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Published in:
Proceedings of IEEEVR 2019

Publication date:
2019

Document Version
Peer reviewed version

Citation for published version (APA):
Willis, D., Powell, W., Powell, V., & Stevens, B. (2019). Visual stimulus disrupts the spatial localization of a tactile sensation in Virtual Reality. In *Proceedings of IEEEVR 2019* IEEE.

Visual stimulus disrupts the spatial localization of a tactile sensation in Virtual Reality

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ABSTRACT

Phantom limb pain is a neuropathic condition in which a person feels pain in a limb that is not present. Cognitive treatments that visually recreate the limb in an attempt to create a cross modal interaction between vision, and touch/proprioception have shown to be effective at alleviating this pain. With improvements in technology, Virtual Mirror Therapy is starting to gain favor, however, there are currently no applications that utilize passive touch in the same way non-virtual reality applications do. This paper investigates whether a visual stimulus can relocate a tactile stimulus to a different location using principles from the rubber hand illusion and mirror therapy. We demonstrate that a displaced visual stimulus in virtual reality can disrupt accurate spatial perception of a physical vibrotactile sensation however the effects are small and require further investigation.

Keywords: Virtual mirror therapy, Rubber hand Illusion, Vibrotactile, Visuotactile interactions, cross modal interactions, Virtual reality, phantom limb pain

Index Terms: • **Human-centered computing~Virtual reality** • **Human-centered computing~Haptic devices** • Human-centered computing~Empirical studies in HCI • Human-centered computing~Scenario-based design • Human-centered computing~Contextual design • Human-centered computing~Interface design prototyping

1 INTRODUCTION

Phantom Limb Pain (PLP) is a common condition suffered by 45-85% of amputees, where a person experiences pain in a limb that is not present [1, 2]. It is generally classified as Neuropathic in nature, which means the pain derives from the brain and other parts of the central nervous system [1]. There are many treatments for phantom limb pain including various pharmacological and surgical methods, however, cognitive methods such as Mirror Therapy (MT) and in extension, Graded Motor Imagery (GMI) have gained favor as they are non-invasive and have fewer evident side effects [3] [4]. Cognitive treatments have shown to elicit a reversal of cortical reorganization, which is viewed as a positive therapeutic outcome [5]. Mirror therapy is the third stage in GMI and has been used as a standalone treatment for phantom limb pain (and other complex regional pain syndrome therapies) [6]. Mirror therapy was pioneered by Ramachandran [7] and consists of having the patient place his/her intact limb in front of the mirror and occlude their residual limb behind the mirror. They are then told to carry out simple actions like moving the fingers, moving

the hand and wrist or to just observe the reflection, in some cases a therapist will manipulate the intact arm. From the perspective of the amputee, the reflected limb is now superimposed over where the phantom limb and visually replaces it [7-9].

Mirror therapy follows the premise that when the patient experiences a visual representation of the phantom limb, and they embody it, it has the possibility of stimulating the corresponding area in the brain; specifically, the sections that was originally innervated by the missing limb, such as the somatosensory cortex and the motor cortex. The reason for these cross modal interactions have been attributed to underlying mechanisms in the brain such as the mirror neuron system and spike timing dependent plasticity [1, 5, 7, 10-14].

Mirror therapy has been translated technologically with Virtual Mirror Therapy (VMT) as the closest treatment in terms of procedure and underlying premises. Amputees are placed in a virtual environment with either a data glove or optical tracking on the intact limb [15, 16]. The tracking is then mapped to a digital representation of the missing limb reflected, to give the impression that it is the phantom limb which will be referred to as Virtual Mirroring. The amputee can then control their intact limb in such a way as to attempt to alleviate the pain in their phantom limb [17, 18]. There are also applications that use devices such as myoelectric sensors, to interpret muscle movements in the residual limb, which can be mapped to a virtual limb circumventing the need for an intact limb, which will be referred to as ‘simulated extension’.

Virtual mirroring and simulated extension have both shown to be useful however, current virtual reality applications have focused on reintroducing motor cortex stimulation over the reintroduction of somatosensory stimulation via tactile sensation. Although tactile sensation and movement are interlinked, they are represented differently in the brain and activation of both these areas of the brain have shown to be useful in the alleviation of phantom limb pain [1] [19] [20].

