A NEW VISUAL-ELECTROTACTILE MAPPING BY DISTANCE BASED ELECTRICAL STIMULATION IMPROVES THE CONTROL ACCURACY OF FINGER APERTURE

A Thesis

by

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ABSTRACT

Finger motor tasks often need high manipulation accuracy because the fingers are frequently used in sophisticated tasks. Finger aperture control (the gap between a pair of fingers e.g., thumb and index) in a finger reaching task is one of the critical maneuvers for surgical operation, to grab and manipulate the tissue structures. The planning and execution of such a finger reaching task to control the finger aperture is based on the visual and proprioceptive feedback. The visual and proprioceptive feedback is integrated optimally to provide a minimum-variance estimation of the position of the fingers *i.e.,* each estimate of the sensory feedback is combined as their weighted averages where the weights are inversely proportional to the variance of the estimates. However, the visual-proprioceptive mapping error due to the mismatch between an allocentric visual feedback, specialized to perceive the body position relative to the target, and an egocentric proprioceptive feedback, specialized to perceive the intrinsic spatial representation of the body, limits the sense of distance perception between our hand and an object accurately before touching it, resulting in an error in the motor output. To adjust the visual-proprioceptive mapping error and truly improve the control accuracy of the finger aperture, we introduce distance-based electrotactile feedback which works as the new sensory reference optimally combining with the original visual and proprioceptive feedbacks. The electrotactile stimulation was applied with a frequency inversely proportional to the finger aperture distance. We tested the efficacy of the distance-based E-stim against conventional visual sensory feedback method, on enhancing the accuracy

of the interactive finger reaching. We observed that the control accuracy of the finger aperture significantly improved on application of the stimulation ($p < 0.0001$) compared to the baseline value. Moreover, on removal of the stimulation, the control accuracy decreased slightly but still significantly improved compared to its baseline value ($p < 0.0001$) indicating a retention of the finger aperture accuracy even after the removal of stimulation. We believe that the new electrotactile method generates a new schema of representing visual target in the tactile working memory of the brain resulting in a longer retention.

DEDICATION

To my father, mother and grandmother.

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Contributors

This work was supervised by a thesis committee consisting of Dr. Hangue Park (Committee Chair), Dr. Krishna Narayanan (Committee Member) and Dr. Raffaella Righetti (Committee Member) of the Department of ECEN and Dr. Rainer Fink (Committee Member) of the Department of ETID.

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NOMENCLATURE

E-Stim	Electrical Stimulation
E_{VT}	Extrinsic coordinates of the visual target from visual feedback
E_{VF}	Extrinsic coordinates of the finger from visual feedback
I_{VT}	Intrinsic coordinates of the visual target from visual feedback
I_{VF}	Intrinsic coordinates of the finger from visual feedback
I_P	Intrinsic coordinates of proprioception
Δ_V	Visual Feedback Error
Δ_C	Extrinsic to Intrinsic conversion error in visual system
Δ_P	Proprioceptive Feedback Error
Δ_M	Motor Output Error
f	Frequency of electrical stimulation
d	Distance between the index and thumb fingers
V_{sense}	Minimum Sensible Voltage for electrical stimulation
$V_{discomfort}$	Maximum Comfortable Voltage for electrical stimulation
f_{min}	Minimum frequency for electrical stimulation
f_{max}	Maximum frequency for electrical stimulation
d_{min}	Minimum distance between the fingers measured by the system
d_{max}	Maximum distance between the fingers measured by the system

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1. INTRODUCTION

1.1. Problem: Humans have limited accuracy in translating visual distance to finger aperture distance, which limits the control accuracy at approach

In many cases of our day-to-day finger activities, such as grabbing a bottle or opening a door, the first step of motor control is visually perceiving the locations of a target and an end effector (*e.g.,* fingertip.) The visually perceived locational information is processed by the brain, which, then, delivers command to each muscle based on the internal mapping established by prior experience, as a feedforward solution [1], [2].

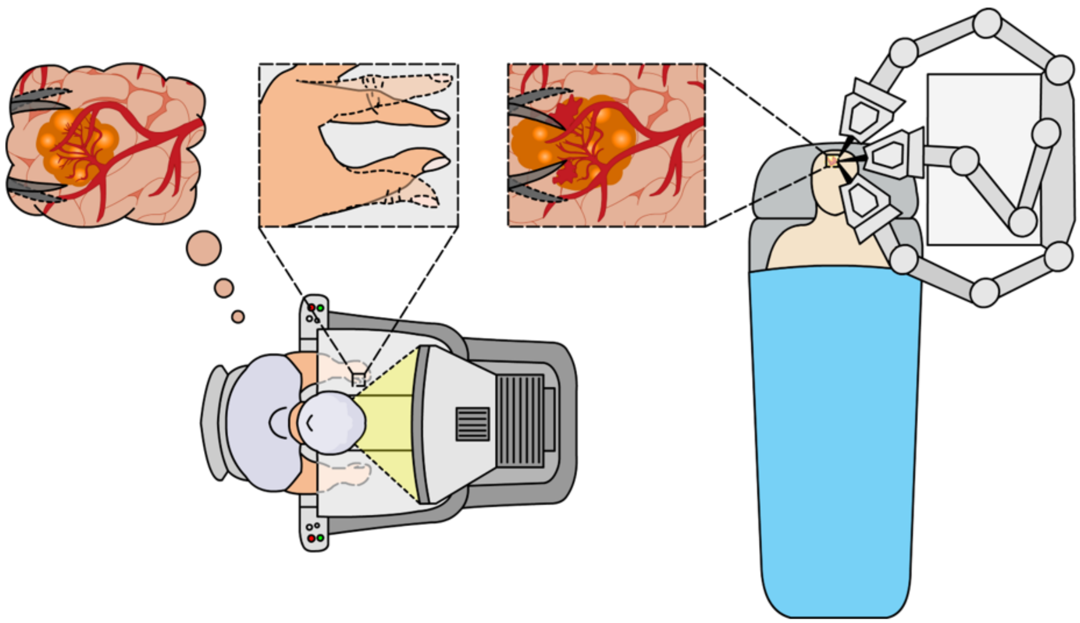

Figure 1: Finger manipulation task in tele-robotic surgery. The figure shows a surgeon operating remotely on a patient with brain tumor using a robotic surgical tool. The brain tumor is nurtured by several blood vessels. The surgeon expects to approach the tumor without damaging the nearby blood vessels. However, due to limited perception of how close the surgical tool is from the tissue structure, the surgeon applies a high initial contact force on the tumor, unintentionally, rupturing the blood vessels and resulting in bleeding into the surrounding tissue structures. This demonstrates the dexterity required in a finger reaching task.

However, the feedforward solution is often inaccurate and the motor command is tuned in real-time by sensory feedback (*i.e.,* visual and proprioception), especially when the manipulation requires high accuracy. In this real-time tuning process, visual-proprioceptive mapping [3]–[5] plays an important role because the nervous system reduces error by the process of integration of visual and proprioceptive feedback in an optimal fashion.

