment." *The Lancet Neurology* 1, no. 3 (2002): 182-189.

[5] Bosanquet, D. C., J. C. D. Glasbey, A. Stimpson, I. M. Williams, and C. P. Twine. "Systematic review and meta-analysis of the efficacy of perineural local anaesthetic catheters after major lower limb amputation." *European Journal of Vascular and Endovascular Surgery* 50, no. 2 (2015): 241-249.

[6] Chan, Brenda L., Alexandra P. Charrow, Robin Howard, Paul F. Pasquina, Kenneth M. Heilman, and Jack W. Tsao. "Mirror therapy for phantom limb pain." *The New England journal of medicine* 357, no. 21 (2007): 2206.

[7] L. H. Colmenero, J. M. P. Marmol, C. Martí-García, María De Los Ángeles Querol Zaldivar, R. M. T. Haro, A. M. C. Sánchez, and M. E. Aguilar-Ferrándiz, “Effectiveness of mirror therapy, motor imagery, and virtual feedback on phantom limb pain following amputation: A systematic review,” *Prosthetics and Orthotics International*, vol. 42, no. 3, pp. 288–298, 2017.

[8] V. Ramachandran, “The perception of phantom limbs. The D. O. Hebb lecture,” *Brain*, vol. 121, no. 9, pp. 1603–1630, 1998.

[9] P. W. Halligan, J. C. Marshall, D. T. Wade, J. Davey, and D. Morrison, “Thumb in cheek? Sensory reorganization and perceptual plasticity after limb amputation,” *NeuroReport*, vol. 4, no. 3, pp. 233–236, 1993.

[10] DeFranco, Daniel J. 2018. “Phantom Sensations: What’s a Brain to Do? A Critical Review of the Re-mapping Hypothesis.” Journal of Cognition and Neuroethics 5 (1): 1–25.

[11] Carruthers G. The case for the comparator model as an explanation of the sense of agency and its breakdowns. Consciousness and cognition. 2012 Mar 1;21(1):30-45.

[12] Synofzik M, Vosgerau G, Newen A. Beyond the comparator model: a multifactorial two-step account of agency. Consciousness and cognition. 2008 Mar 1;17(1):219-39.

[13] Kahl S, Kopp S. A predictive processing model of perception and action for self-other distinction. Frontiers in psychology. 2018 Dec 3;9:2421.

[14] R. C. Miall and D. King, “State Estimation in the Cerebellum,” *The Cerebellum*, vol. 7, no. 4, pp. 572–576, 2008.

[15] C. D. Frith, S.-J. Blakemore, and D. M. Wolpert, “Abnormalities in the awareness and control of action,” *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, vol. 355, no. 1404, pp. 1771–1788, 2000.

[16] E. J. Lier, J. Harder, J. M. Oosterman, M. D. Vries, and H. V. Goor, “Modulation of tactile perception by Virtual Reality distraction: The role of individual and VR-related factors,” *Plos One*, vol. 13, no. 12, 2018.

[17] P. R. Davidson and D. M. Wolpert, “Internal models underlying grasp can be additively combined,” *Experimental Brain Research*, vol. 155, no. 3, pp. 334–340, 2004.

[18] D. A. Nowak, C. Koupan, and J. Hermsdörfer, “Formation and decay of sensorimotor and associative memory in object lifting,” European Journal of Applied Physiology, vol. 100, no. 6, pp. 719–726, 2007.

[19] A. J. Bastian, “Understanding sensorimotor adaptation and learning for rehabilitation,” *Current Opinion in Neurology*, vol. 21, no. 6, pp. 628–633, 2008.

[20] A. Avenanti and S. M. Aglioti, “The Sensorimotor Side of Empathy for Pain,” *Psychoanalysis and Neuroscience*, pp. 235–256, 2006.

[21] M. Carrasco, S. Ling, and S. Read, “Attention alters appearance,” *Nature Neuroscience*, vol. 7, no. 3, pp. 308–313, 2004.

[22] G. Juravle, H. Deubel, H. Z. Tan, and C. Spence, “Changes in tactile sensitivity over the time-course of a goal-directed movement,” *Behavioural Brain Research*, vol. 208, no. 2, pp. 391–401, Dec. 2009.

[23] Department of Biochemistry and Molecular Biophysics Thomas Jessell, Siegelbaum S, Hudspeth AJ. Principles of neural science. Kandel ER, Schwartz JH, Jessell TM, editors. New York: McGraw-hill; 2000 Jan.

[24] Y. B. Saalmann and S. Kastner, “Gain control in the visual thalamus during perception and cognition,” *Current Opinion in Neurobiology*, vol. 19, no. 4, pp. 408–414, 2009.

[25] K. A. Ferguson and J. A. Cardin, “Mechanisms underlying gain modulation in the cortex,” *Nature Reviews Neuroscience*, vol. 21, no. 2, pp. 80–92, 2020.

[26] M. Drouin, D. H. Kaiser, and D. A. Miller, “Phantom vibrations among undergraduates: Prevalence and associated psychological characteristics,” *Computers in Human Behavior*, vol. 28, no. 4, pp. 1490–1496, 2012.

[27] V. C. Anderson-Barnes, C. Mcauliffe, K. M. Swanberg, and J. W. Tsao, “Phantom limb pain – A phenomenon of proprioceptive memory?,” *Medical Hypotheses*, vol. 73, no. 4, pp. 555–558, 2009.

[28] R. Chen, B. Corwell, Z. Yaseen, M. Hallett, and L. G. Cohen, “Mechanisms of Cortical Reorganization in Lower-Limb Amputees,” *The Journal of Neuroscience*, vol. 18, no. 9, pp. 3443–3450, Jan. 1998.

[29] E. D. P. Capelari, C. Uribe, and J. P. Brasil-Neto, “Feeling Pain in the Rubber Hand: Integration of Visual, Proprioceptive, and Painful Stimuli,” *Perception*, vol. 38, no. 1, pp. 92–99, 2009

[30] Tingling sensation in the forehead? Available from: http://www.abovetopsecret.com/forum/thread516797/pg1.

[31] D. M. Ehde, J. M. Czerniecki, D. G. Smith, K. M. Campbell, W. Edwards, M. P. Jensen, and L. R. Robinson, "Chronic phantom sensations, phantom pain, residual limb pain, and other regional pain after lower limb amputation," *Archives of Physical Medicine and Rehabilitation*, vol. 81, no. 8, pp. 1039–1044, 2000.

[32] K. Pacheco-Barrios, X. Meng, and F. Fregni, "Neuromodulation Techniques in Phantom Limb Pain: A Systematic Review and Meta-analysis," *Pain Medicine*, 2020.

[33] Ganguli A. Why do we feel a strange sensation when something is pointed between our eyes, just above the nose, on the forehead? 2015. Available from: http://qr.ae/TUhIoj.

[34] K. P. Körding and D. M. Wolpert, "Bayesian integration in sensorimotor learning," *Nature*, vol. 427, no. 6971, pp. 244–247, 2004.

[35] E. Frid, J. Moll, R. Bresin, and E.-L. S. Pysander, "Haptic feedback combined with movement sonification using a friction sound improves task performance in a virtual throwing task," *Journal on Multimodal User Interfaces*, vol. 13, no. 4, pp. 279–290, 2018