Reintroducing tactile sensation on a limb that is not tangible has proven to be challenging but not impossible. Unlike mirror therapy where clinician will generally massage the intact limb or stretch the limb while reflected into a mirror to relieve pain in the phantom limb in the same way that someone would instinctively rub, massage or stretch a cramp in an intact limb, technological treatments have made the reintroduction of tactile sensation difficult, as commercial data gloves inhibit the use of passive touch, which is sometimes used in mirror therapy. In addition, independent solo treatment is encouraged in virtual mirror therapy, which means another person is not present to passively touch the arm of an upper limb amputee. Currently there is only one study that has explored the use of active touch in virtual reality specifically for use in phantom limb pain treatments. Sano [21] found that active tactile feedback could be delivered to a phantom limb using principles from virtual mirror therapy (visuo-

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tactile sensation). This inclusion of active tactile sensation had a 13% increase to pain alleviating efficacy. This study not only gives some indication that delivering tactile sensation can be accomplished in virtual reality, but it also shows that reintroducing a sense of touch holds benefits over exclusive motor imagery or virtual mirror therapy. Unlike most mirror therapy protocols, Sano utilized active touch in this study, which means the user had intention to touch or manipulate another object. Tactile feedback via vibration actuators was then used to signal to the user that they had collided with the object giving the impression that the user touched something (haptic technology was not used). This type of interaction has shown to be useful in pain reduction, but it does not reflect the methods used in mirror therapy in which a clinician would touch, massage or manipulate the arm (passive touch). Passive touch, as used in some Mirror Therapy protocols elicits a greater somatosensory response than active touch may be possible [22]. When experiencing the mirrored visual stimulus as well as the tactile stimulus from the clinician, tactile acuity has shown to be heightened [23]. In addition, passive touch has also shown to be disproportionately better at activating neurons in the somatosensory cortex than active touch [22]. Furthermore, Sano's paper required an intact limb in order to create the tactile perception which in some circumstances maybe an issue.

This paper aims to follow up Sano's findings in investigating whether tactile perceptions can be transferred to a virtual arm in virtual reality in the form of passive rather than active touch. In addition, an investigation into whether this technique has potential for simulated extension applications using visuals cues with decoupled tactile stimulus, which will ultimately provide insight into visuo-tactile perceptual interfaces.

2 RELATED WORK

Visuo-tactile interactions have been evidenced in cognitive studies such as the rubber hand illusion. The rubber hand Illusion is a somatic phenomenon which can induced by visually obstructing a body part replacing it with another object (generally a representation of the hand). A tactile sensation is administered to both the hand and the object in a congruent and synchronous manner. This can create a visceral illusion that the object has either replaced or merged with their body part. Subsequently, when this object is stimulated in a tactile or proprioceptive manner in irrespective of the actual body part being stimulated, it has been found that participants report a corresponding tactile perception in their own body part. This visuo-tactile phenomenon has been coined 'visual capture' by Botvinick [24] and describes some of the underlying mechanisms of the emergence of the phenomenon. The neural mechanisms for why visual capture can happen are not entirely understood, however there seems to be amount overlap with spike time dependent plasticity and mirror neurons in the same way that mirror therapy functions [25] [26] [27]. The effects of the rubber hand illusion have been observed and corroborated by other researchers in both non-technological and technological experiments (including virtual reality) [28] [29] [30].

There have been attempts to use the rubber hand illusion for therapeutic purposes, however studies investigating this potential have shown it to be ineffective for the reduction of acute, lab induced pain [31]. Currently there are no studies that have investigated the translation of the rubber hand illusion to chronic pain (more akin to PLP) or specifically neuropathic pain. Mohan [31] suggests that the translation could be beneficial for PLP but does not expand on this idea.

The rubber hand illusion has been explored and successfully applied to technological means however has not been successful in being applied in a therapeutic manner. The fundamental principles behind the rubber hand illusion show potential for use in a mirror therapy protocol trying to explore the use of passive touch. This paper will investigate how the application of fundamental principles for the rubber hand illusion (visual capture) can be applied to a mirror therapy protocol could allow virtual reality clinicians to apply passive touch to amputee similar to non-virtual mirror therapy.

3 DESIGN

Following principles from mirror therapy there will be an investigation into whether a passive tactile perception can be relocated down the arm towards the fingers from the forearm (distally) or to the opposite arm (contralaterally) by using an innocuous visual cue with a decoupled vibrotactile stimulus. Non-amputees will be used in this quasi-experiment to establish whether visuo-tactile interactions are possible with this protocol.