1.2. Example: Telerobotic surgery

Finger motor tasks often need high manipulation accuracy because the fingers are frequently used in sophisticated tasks. Tele-robotic surgery is one such challenging finger motor task [6]–[8], because surgeons operate on a delicate tissue structure remotely using a robot and a single unintended touch can cause serious damage [9]–[11]. The problem becomes more critical if the visual feedback is obstructed by the robotic tool or the surgical environment, which is often the case during the surgery. Without an accurate perception of the finger movement, it is challenging to delicately manipulate the tool and hence, a surgeon may reach to a target tissue structure with a high initial contact force causing permanent tissue damage [10] as shown in Fig. 1. This initial touch can be extremely important when surgical tools access sensitive nerves or sophisticated tissues like brain and cornea [12]–[15].

1.3. Visual-proprioceptive mapping error in motor planning and execution

Finger aperture control (the gap between a pair of fingers *e.g.*, thumb and index) in a finger reaching task is one of the critical maneuvers [16] for surgical operation, to grab and manipulate the tissue structures. Not to apply excessive amount of force and to protect the tissue structure, finger aperture should be controlled with minimal error. The planning and execution of such a finger reaching task to control the finger aperture is based on the visual and proprioceptive feedback, and largely composed of the following steps as shown in Fig. 2: **1)** The visual system perceives a desired target distance and the actual distance between the two fingers (the finger aperture) as the extrinsic coordinates E_{VT} and E_{VF}, respectively. The brain converts the distance perceived in extrinsic coordinates to the one in intrinsic coordinates I_{VT} and I_{VF}[17]. Similarly, the proprioceptive feedback [18] from the muscles, tendons and tactile afferents, *i.e.,* skin stretch of the hand [4], [19], is represented in intrinsic coordinates as I_P. Note that, the sensory inputs are also fed back to their corresponding memory systems which can provide an estimate of these intrinsic

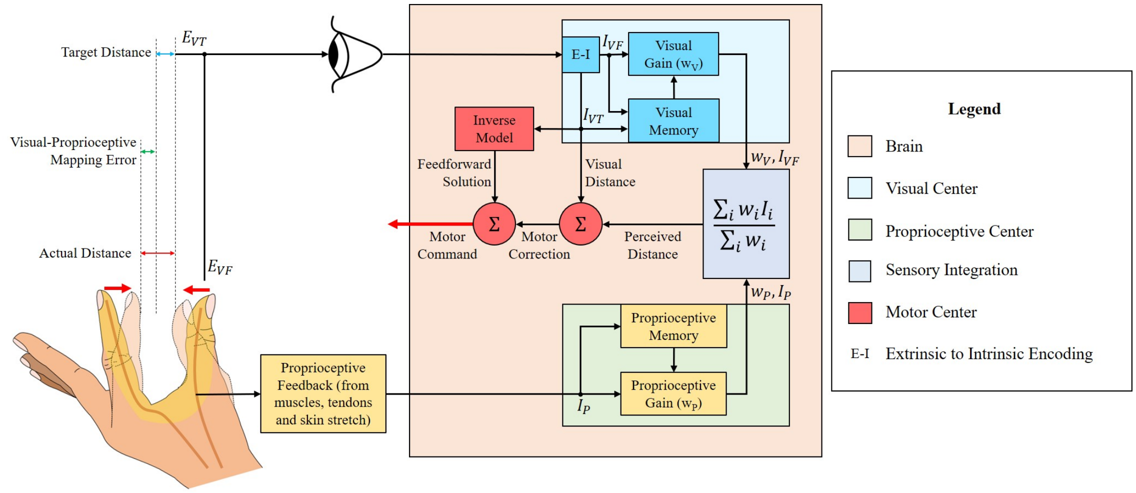

Figure 2: Planning and execution of a finger reaching task to control the finger aperture. The figure illustrates how a target distance and finger aperture distance is mapped from extrinsic coordinates, E_{VT} and E_{VF}, to intrinsic coordinates, I_{VT} and I_{VF}, respectively. Similarly, the proprioceptive feedback from the hand is encoded as intrinsic coordinates I_P. The feedforward solution for a desired target distance based on the past experience (inverse model) provides the motor command for the hand which is tuned in real time by an optimal combination of visual and proprioceptive feedback. The combination is a weighted average of each sensory estimate where the weight is proportional to the reliability (or inverse of variance) of that sensory modality.

coordinates in the absence of one or more sensory inputs. **2)** Based on experience and desired target distance (I_{VT}), the brain brings a feedforward solution and issues a motor command to the muscles and tendons of the hand to control the finger aperture distance. **3)** The visual and proprioceptive feedback is integrated optimally to provide a minimum-variance estimation [20]–[22] of the position of the fingers *i.e.,* each estimate of the sensory modality is combined as their weighted averages where the weights are inversely proportional to the variance of the estimates [3] **4)** The estimated distance is compared with the desired target distance to provide a motor corrective feedback which adjusts the feedforward solution to control the motor output of the fingers.

However, this process results in a residual error caused by the incompleteness of the sensory perception and processing. The visual feedback may have an error, Δ_V, (*e.g.,* parallax effect) which may result in misperception of the target distance and the finger aperture. Furthermore, the extrinsic-to-intrinsic conversion error, Δ_C, is added in the conversion process from extrinsic to intrinsic coordinates *i.e.* conversion of visually perceived information of the target distance and the finger aperture distance based on external objects into neural encodings in the brain based on the body schema [23]. Consequently, the brain might have this systematic error Δ_C in the visual perception of distance (*e.g.*, 4 mm might be perceived as 10 mm). Similarly, the proprioceptive feedback, which brings the intrinsic coordinate I_P to the brain, may have an error, Δ_P, in perceiving the kinematic changes in the limbs; it is perhaps because proprioceptive feedback is not designed to measure the body position relative to the target (*i.e.,* allocentric distance) but designed to update the egocentric spatial representation of the body. The overall error caused by the all three steps are called *visual-proprioceptive mapping error*. Note that, the visual-proprioceptive mapping error is intrinsic as visual feedback is specialized to perceive the body position relative to the target while proprioceptive feedback is specialized to perceive the intrinsic spatial representation of the body [17], [18]. This visual-proprioceptive mapping error, as a combination of Δ_V, Δ_C and Δ_P, limits the sense of distance perception between our hand and an object accurately before touching it, resulting in an error in the motor output, Δ_M [24], [25].

1.4. Conventional Solutions to compensate for the limited visual-proprioceptive mapping accuracy

1.4.1. Visual/Auditory assistance and their limitations

To compensate for the limited visual-proprioceptive mapping accuracy and distance estimation, researchers have employed sensory substitution methods such as auditory and visual assistance to provide additional sensory information to the fingertip. For instance, an auditory feedback system could augment the interaction force or distance to the target, by changing the intensity or frequency of sound [26], [27]. Visual assistance is another popular approach, providing necessary information as a form of graphical representation [28] or color tone [29]. Such an abstract representation of data in the form of curves and colors reveal only the necessary details required for the user to sense the distance [30].

