Differential effects of explicit verbal and visual feedback on proprioceptive learning: Examining position sense acuity of the forearm during active and passive displacement

A THESIS

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Dedication

This thesis is dedicated to my parents and my friends who always support me and give me help.

Abstract

Both *intrinsic* feedback derived from proprioceptive and tactile mechanoreceptors, and *extrinsic* visual or auditory feedback play an important role in sensorimotor learning. However, the interaction between intrinsic and extrinsic forms of feedback and the effect of extrinsic feedback on proprioceptive function during sensorimotor learning are only incompletely understood. The purpose of this study was to compare the differential effects of intrinsic and extrinsic verbal and visual feedback on proprioceptive learning. Specifically, this study investigated how the acuity of the forearm position sense changes during sensorimotor learning under different conditions of feedback. **Methods:** Thirty healthy young adult participants underwent a sensorimotor training program delivered in two training sessions in a single day. Using a forearm manipulandum, participants performed forearm flexion movements and learnt to actively match a previously experienced forearm position. After the matching movement, participants received either *proprioceptive only* or a combination of intrinsic and extrinsic feedback (*proprioceptive* + *visual* or *proprioceptive* + *verbal* feedback) about the final forearm position error. Vision was blocked for the *proprioceptive only* and *proprioceptive* + *verbal* feedback conditions. All participants received 150 training trials. Retention was tested 24 hours after training. Proprioceptive acuity was evaluated: *Just-noticeable difference (*JND*)* position sense thresholds served as a measure of passive elbow proprioceptive acuity. *Absolute joint position matching error (*JPME*)* represented a measure of active proprioceptive acuity. **Results:** First, none of feedback conditions led to a significant decrease in JND after training ($p > 0.05$). Second, all three feedback conditions induced a statistically significant reduction in JPME after training ($p < 0.05$) with both the *proprioceptive only* (Cohen's $d = 1.62$) and *proprioceptive* + *verbal* (Cohen's $d = 1.57$) feedback conditions showing the very large effect sizes. However, change in JPME with training was not significantly different between the three feedback conditions ($p > 0.05$). Third, the observed reduction in JPME at post-test had vanished 24 hours after training. **Discussion**: I found no evidence that providing additional extrinsic feedback in a proprioceptive learning task can boost joint position sense accuracy. Proprioceptive training relying solely on proprioceptive signals is sufficient to induce measurable improvements of active position sense. However, such learning was not retained after 24 hours.

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Other (list of abv.)

JND	Just-noticeable difference threshold
JPME	Joint position matching error

Introduction

It is well documented that sensorimotor learning can improve motor performance as well as proprioceptive accuracy [1]. Feedback positively impacts sensorimotor learning, specifically in the correction of movement errors [2]. Feedback can be classified as either intrinsic or extrinsic. Intrinsic feedback relies on information derived from proprioceptors or other somatosensory receptors, which is critical to motor learning. Extrinsic feedback relies on information that cannot be elaborated without an external source, such as a human expert or a technical display [3], and it is typically provided after the completion of the desired movement.

According to Sherrington [4], proprioception refers to the ability to sense the current position and motion of the body and its limbs in space, in the absence of vision or other senses. Proprioceptive feedback is essential for the accurate movement execution. It can regulate motor command generation by using temporal and spatial cues to correct movement errors. Such correction of movement errors are especially important in activities of daily living (ADL) like reaching, throwing, and eating that rely on upper limb proprioception [5]. Loss of proprioceptive feedback will significantly impair movement control in neurological diseases such as cerebellar ataxia, Parkinson’s disease, peripheral sensory neuropathy, cortical stroke, and developmental coordination disorder [5]. This necessitates therapies that focus on improving proprioceptive function, especially in the upper limb.

Somatosensory-focused training is a special form of sensorimotor training applied with intrinsic proprioceptive feedback, and/or extrinsic visual or verbal feedback. Application of either intrinsic proprioceptive or extrinsic verbal/visual feedback in such somatosensory-focused training have been shown to improve motor performance and somatosensory function [6, 7]. For instance, proprioceptive training is a type of somatosensory-focused training that utilizes intrinsic proprioceptive feedback to induce and/or enhance sensorimotor learning [5]. There is converging evidence that proprioceptive training can yield meaningful improvements in somatosensory and sensorimotor function [5]. Additionally, extrinsic feedback, provided by a trainer or a display, also effectively enhances sensorimotor learning [8]. However, the interaction between intrinsic and extrinsic forms of feedback and differential effects of extrinsic feedback for improving proprioceptive acuity during sensorimotor learning are only incompletely understood.