A within subjects repeated measures study was created in which participants viewed virtual arms which were textured, such that the skin surface was divided into distinct sections (Fig 1). A vibrotactile sensation (passive) was delivered to one of 4 positions on the arms. During some conditions a virtual light was located on in 1 of 4 positions. The location in which the participant felt the vibrotactile sensation was recorded. A distribution of the responses was then visualised in a heat map. This indicated if the visual stimulus influenced tactile perception and in addition signify any perceptual relocation.

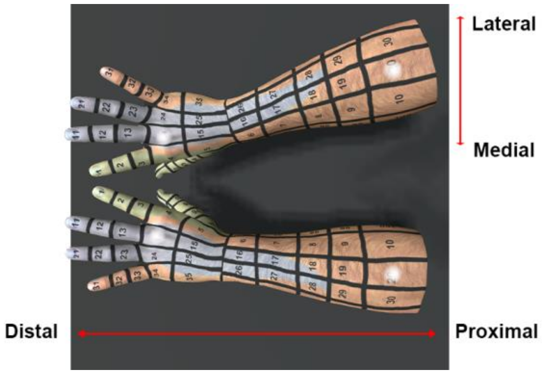


Figure 1: Showing virtual hands with grid section plus light locations

3.1 Participants

A total of 16 adults with intact limbs participated in the study (10 female 6 male), with an age ranging 22-57 (M= 32.9, SD=8.8). 13 participants were right handed, two were left handed and one person was ambidextrous. Participants were recruited from the University of Portsmouth and were a mixture of staff and students. The exclusion criteria for this study were: Visual impairments, visual field epilepsy, heightened tactile defensiveness, any known tactile discrimination deficits or recurrent/chronic pins and needles or numbness in the arms. This study was reviewed by the University of Portsmouth ethics committee and given a favourable opinion in accordance to the University of Portsmouth guidelines. All participants gave written consent to take part in the study and for results to be published.

3.2 Condition and groups

	Condition	V	L	Code
Control & Post Control	Left Forearm Vibration	LF		Con-LFV PCon-LFV
	Left Hand Vibration	LH		Con-LHV PCon-LHV
	Right Forearm Vibration	RF		Con-RFV PCon-RFV
	Right Hand Vibration	RH		Con-RFV PCon-RFV
Association	Left Forearm Vibration/ Left Forearm Light	LF	LF	Asso-LFVLHL
	Left Hand Vibration/ Left Hand Light	LH	LH	Asso-LFVLHL
	Right Forearm Vibration/ Right Forearm Light	RF	RF	Asso-LFVLHL
	Right Hand Vibration/ Right Hand Light	RH	RH	Asso-LFVLHL
Disruption 1	Left Forearm Vibration/ Right Forearm Light	LF	RF	Dis1-LFVRFL
	Left Hand Vibration/ Right Hand Light	LH	LH	Dis1-LHVRHL
	Right Forearm Vibration/ Left Forearm Light	RF	LF	Dis1-RFVLFL
	Right Hand Vibration/ Left Hand Light	RH	LH	Dis1-RHVLHL
Disruption 2	Left Forearm Vibration/ Left Hand Light	LF	LH	Dis2-LFVLHL
	Left Hand Vibration/ Left Forearm Light	LH	LF	Dis2-LHVLFL
	Right Forearm Vibration/ Right Hand Light	RF	RH	Dis2-RFVRHL
	Right Hand Vibration/ Right Forearm Light	RH	RF	Dis2-RHVRFL
Expectation	Left Forearm Vibration		LF	Exp-LFL
	Left Hand Vibration		LH	Exp-LHL
	Right Forearm Vibration		RF	Exp-RFL
	Right Hand Vibration		RH	Exp-RHL

Table 1: Condition list. V = Vibration, L = Light, LF = Left Forearm, LH=Left Hand, RF=Right Forearm, RH=Right Hand. Each condition was conducted 4 times per participant.

Conditions were categorized into groups: Control, association, disruption 1 & 2, expectation, and a post control group. The control group (including the post control group) was vibrations without any lights. This was used to gauge where the participants felt the vibrations and to situate/ calibrate the baseline location of the tactile perception. The Association group comprised of vibrations and lights located in close proximity to each other. The vibration and light were not directly collocated so as to disrupt the localization from the control condition. This stopped participants creating a biased pre-picture of the situation but also linking the light with the vibration. There were two disruption groups, one group where the lights were decoupled from the vibrations contralaterally (on the opposite arm) and the other either proximal or distal on the same arm (Fig 1). In the Expectation phase lights were used without vibrations.