Although auditory or visual compensatory approaches can provide information effectively with user-friendly interface, auditory and visual channels are often occupied during the surgery for other communication and surgical planning tasks. Therefore, the engagement of these senses results in a heavy cognitive load that can distract the surgeon [29]. Moreover, the intrinsic mapping error between the auditory/visual feedback and proprioception further limits the efficacy of those approaches [24].

1.4.2. Haptic assistance

Haptic feedback is another sensory modality to provide better distance estimation while requiring lower cognitive load in finger manipulation tasks [30]–[32]. For instance, Martin Culjat et al. [33] had implemented a pneumatic balloon actuator which produces haptic feedback on the user's fingers based on the contact force. Tavakoli et al. [34] proposed an alternative force feedback system that reflects the force experienced by the robotic gripper to the surgeon's fingers to minimize the excessive grasping force of the fingers reaching delicate tissue structures.

1.4.3. Missing Gap - Current haptic approaches cannot address the error in the approach phase

However, the haptic approach has limitations as it is usually given as a repulsive force to avoid the risky area [35]. Since haptic feedback depends on the kinesthetic sensation of the repulsive force (in addition to tactile sensation), it distorts the hand-motor output, and reduces the motor control accuracy of finger manipulation tasks. Further, haptic feedback is mostly given after the end effector touches the object [36], and therefore it does not improve control accuracy of interactive finger reaching. Indeed, we need a new approach to compensate for the limited control accuracy during the interactive finger reaching before the physical contact on the fingertip and to remove the distortive effect of kinesthetic component.

1.4.4. Tactile feedback as a solution: Electrotactile feedback is flexible than vibrotactile feedback

Tactile feedback is a promising method for improving the motor control accuracy of finger manipulation tasks as it requires no kinesthetic component like haptic feedback. It can be evoked by physical vibrations (*i.e.,* vibrotactile feedback) [37], [38] where the mechanoreceptors on the skin respond to the wide frequency of mechanical vibrations [39]. However, vibrotactile feedback has limitations due to mechanical disturbances near the area where the stimulus is applied and slow response time with mechanical time constant. On the other hand, tactile feedback evoked by alternating electrical current (*i.e.,* electrotactile feedback) can effectively deliver the information with its fast and flexible parameter modulation capability and a mechanically robust implementation with surface electrodes.

1.5. Summary of Experimental Procedure

In this study, we selected electrotactile feedback as a modality to deliver distance information to the fingertip (*i.e.,* distance-based E-stim). The E-stim was applied with a frequency inversely proportional to the distance between the fingertip and the target. We tested the efficacy of the distance-based E-stim against conventional visual sensory feedback method, on enhancing the accuracy of the interactive finger reaching.

1.6. Hypothesis

1.6.1. Electrotactile distance feedback will reduce the visual-proprioceptive mapping error and increase retention

First, we *hypothesize* that the visual-proprioceptive mapping accuracy in interactive finger reaching will optimally improve after training with visual feedback of the fingers and will come back to its baseline value over time, idiosyncratically for each subject. Prior works in arm matching with visual training support this hypothesis [20], [24], [40]. Second, we *hypothesize* that the introduction of the distance-based electrotactile feedback through the E-stim applied on the fingertip, with stimulation frequency inversely proportional to the distance, will enhance the control accuracy of the finger aperture in an interactive finger reaching task [41]. Finally, we *hypothesize* that the increased accuracy of interactive finger reaching, with the distance-based E-stim, will be retained even after turning off the E-stim.

1.6.2. Electrotactile feedback bridges between intrinsic and extrinsic representation

We expect the newly established sensorimotor relationship, between the electrotactile feedback and the motor output, will condition the original sensorimotor operation during the approach phase because electrotactile feedback can be uniquely positioned to bridge the gap between the visual and proprioceptive feedback. While proprioceptive feedback represents the spatial information in intrinsic coordinate and visual feedback in extrinsic coordinate, electrotactile feedback will provide the spatial information in both extrinsic and intrinsic coordinates because the body (represented by intrinsic coordinate) contacts with the external target (represented by extrinsic coordinate). We expect that the E-stim will activate the voltage-gated ion channels in cutaneous nerves innervated on the fingertip. This tactile sensation will generate a new schema of representing visual target in the working memory of the brain as a set of intrinsic coordinates, I_E. We expect that this new electrotactile representation will combine optimally with the visual and proprioceptive feedback to decrease the error in motor output Δ_M. Since the frequency of stimulation is related to the target visual distance, we expect that the corrective feedback due to I_E compensates for the inaccuracy of the distance perceived by proprioception. Therefore, electrotactile feedback may be a promising way to decrease the visual-proprioceptive mapping error.

2. METHODOLOGY

2.1. Methods

2.1.1. Human subject recruitment

The study was performed in accordance with the relevant guidelines and regulations described in the protocol approved by the Institutional Review Board of Texas A&M University (IRB ID: IRB2020-0481). Sixteen healthy human subjects participated in the study. The number of subjects was chosen based on the previous studies of agency and embodiment [42]. The subjects consisted of 7 females and 9 males over the age of 18. All the subjects gave informed consent to their participation in this study. Subjects who had problems in using their hands, history of neurological disease or disorder, and electronic implantable medical devices were excluded from the study.

2.1.2. Experiment Materials

Tapes were wrapped around the thumb and index finger to keep the electrodes in position. Furthermore, black and red markings were made on the tapes of the index finger and thumb, respectively, to optically track the locations of each fingertip.

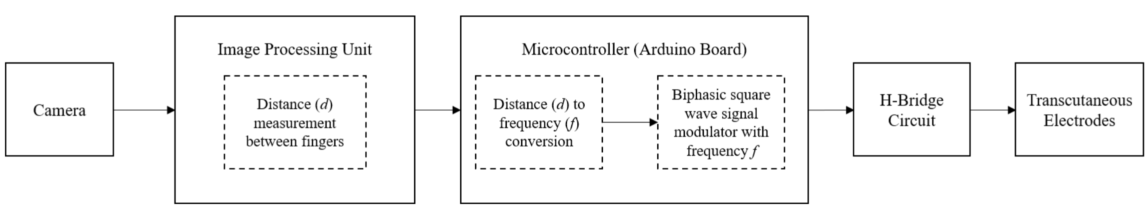

Figure 3: Block Diagram of Experimental Setup. Image sequences of hand captured by a camera were image processed to measure the distance between the index and thumb fingers. The microcontroller board produced a biphasic square wave signal whose frequency was proportional to the distance measured. The biphasic signal drove an H-bridge circuit which produced a biphasic electrical stimulation to the fingers affixed with transcutaneous electrodes.

2.1.2.1. Camera

An 8 Mega Pixel USB document camera with adjustable stand was used to procure sequence of images of the subjects' hand at ~25 frames per second.

2.1.2.2. Image Processing Unit

OpenCV (Python library) was used to process the sequence of input images with the black and red markings on the respective index and thumb fingers to measure the distance between them.

2.1.2.3. Microcontroller

Arduino DUE with SAM3X8E (Microchip) microcontroller was used to control the frequency of electrical stimulation, *f*, to be inversely proportional to the measured distance, *d* (see Eq. 1). The image processing unit transmitted the measured distance serially to Arduino board via Universal Asynchronous Receive-Transmit bus. The Arduino board produced a biphasic signal with a frequency proportional to *d* given by the below relation,

$$f = \begin{cases} f_{max} - d \times \frac{f_{max} - f_{min}}{d_{max} - d_{min}} & if\ d_{min} < d < d_{max} \\ f_{touch} & if\ d \le d_{min} \\ f_{min} & if\ d \ge d_{max} \end{cases} \qquad \text{Eq. 1}$$

here f_{max} and f_{min} are the maximum and minimum frequencies of stimulation, respectively. f_{touch} is the frequency of stimulation applied after the contact. f_{touch} was set as 30 Hz higher than the maximum frequency so that the electrical stimulation can be easily distinguished from the maximum frequency as a touch sensation. The maximum and minimum distances of the approach phase were set as d_{max} = 25 mm and d_{min} = 0 mm, respectively. The biphasic signal has a constant width positive and negative pulses each of 20 ms duration followed by a low output period with varying duration depending on f.

2.1.2.4. Stimulator Circuit

2N3904 transistors and resistors were used to build an H-bridge circuit to convert the control signal to the alternating current between the two electrodes. The circuit was powered by an adjustable DC power supply of 0-30V/0-2mA with an over-voltage and over-current protection. The biphasic signal from the Arduino board drives the H-bridge circuit to produce biphasic electrical stimulation which has a positive pulse of constant amplitude $+V_{sense}$ for 2 ms and a negative pulse of voltage $-V_{sense}$ for 2 ms followed by a 0 V period with varying duration 1/f; where the voltage at which the frequency of stimulation can be discriminated comfortablly without any pain for a given subject is V_{sense}. Biphasic stimulation was chosen to miminize the potential charge imbalance at the area of application of E-stim [43], [44].

2.1.2.5. Transcutaneous Electrodes

Square-shaped gel electrodes of 10 mm x 10 mm dimensions were custom made using a sheet of conductive carbon fiber with adhesive hydrogel. Multi-threaded 36-AWG wire was attached to the carbon layer using silver conductive epoxy to provide electrical contact. The electrodes were fixed on the thumb and index finger of the palm in the distal phalangeal region where the median nerves innervate as shown in Fig. 4. Conductive gel was applied at the site of electrode to reduce the skin impedance. The biphasic voltage from the H-bridge driver circuit provides electrical stimulation to the subjects via these electrodes.

Figure 4: Electrical stimulation applied to the thumb and index finger. The stimulation electrodes were attached in the regions of thumb and index fingers (shown in red) where the medial nerves (shown in yellow) innervate.

2.2. Experiment procedure

Sixteen subjects in total were split into two groups with 8 subjects each. One group received the conventional visual training while the other group received distance-based electrotactile and visual feedback training. The experiment was carried out for two days with a series of trials where subjects were asked to reproduce a target line on a screen as a gap between their fingers (see Fig. 7), with or without electrotactile feedback. All

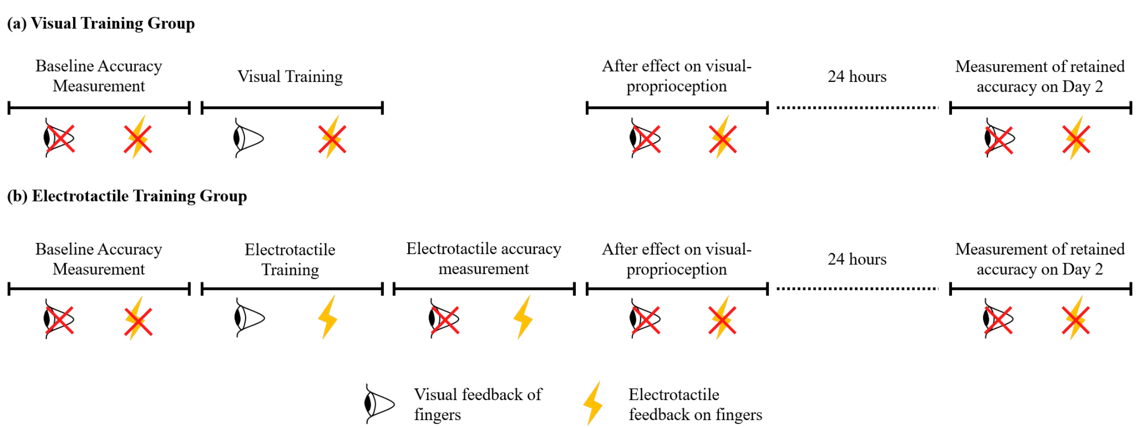

Figure 5: Experimental protocol. The experiment was divided into 3 trial sessions (+1 training session) and 4 trial sessions (+ 1 training session) for visual and electrotactile group, respectively. The feedback given to a human subject from a group during each session is shown below the session line.

subjects were asked to visit the experimental site twice with exactly one day gap between each visit. The experiment overview and timeline are shown in Fig. 5 and 6, respectively.

2.2.1. Experiment 1 – Baselining visual-proprioceptive mapping error

Initially, subjects were asked to keep their index and thumb fingers away from each other. Subjects were, then, asked to look at the monitor screen where different lines representing the target distance was displayed. The length of the lines changed between 2 and 20 mm, in steps of 2 mm, and was displayed in random order, one at a time. Without