During a pilot study it was found that repeating over 100 trials caused an issue with arm fatigue so the amount of trials per participant was constrained to under 100 trials. Conditions were counter balanced using a Latin square approach organized into 6 groups: Control, association, disruption 1 & 2, expectation, and a post control group. Each group had 4 conditions and each condition was conducted 4 times per participant, totaling 96 trials per participant (Table 1). To negate any order effects the disruption groups (Disruption 1&2) were further alternated between participants as there was no prior knowledge of how experience of a contralateral decoupling would affect a proximal or distal decoupling and vice versa. Participants were exposed to all conditions in the quasi-experiment.

4 MATERIALS AND APPARATUS

4.1 Physical Set up

The application was created in Unity and assets created in 3ds Max 2015. An Oculus Rift CV1 was used to display the virtual environment for the participant. A LEAP motion device was used to track the participants hands and mapped the movement to the arms in the virtual environment (VE). Attached to these arms were four virtual lights (switched off by default). The lights were situated on the hand (between the middle and ring finger knuckles) and the forearm on the left and right sides respectively (Figure 1). The lights were luminous icosahedrons with a diameter of 1cm. The diameter of the luminosity was 4.8 cm which radiated around the icosahedron.

Physical vibration modules were attached to the participant's arms using medical grade adhesive. The vibration modules were seated on plastic stoppers and were cut to different sizes as to accommodate to the receptive fields on the arms respectively (hands 1cm diameter and for the forearms 3.5 cm diameter). Vibration motors on the hand was placed 2 cm proximal along the tendon extensors from the index fingers metacarpophalangeal joint. The motor was placed slightly medial of the tendon extensor on a pronated hand. The forearm motor was placed 5 cm from the hand following the C8 dermatome along the extensor tendon proximal to the body. Anatomical land marks were used to be as consistent as possible with each participant (Fig 2). Due to the risk of participants remembering the positions of the vibration motors when they were applied to the skin, the lead researcher gave false indications that there may have been more motors attached to the arm. These false indications took the form of pressing the skin in random places, as placing additional false motors may have had an unexpected effect on the skin.

These vibration modules were connected via wires to a core electronics platform worn on the participants back. Efforts were made to keep the wires away from the participants arms by reinforcing the wires to give sufficient rigidity to trail away from the arms, ensuring that the only contact point on the participants were the attached vibration modules. The vibrations were delivered through an Arduino mini pro. The Arduino communicated with unity via a serial cable. Once the space bar is pressed a signal is sent to the Arduino issuing a command to a vibration motor to turn on an off. The duration of the vibration was 1 second (230Hz and 1.2g amplitude).

The location of the vibration modules was set at section 15 for the hands and section 17 for the forearms for the males and female arms respectively.

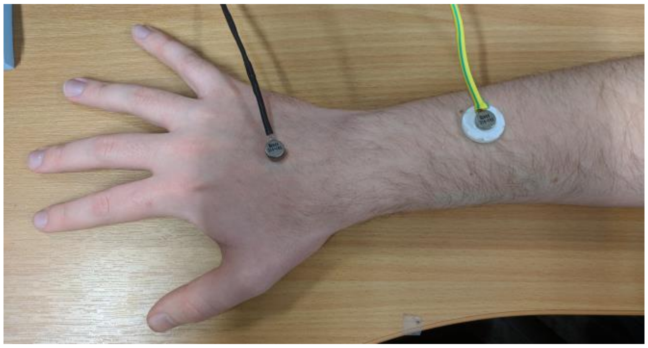


Figure 2: Physical vibration set-up on hand.

4.2 Virtual Environment

Participants had a choice of either male or female arms. Sections followed anatomical landmarks such as fingers, wrist and knuckles. The arms were divided into 100 sections in total. These sections were not equal in size as however each section was big enough for the vibration modules to fit into, the sections went from 1 to 100 wrapped around the arm. The sections were set in numerical order up the arm for easier identification. A colored overlay was placed on the hands and forearms that represented the c6 and c8 dermatomes for validation on some sections, to mitigate human error in reporting which was evidenced in the pilot study. Vocal verification of section with a color associated was encouraged.