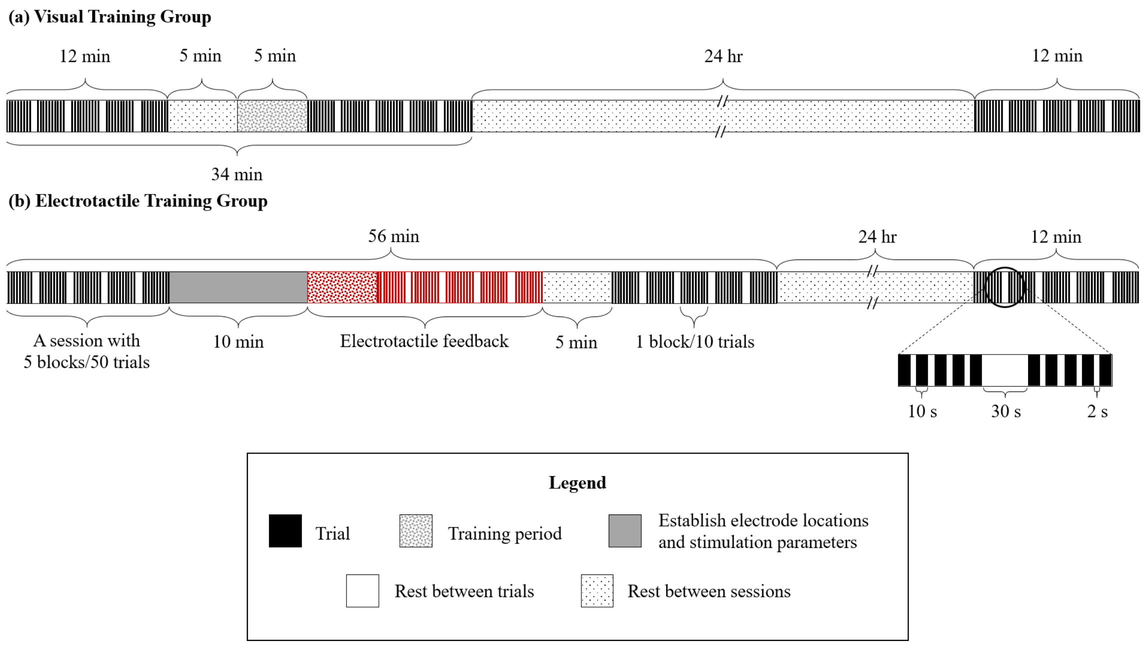

Figure 6: Timeline of the visual and electrotactile group experiment. Visual and electrotactile group has 3 and 4 trial sessions, respectively. Each session has 5 blocks of 10 trials totaling to 50 trials per session and in each block, 10 target lines of 2 – 20 mm in steps of 2 are displayed on the screen in random order. Each trial lasts for 10 seconds with 2 seconds gap between them to reset the fingers to the initial stretched position. Between each block, there is a 30 second gap to avoid finger fatigue. Visual feedback of the fingers is given only during the training period. In electrotactile group, before the training period, 10 minutes is used to establish the electrode location on the index and thumb fingers, the frequency range (f_{min} to f_{max}) and the stimulation voltage (V_{sense}) for the subject. The sessions with the electrotactile feedback are marked in red. In both the groups, after establishing the after-effect of visual and electrotactile feedback on visual-proprioception, there is a 24-hour gap before the final session. The final session on the second day is used to establish the retained motor-control accuracy even after resting.

looking at the hands, the subjects moved their fingers to adjust the gap between them to match the target line length. Subjects were given 10 seconds to position their fingers before the next target line was displayed. After the 10 seconds, the distance between the fingertips was measured and recorded using the camera over the subject's hands and the subjects were, then, asked to return their fingers to the initial position. Hence, 10 target lines of different lengths were displayed with 10 seconds positioning time for each. The experiment was repeated for 5 times to obtain sufficient data to test the three hypotheses. A baseline value of visual-proprioceptive mapping error before the introduction of electrotactile feedback was obtained using this experiment in both the groups.

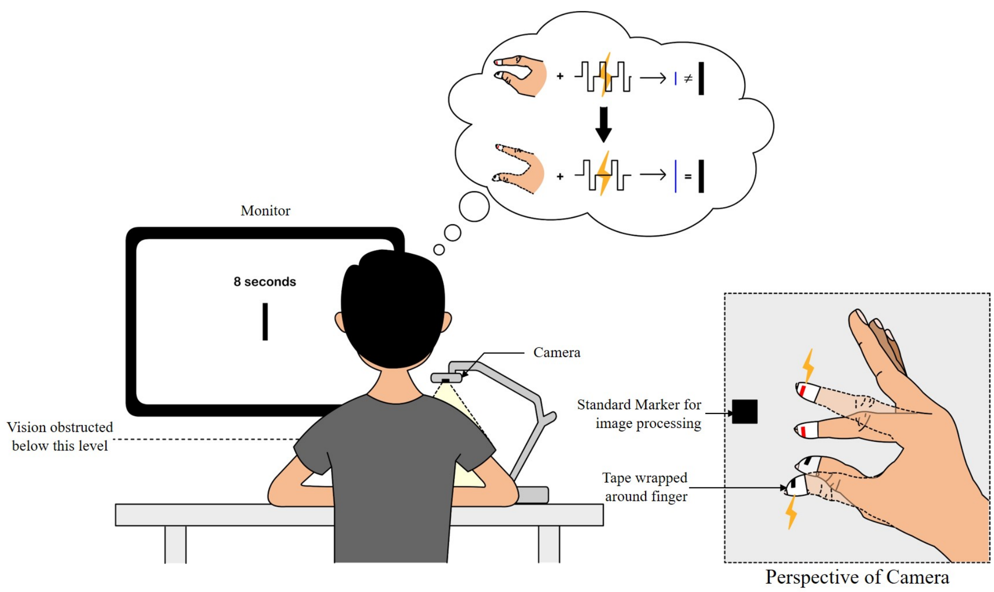

Figure 7: A subject performing experiment 3. The camera processes the finger aperture and the experimental hardware controls the stimulation frequency. The subject feels that the stimulation frequency increases as the gap between the fingers decreases. (Inset - Screen during the training) During the training period, the subject sees his hand on the screen with a virtual line overlaid on the gap between the fingers. He maps the line between the fingers with corresponding electrical stimulation frequency and memorizes them. (Left - After training) The subject is mapping the target line on the screen with the stimulation frequency felt on the fingers based on the learning from the training period. The camera processes the error in the mapping.

2.2.2. Experiment 2 – Visual-proprioceptive/Electrotactile training and its effect

For one group, biphasic electric stimulation was applied, and voltage was gradually increased to determine V_{sense} and $V_{discomfort}$, where subjects start to feel electrotactile feedback and feel any discomfort, respectively. Finally, the average of these two voltage levels was set as the E-stim amplitude throughout this experiment as shown in Fig. 8(a). The frequency range of the applied E-stim was also determined based on the verbal reports of the subjects. Initially, the maximum frequency was set as 80 Hz and the minimum frequency as 10 Hz. The subjects were asked to vary the finger aperture between 25 mm and 0 mm and to report each finger aperture gap at which they felt the difference. If they felt a difference in E-stim sensation (pulsating or pinching) in decrements of at most 2.5 mm, the corresponding minimum and maximum frequency was used; if not, the maximum frequency was reduced in decrements of 5 Hz until an aperture gap decrement of less than or equal to 2.5 mm was achieved for the differential sense of E-stim. The

(a) (b)

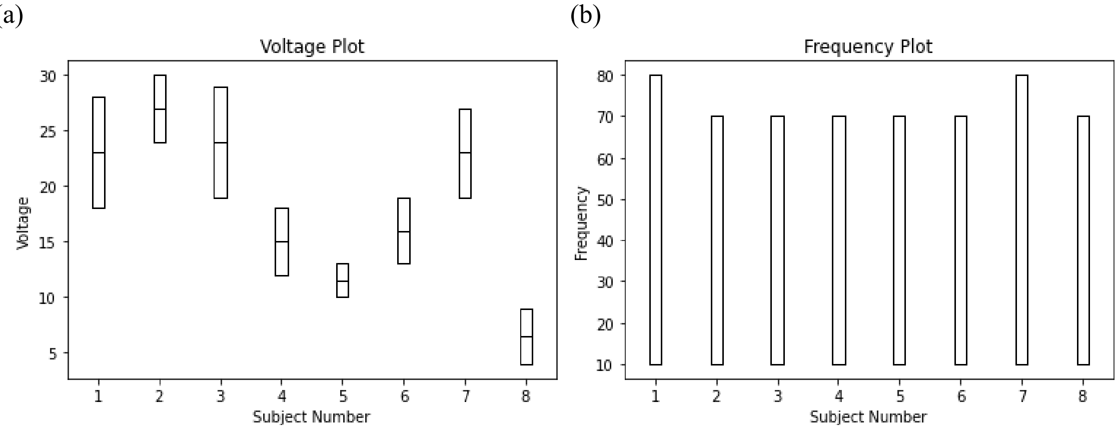

Figure 8: (a) Voltage and (b) Frequency range for each subject in the electrotactile group. (a) The top and bottom line indicates the discomfort and minimum sensible volage level for each subject. The middle line indicates the actual applied voltage. (b) The bar graphs indicate the frequency range for each subject. The maximum frequency corresponds to d_{min} = 0 mm and the minimum frequency corresponds to d_{max} = 25 mm.

frequency range for each subject in the electrotactile group is shown in Fig. 8(b). The above initial setup was performed only for subjects from the electrotactile group.