There is little evidence to suggest this colouring would influence relocation of the vibrotactile sensation however caution in findings will be taken.

4.3 Task

Conditions were triggered on a button press; once triggered, the preset combination of lights and/or vibrations were presented to the participant depending on the phase the participant was in. The participant was asked to state the section number location in which they felt the vibration. They were also asked to give any other comments about the experience after each condition. They were asked to keep the entire virtual arm in view for the duration of the study. Participants were able to move their arms throughout the study, but they were asked to not make any sudden or large movements, this limited the amount the cables moved and kept the tracking stable. Visual observations were made by the lead researcher to make sure this was the case.

To alleviate arm fatigue, enforced breaks were issued after trials 23, 39 and 59. This break was issued in the middle of a group as to not disrupt the flow of the groups and to control for rhythm tendencies in participants. During the break's participants were asked to lower their arms to their sides for a minimum of 30 seconds, so they had time to recover from any arm or neck fatigue.

5 RESULTS

The mode was used to show the most frequent sections reported for each of the conditions. Inferential statistics would not be possible with is data set as the data gathered was nominal. The results were screened to investigate whether the wire was a confounding variable by checking the sections that the wire may have touched on the lateral sides of the arms however no anomalous responses were apparent which suggests that any such occurrence did not influence the results. All conditions showed participants were able to accurately locate the vibrotactile stimulus however it was evident in the heat maps that a displaced visual stimulus in virtual reality can disrupt accurate spatial perception, as the distribution of response had high variance towards the virtual visual stimulus. In order to check whether participants were stating the position of the vibration modules based on the inactive sensation on their skin, a post questionnaire at the end of the study asking people "how aware were you of the vibration modules when they were not vibrating?" on a scale of 0-9 was issued with 0 being unaware of them all together and 9 being aware of them.

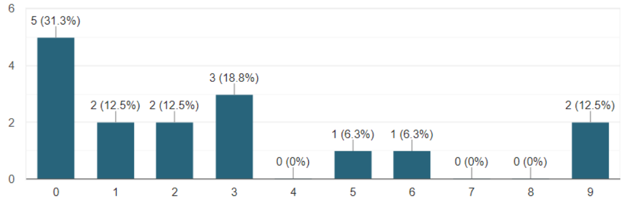


Figure 3: Results for questionnaire stating whether there was a passive sensation due the presence of the vibration motors.

The results show that the majority of the participants were not very aware of the vibration modules on their skin when they were not vibrating which means they were not stating the locations of vibration modules and were stating where they felt the vibrations (Fig 3).

Further investigation into the distribution of responses was undertaken. Results have been truncated as there were no participants that reported a sensation on the palmer side of their hand (sections 41-81). It is also worth noting that some conditions had a reduced number of responses as there were technical difficulties on some trials. Each condition should contain 64 responses, however, there were a minimum of 58 responses for some conditions. Exact numbers are reported below.

5.1 Control

Within the control condition where no light was present responses were centered around the physical vibration location. For both the right and left hand control conditions, 64 responses were recorded. For the left and right forearm control conditions 62 responses were recorded. Mode of responses: Left forearm = section 17, Left hand = section 15, Right forearm = section 17 and Right hand = section 15. Distribution around these modes were generally adjacent sections. There were responses in the proximal positions (closest sections) on the forearms where the light would have been in a different condition (Fig 3).

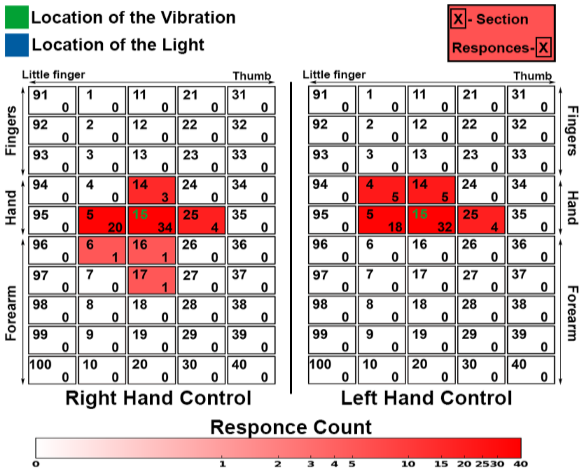


Figure 4: Right hand Control responses and Left Hand control Response in a heat map

5.2 Association

In the association condition, where the visual stimulus was present in close proximity to the physical stimulus, responses were centered around the physical vibration location. For both the right and left hand association conditions, 64 responses were recorded. For left forearm association condition 62 responses were recorded and for the right forearm 62. Mode: Left forearm = section 17, Left hand= section 15, Right forearm = section 17 and Right hand = section 15, however there was a large redistribution of responses towards the visual stimulus especially on the forearm responses.