A top view of the subjects' hand captured by a camera was displayed on the monitor screen for both the group. A virtual line was overlaid between the gap of their fingers on the screen. The subjects were then asked to move their fingers closer and further apart in steps of varying distances between the fingers. For each step, subjects were asked to map the corresponding virtual line between the fingers and the stimulation frequency in their memory. This experiment constituted the training period for visual-electrotactile mapping. For the other group, an identical training session was carried out without E-stim.

2.2.3. Experiment 3 – Establishing the post-training mapping error

Once the training was completed, with the E-stim applied to one group and not applied to the other group, experiment 1 was repeated to determine the corresponding mapping error. Subjects were asked to use their learning in training period to replicate the target distance by their fingers. Fig. 7 describes the detailed procedure of the training and post training sessions. For the group trained with E-stim, experiment 1 was repeated again with E-stim turned off, to identify the after-effect of the E-stim on visual-proprioceptive mapping accuracy.

2.2.4. Experiment 4 – Determining the learning effect of day 1 training on mapping error on day 2

On the day 2 visit, with no E-stim applied, experiment 1 was repeated to determine whether the motor learning of visual-proprioceptive mapping on day 1 is retained.

3. RESULTS

The standard error plots from the subjects of each group are shown in Fig. 9. The relative error along the y-axis of the figure represents the ratio of finger aperture error (*i.e.,* target distance – actual finger aperture distance) to target distance for each experiment represented along the x-axis. The statistical significance between each experiment for a group is determined via unpaired t-test with 95% confidence interval. The baseline visual-proprioceptive mapping has a standard error mean, $SEM \cong 0.062$ and mean, $m \cong 1.06$ for the visual group and $SEM \cong 0.051$ and $m \cong 1.22$ for the group trained with E-stim. The corresponding values after training for groups without and with E-stim are $SEM \cong 0.053$ and $m \cong 0.84$ and $SEM \cong 0.035$ and $m \cong 0.43$, respectively.

The after effect of E-stim on visual-proprioceptive mapping is $SEM \cong 0.052$ and $m \cong 0.87$ for the E-stim group. Furthermore, the visual-proprioceptive mapping values on

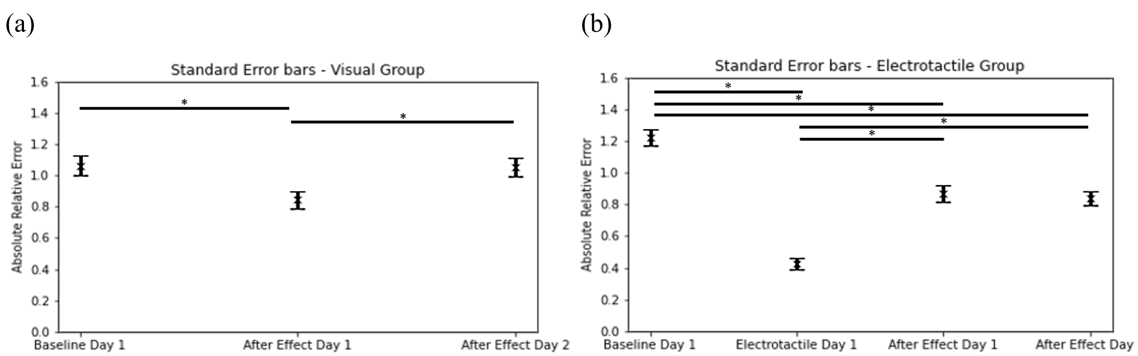

Figure 9: A standard error plot of (a) visual and (b) electrotactile group. The crosses represent the mean error while the bars represent the corresponding standard error. The value on the y-axis is the relative error ratio (error distance/ actual distance) where 0 indicates no error and 1 indicates 100% increase in error from its true value. The asterisk (*) indicates statistical difference with 95% confidence interval via unpaired t-test.

day 2 for groups without and with E-stim are $SEM \cong$ 0.060 and $m \cong 1.05$ and $SEM \cong$ 0.044 and $m \cong 0.84$, respectively.

For the visual group, the relative error has significantly improved in day 1 after effect test compared to day 1 baseline test ($p < 0.0071$.) The error in day 2 after effect test is statistically insignificant compared to the baseline error value ($p = 0.9108$) indicating that the finger aperture accuracy comes back to the baseline value.

For the electrotactile group, the relative error for day 1 test with electrotactile feedback is extremely significant compared to the day 1 baseline test ($p < 0.0001$) indicating that the E-stim has produced significant improvement in the control accuracy. After removing the E-stim in the day 1 after effect test, the relative error has increased compared to the feedback case ($p < 0.0001$). However, the relative error of day 1 after effect test has significantly improved compared to its baseline value ($p < 0.0001$). Moreover, the error values of day 1 and day 2 after effect test are statistically not significant ($p = 0.7019$) indicating a retention of the control accuracy even after the removal of E-stim.

4. DISCUSSIONS

4.1. The effect of visual-proprioceptive training on finger aperture accuracy in finger reaching task degrades quickly

During the baseline test of the visual group, where no visual feedback of the fingers was provided, subjects had to solely rely on their proprioceptive feedback to map the target visual distance, which formed the baseline visual-proprioceptive mapping error, as in Fig. 10(a). Note that, a visual estimate with zero offset from the visually perceived distance arises as a result of visual memory due to the absence of the visual feedback; this visual estimate is extremely unreliable, as shown with a smaller sensory weight in Fig. 11(a), compared to the proprioceptive estimate.

As the visual feedback has Δ_V and Δ_C as errors, it perceives the target distance as intrinsic coordinates with a systematic error [24]. However, it still represents the exact same target distance in the extrinsic coordinates. For instance, the visual system may perceive the target distance of 10 mm, 12 mm and so on as 12 mm, 14 mm and so on, internally. However, if the visual system were to map this internally perceived distance with a target distance, it would do so with zero error as the intrinsic encodings can be transformed back to the extrinsic coordinates *e.g.,* 12 mm internally is indeed 10 mm in extrinsic coordinates indicating zero offset. Also, we believe that proprioceptive estimate has positive offset from the visually perceived distance due to the mismatch between the two sensory modalities in representation of the target distance *i.e.,* proprioceptive feedback is not with respect to the target (allocentric) but rather with respect to the body (egocentric) resulting in a systematic error of Δ_P.

It can be observed from the results of the visual group that visual-proprioceptive mapping accuracy improved from the baseline accuracy after training with the visual feedback of fingers but drifted back to the baseline value on the second day of the experiment. Smeets et al [20] explained this "no improvement in hand positioning error after training" by the different strategies of the nervous system in estimating the positions of the hand. With the vision of subject's own fingers, the nervous system depends on both the visual and proprioceptive feedback of the fingers, and therefore the resulting error is in between the visual and proprioceptive errors, as in Figs. 10(b_1) and 11(b_1). However, in the absence of the visual feedback, the uncertainty in the actual position of the fingers will be amplified over the trials and the effect of visual estimate fades out. Therefore, without the visual feedback, the nervous system mainly depends on the proprioception from the fingers, which would increase the finger aperture estimate closer to the proprioceptive estimate (see Figs. 10(d_1) and 11(d_1)) and eventually, returns to the baseline value, as in Figs. 10(e_1) and 11(e_1), due to extremely low precision visual estimate. The important point here is that, based on current knowledge, the nervous system simply changes the dependency on each sensory feedback during and after the training, instead of renovating its process to decrease the error.

4.2. Distance-based electrotactile feedback improves the interactive finger reaching accuracy

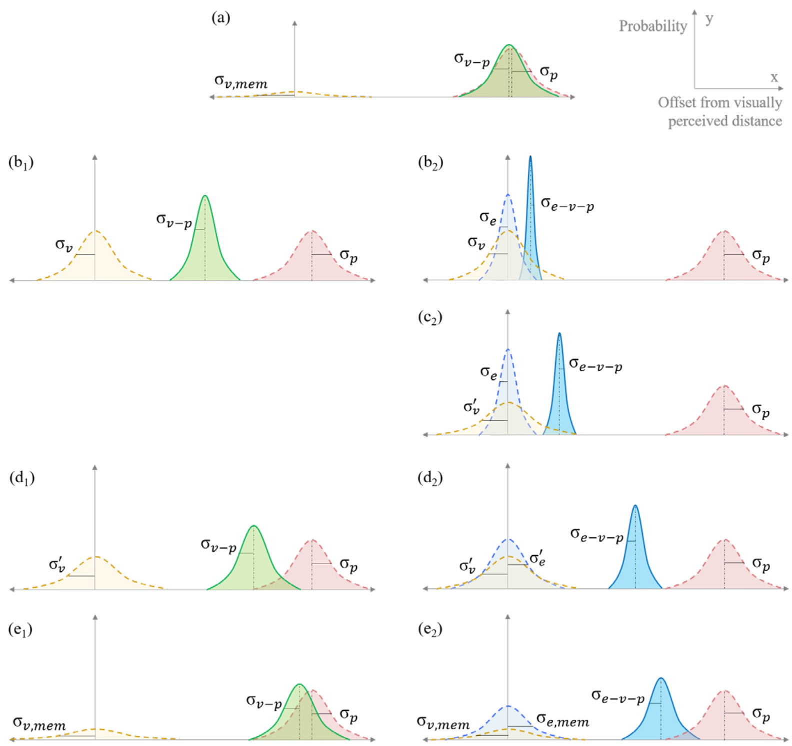

Figure 10: Error estimates of different sensory modalities and their combinations. The discontinuous curves represent the Gaussian distribution of distance estimate for different sensory modalities whereas the continuous curves indicate the optimum combination of individual sensations to produce the final error estimate. The x-axis indicates the offset from the visually perceived target distance by the brain. Visual group: The green curve in (a) indicates the optimal combination of visual and proprioceptive estimates to produce combined baseline error estimate. The visual estimate in (a) is less precise which after training in (b_1) becomes more precise, reducing the baseline error. However, immediately after training, in the absence of feedback, due to uncertainty, visual estimate becomes less precise causing the combined estimate to drift towards the proprioceptive estimate on day 1 after effect test (d_1) and completely return to its baseline value on day 2 after effect test (e_1). Electrotactile group: As in visual experiment, the green curve in (a) indicates the optimal error estimate in the baseline experiment. However, during training as in (b_2), the presence of very precise electrotactile estimate (due to direct representation of distance as frequency of electrical stimulus) causes the optimum error estimate to shift greatly towards the more precise electrotactile estimate improving the finger aperture accuracy. After training, when visual feedback is removed in (c_2), the visual estimate becomes less precise due to uncertainty shifting the combined estimate slightly towards the right. When the electrotactile stimulus is removed as in (d_2), its corresponding tactile sensation updated in the tactile working memory of brain during previous session, becomes less precise shifting the combined estimate a bit more to the right. Finally, as in (e_2), the uncertainty in visual estimate and the act of forgetting in tactile memory causes the combined estimate to drift slightly to the right; however, more precise than the baseline estimate.

One important fact in the positioning estimate of the fingers is that, both visual and proprioceptive feedback have an intrinsic error in reporting the finger position, respectively. Even though we reduce the visual-proprioceptive mapping error, those intrinsic errors cannot be addressed. In other words, we need a new "sensory reference"