This disruption was most evident in on participants right forearm, where there was a true bimodal distribution between section 15 and 20. This condition presented the vibration stimulus in section 15 and the visual stimulus on section 20 which suggests the visual stimulus had an effect of the accurate special localization of the vibrotactile sensation. Not as evident but still noteworthy was on the left forearm where the number of responses on section 20 rose from 2 responses to 13 responses (Fig 4).

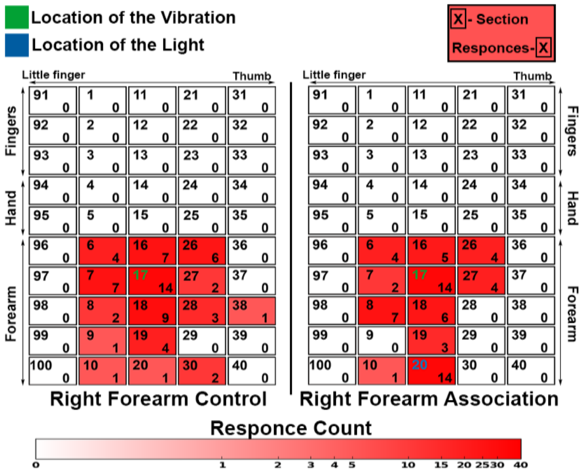


Figure 5: Right Forearm Control Compared to Left Forearm Association responses

5.3 Disruption 1

In the disruption 1 condition, where the visual stimulus was presented on the contralateral side, responses were centered around the physical vibration location. For both the right and left hand Disruption 1 conditions, 64 responses were recorded. For the left forearm Disruption 1 condition 60 responses were recorded and for the right forearm 64. Mode: Left forearm = section 17, Left hand = section 15, Right forearm = section 17 and Right hand = section 15. Distribution of responses were similar to their control counterparts on all sites apart from on the left forearm where there was a drastic redistribution towards the C8 dermatome. The left hand also had an anomalous result however this was only 1 response (Fig 5).

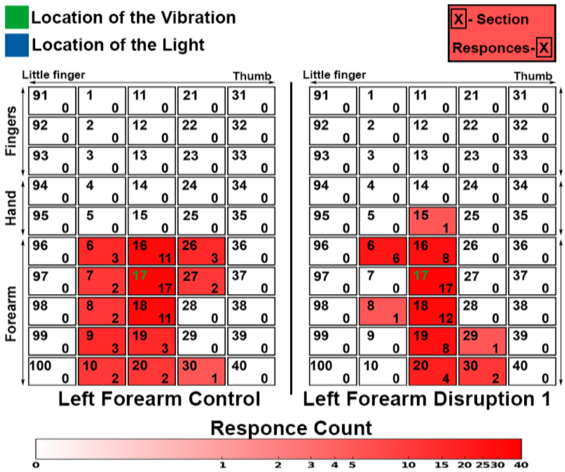
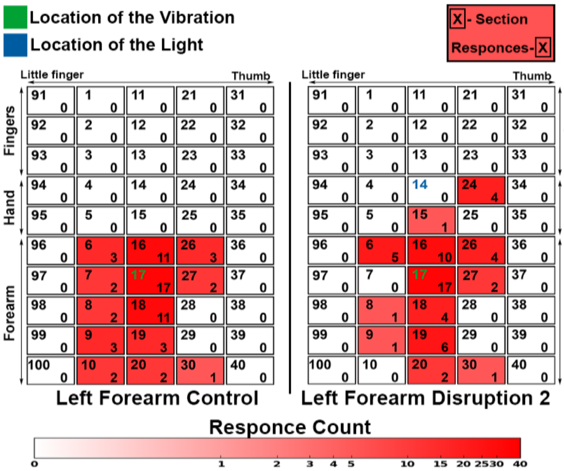