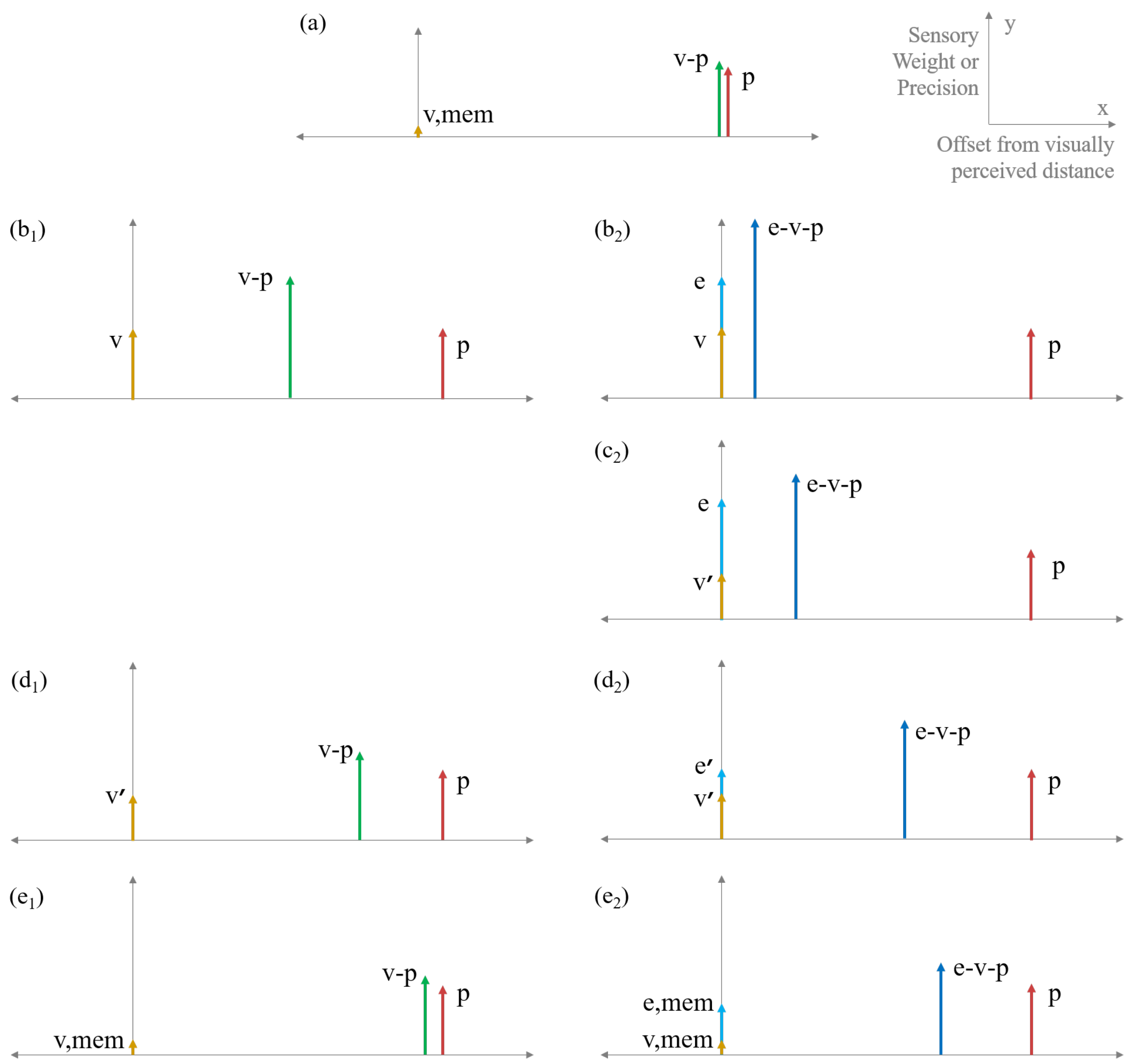

Figure 11: Sensory weights of different sensory modalities and their combinations. The y-axis indicates the sensory weight or contribution of each modality. The x-axis indicates the offset of that modality from the visually perceived target distance by the brain. The optimum sensory weights shown as a combination of different modalities is obtained as a weighted average of each of the feedback with the weight proportional to the sensory weight or to the inverse of the variance. Refer to Fig. 10 for a detailed description.

that can deliver the position information to the nervous system with higher accuracy. We speculate that the distance-based electrotactile feedback would work as a new sensory reference for interactive finger reaching. Indeed, when subjects were trained using distance-based electrotactile feedback in repeated trials, the accuracy of interactive finger reaching increased significantly. This result suggests that distance-based electrotactile feedback provided accurate positioning information to the subjects. This result also indicates that distance-based electrotactile feedback somehow dominated both visual and proprioceptive feedback in positioning the fingertip.

We posit that the E-stim applied on the skin surface causes excitation of the nerve fibers attached to mechanoreceptors, especially Meissner corpuscles and Merkel cells due to their closer proximity to skin surface and slow-adapting nature to the applied low frequency range of stimulation (*i.e.* electrotactile feedback) [45]. We believe that the oscillatory tactile sensation, due to excitation of the cutaneous afferents, created a new tactile working memory in the brain consisting of an encoding of the perceived electrotactile frequency [46]. This has been represented as a more precise electrotactile estimate, compared to visual or proprioceptive estimate, as shown in Figs. 10(b_2) and 11(b_2) depicting the training period estimates. Since the E-stim accurately represents the error between the allocentric target distance and the egocentric finger aperture, the electrotactile estimate has a zero offset from the visually perceived distance. Thus, the optimal combination of electrotactile, visual and proprioceptive estimate causes the combined estimate to be shifted towards the highly precise E-stim estimate resulting in improved accuracy compared to the baseline experiment. As in Figs. 10(c_2) and 11(c_2), during day 1 test with E-stim, the absence of visual feedback reduces the precision of visual estimate causing the combined optimal estimate to drift slightly towards the proprioceptive estimate.

4.3. Training with distance-based electrotactile feedback has a strong aftereffect

To adjust the visual-proprioceptive mapping error and truly improve the positioning accuracy of the hand or the finger, we need a new sensory reference that can condition the mapping between the visual and proprioceptive feedback. Based on our experimental result, it seems like the distance-based electrotactile feedback works as the new sensory reference, which conditions the original visual-proprioceptive mapping.

This notion is supported by the observation that, even after turning off the electrotactile feedback, the accuracy error did not completely drift back to its baseline value. The tactile working memory formed by the E-stim persisted even after it is removed [47]–[49], which has an improved finger aperture accuracy compared to the baseline value. However, the absence of E-stim causes an uncertainty in the tactile estimate in the working memory which results in a less precise electrotactile estimate as shown in Figs. 10(d_2) and 11(d_2). This may have caused an increase in the finger aperture error after removing the electrotactile feedback (*i.e.,* change from Figs. 10(c_2) to 10(d_2) or 11(c_2) to 11(d_2)). We believe that the tactile working memory for the E-stim persists as a long-term memory resulting in less drift compared to the visual estimate. This explains the reason for the lasting effect of the E-stim on the visual-proprioceptive mapping. Even a day post the electrotactile training, the interactive finger reaching accuracy stays almost at the same level as the one right after the training (Figs. 10(e_2) and 11(e_2)). Note that, the finger aperture accuracy on a day after the electrotactile training was statistically same as the accuracy right after turning off the E-stim. In fact, it can be observed that E-stim provides significant improvement in control accuracy of the finger aperture and longer retention even when it is not present.

4.4. Enhanced accuracy in interactive finger reaching will improve the surgical performance, telerobotic control, and virtual-reality behavior

Providing distance-based E-stim on the fingertip may improve the performance of surgeons in surgical tasks requiring complex finger movements with high control accuracy (*i.e.,* assistive effect). Furthermore, the training with distance-based E-stim may form a new sensory reference, which will enhance the finger control accuracy even after the training (*i.e.,* learning effect). We believe that these assistive and learning effects of distance-based E-stim will be helpful especially for the novice surgeons who are struggling with the novel surgical systems. Electrotactile stimulation may also find applications in virtual-reality operations where a tactile sensation of virtual objects would help the users to be completely engaged in the virtual environment [50].

4.5. Limitations in our approach and future plan

This study is limited in the duration of the trial period, as we observed after-effect only till one day post training. In the follow-up study, we plan to extend the trial period to one week and identify any changes in the visual-proprioceptive mapping error with any potential drift in the electrotactile reference. We also plan to increase the number of subjects to confirm the results over the biological variation.

5. CONCLUSIONS

Our study supports the hypothesis that the distance-based E-stim on the fingertip improves the interactive finger reaching accuracy, both during and after the application of the E-stim. The distance-based electrotactile sensation discussed in our study would improve surgeons' intuition on the relative position between end effectors or between end effector and target object. We conclude that the electrotactile feedback has a great potential to improve the dexterity of surgeon's hands in tele-robotic maneuvering and reduce the potential damage on the tissue during the surgical procedure.

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