Figure 6: Left Forearm Control compared to Left forearm Disruption 1 responses

5.4 Disruption 2

In the disruption 1 condition, where the visual stimulus was presented either proximal or distal from the vibration stimulus, responses were centered around the physical vibration location. For both the right and left hand Disruption 2 conditions, 64 responses were recorded. For the left forearm Disruption 2 condition 58 responses were recorded and for the right forearm 64. Mode: Left forearm = section 17, Left hand = section 15, Right forearm = section 17 and Right hand = section 15. However, there were some profound redistributions. The left forearm had many more responses near the hand where the visual stimulus was located (section 14), which was not observed on any other condition on the left forearm. The right forearm had very similar responses similar to the left forearm where there were responses on the hand unlike any other condition for the right forearm. When the vibration was present on the hands and the visual stimulus was present on the forearms there was also a disruption of accurate tactile perception towards the visual stimulus on the forearm. Although the visual stimulus disrupted accurate spatial localization to a large degree on the right hand and forearm and the left forearm, the left hand become very localized with an increase of 38 more responses from the control (Fig 6).



Left Forearm Control

	Little finger				Thumb
Fingers	91 0	1 0	11 0	21 0	31 0
	92 0	2 0	12 0	22 0	32 0
	93 0	3 0	13 0	23 0	33 0
Hand	94 0	4 0	14 0	24 0	34 0
	95 0	5 0	15 0	25 0	35 0
Forearm	96 0	6 3	16 11	26 3	36 0
	97 0	7 2	17 17	27 2	37 0
	98 0	8 2	18 11	28 0	38 0
	99 0	9 3	19 3	29 0	39 0
	100 0	10 2	20 2	30 1	40 0

Left Forearm Disruption 2

	Little finger				Thumb
Fingers	91 0	1 0	11 0	21 0	31 0
	92 0	2 0	12 0	22 0	32 0
	93 0	3 0	13 0	23 0	33 0
Hand	94 0	4 0	14 0	24 4	34 0
	95 0	5 0	15 1	25 0	35 0
Forearm	96 0	6 5	16 10	26 4	36 0
	97 0	7 0	17 17	27 2	37 0
	98 0	8 1	18 4	28 0	38 0
	99 0	9 1	19 6	29 0	39 0
	100 0	10 0	20 2	30 1	40 0

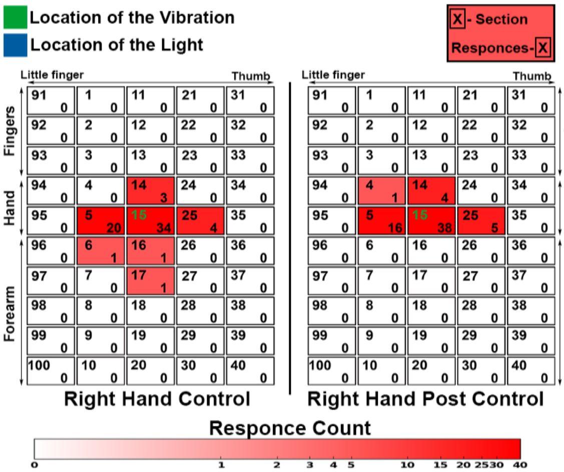
Figure 7: Left Forearm Control Compared to Left forearm Disruption 2 responses

5.5 Expectation

In The expectation condition, where the visual stimulus was presented with no vibration stimulus, there were no responses apart from one isolated case where a participant felt something in section 5 on their left hand when the visual stimulus was presented on their left hand.

5.6 Post Control

Within the control condition, where no light was present, responses were centered around the physical vibration location. For both the right and left hand Post Control conditions, 64 responses were recorded. For the left forearm Post Control condition 60 responses were recorded and for the right forearm 64. Mode: Left forearm = section 17, Left hand = section 15, Right forearm = section 17 and Right hand = section 15. Compared to the control, the post-control responses were more accurate at pinpointing the physical vibrotactile sensation however the results were very similar in terms of distribution (Fig 7).



Right Hand Control

	Little finger				Thumb
Fingers	91 0	1 0	11 0	21 0	31 0
	92 0	2 0	12 0	22 0	32 0
	93 0	3 0	13 0	23 0	33 0
Hand	94 0	4 0	14 3	24 0	34 0
	95 0	5 20	15 34	25 4	35 0
Forearm	96 0	6 1	16 1	26 0	36 0
	97 0	7 0	17 1	27 0	37 0
	98 0	8 0	18 0	28 0	38 0
	99 0	9 0	19 0	29 0	39 0
	100 0	10 0	20 0	30 0	40 0

Right Hand Post Control

	Little finger				Thumb
Fingers	91 0	1 0	11 0	21 0	31 0
	92 0	2 0	12 0	22 0	32 0
	93 0	3 0	13 0	23 0	33 0
Hand	94 0	4 1	14 4	24 0	34 0
	95 0	5 16	15 38	25 5	35 0
Forearm	96 0	6 0	16 0	26 0	36 0
	97 0	7 0	17 0	27 0	37 0
	98 0	8 0	18 0	28 0	38 0
	99 0	9 0	19 0	29 0	39 0
	100 0	10 0	20 0	30 0	40 0

Figure 8: Right hand Control Responses compared to Right Hand Post Control responses

6 DISCUSSION

The results suggest that visual stimulus in virtual reality can disrupt accurate spatial localization of a vibrotactile sensation. This disruption of tactile sensation seems to follow the location of a visual stimulus. This finding corroborates and expands on some of the findings in the rubber hand illusion and mirror therapy.

Disruption 2 had some of the most profound responses on all positions especially the forearms, with responses on the hands when the physical vibrotactile sensation was presented on their forearms. Although there were few responses in these positions the results are promising for amputees, as it suggests that a passive tactile sensation can be relocated distally down the arm without a physical sensation being delivered to that location. Further investigation needs to be conducted to determine to what degree this decoupling can be effective and how to increase the response rate. Also, these finding need to be tested with amputees, where this decoupling may be more successful, as a population in pain (including phantom limb pain) has been shown that the primary (S1) and secondary somatosensory cortex (SII) physically alter in size and effectiveness, leading to worse tactile discrimination [32] [33]. This degradation may lend itself to higher rates of visuo-tactile disruptions. Although this relationship has been evidenced in two-point discrimination tests, these tests focused on two simultaneous congruent tactile sensations and not a visual and tactile sensation, as presented in this study. Further testing is needed to determine the relationship pain has on simultaneous incongruent visuo-tactile discrimination.

There was a slight lateral displacement from the light on the results of Disruption 2 when the physical stimulus was presented on the forearms. Both sides reported sensation slightly to the right of the visual stimulus. Speculations around perspective may have created the impression of the light being located slightly right of the actual location would not explain these results well, as that would mean the left hand was always observed in a very pronated position (thumb facing down). This situation did not happen throughout the duration of this quasi-experiment as the participants hands were being monitored throughout. Further investigation is needed.

It was hypothesized that the responses would become more spatially accurate throughout the duration of the quasi-experiment with the post control responses having less variation in results than the control however the results were very similar with no drastic changes. This adds credibility to the visual stimulus having an influence on the special localization of a tactile sensation rather than participants becoming aware of the location due to exposure alone.

This study did not corroborate findings from virtual mirror therapy where contralateral tactile decoupling was achieved. Sano et al. provided evidence that contralaterally relocating a tactile sensation via visual stimulus was achievable. These results beg the question, is active touch necessary in contralateral decoupling or are there other factors that need to be considered? Ramachandran [10] suggested that context and prior memories can influence our ability to perceive visceral perceptions. Further investigation is needed into whether memories and prior expectations are factors for contralateral transfer of passive tactile sensation.

The results of this study demonstrated a cross modal interaction between vision and touch however it did not demonstrate a substitutional experience. In the Expectation condition with no tactile stimulus, participants did not substitute the visual stimulus with a tactile sensation as shown in some rubber hand illusion results [34]. There are multiple reasons why this may have been the case. One being, although a synchronous stimulus was presented, the visual stimulus was not congruent, as a light is generally not attributed to a vibration. Another could be inherent properties of the stimulus delivered. In this study a vibrotactile sensation was used while in many rubber hand illusion protocols they use stroking as the core stimulus. There are studies that show how stroking can impart a different tactile response than other tactile stimulus, such as in Croy et al's [35] study which shows how different frequencies of stoking can change the types of afferent nerves that receive and signal the sense of touch and in turn changes the way this tactile sensation is perceived. Further investigation into whether a stroking device may change the efficacy of inducing this visuo-tactile interaction. Additionally, time between stimulations may have had an impact on the ability to substitute the visual stimulus for a tactile sensation.

Overall, this paper demonstrates that visual capture of a tactile stimulus may be possible in virtual reality for use in phantom limb pain treatment using a decoupled visuo-tactile interface, however further investigation is needed.

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