Review of Literature

The following literature review defines the terms proprioception, proprioceptive receptors, and proprioceptive acuity. In addition, the review will present evidence on the role of both intrinsic and extrinsic feedback in sensorimotor learning. Finally, the review discusses the limited evidence of differential effects of intrinsic and extrinsic feedback on sensorimotor learning.

Proprioception and proprioceptive receptors

Proprioception refers to the conscious awareness of body and limb position, motion and orientation. The different aspects or submodalities of proprioception are passive motion sense, active motion sense, limb position sense, and sense of heaviness [9]. Proprioception is mediated by proprioceptive receptors such as muscle spindles that are primarily responsible for position and movement sense, and Golgi tendon organs that provide the sense of force (tension) [10] as discussed below.

Muscle spindles

Muscle spindles are proprioceptive receptors that consist of intrafusal muscle fibers enclosed in a sheath (spindle) [11]. Muscle spindle receptors respond in a nonlinear fashion to changes in the lengths of muscle fibers in large part because of the mechanical properties of the contractile intrafusal muscle fibers [12]. Although the muscle spindle reacts to stretch, it does not simply "turn off" when the muscle is no longer stretched; the fibers continue to send messages when the muscle has begun to concentrically contract and shorten. The muscle spindle activity is modulated by *alpha-gamma coactivation*, which contributes to muscle tone and thus to the intrinsic stiffness of the muscle [13].

Golgi tendon organs

Golgi tendon organs (GTOs) are proprioceptive receptors activated by stretch or active contraction of a muscle and transmit information about muscle tension. GTOs are located in the tendons, close to the point of muscular attachment [10, 13]. The stretch of the tendons reflects the force on the tendon that is developed by all of the muscle. The firing rate of the Golgi tendon organ encodes muscle force rather than stretch, even though it senses stretch [14].

Evaluation of proprioceptive acuity

Proprioceptive acuity is defined as the ability to accurately sense joint position in space, force of muscle contraction, and to accurately discriminate between two joint positions [15]. Researchers have documented proprioceptive acuity typically observed in healthy adults at several joints such as knee flexion and extension, shoulder flexion, elbow flexion [16-18].

Proprioceptive acuity can be evaluated using psychophysical methods that are known to provide reliable and valid measures of proprioceptive function [19]. Evaluation of proprioceptive accuracy has two components - *bias* represents the systematic error and *precision* indicates random error [4]. Bias in proprioceptive acuity is usually evaluated in terms of *Just-noticeable difference (*JND*)* position sense thresholds, and/or absolute *joint position matching error (*JPME*)* [19]. Threshold defined as the smallest amount of stimulus energy necessary to produce a sensation, can be measured as detection or discrimination thresholds. Detection threshold is defined as the smallest perceivable change in position whereas discrimination threshold is the critical perceivable difference between two positions [19]. A *forced-choice paradigm* is a psychophysical method in which the subjects are forced to identify an odd stimulus from two different stimuli. This method can be used to test either passive or active movements [19, 20]. JPME is the angular difference measured between target and matched positions. It indicates a joint position error in the ipsilateral and/or contralateral matching tasks [19, 21, 22].

The role of intrinsic feedback for sensorimotor learning

Proprioceptive training is a form of sensorimotor training applied with intrinsic proprioceptive feedback. Proprioceptive training targets the improvement of proprioceptive function. It relies on the somatosensory receptors such as proprioceptive receptors in the absence of vision or other senses [5]. Such somatosensory training while enhancing proprioceptive function can result in concurrent motor learning. This concurrent motor learning will manifest as motor performance improvements [23]. Long-term proprioceptive training in stroke documented that proprioceptive training can result in not only motor learning but also somatosensory learning. It has been shown to alter cortical activity both in somatosensory and sensorimotor processing areas. A study by Dechaumont-Palacin (2008) found a passive proprioceptive training with wrist extension applied for 4 weeks can modify brain sensorimotor activity in 7 subcortical stroke patients. This proprioceptive training of the wrist showed a significantly increased activation of the ventral premotor and parietal cortices in the contralesional hemisphere ($P < .01$) [24].

Proprioceptive training may utilize different types of intrinsic somatosensory feedback such as muscle vibration, vibro-tactile stimulation and haptic feedback [25, 26]. A study demonstrated a 3-day robot-assisted wrist proprioceptive training with added vibro-tactile feedback can enhance somatosensory and motor performance. Proprioceptive acuity of the wrist joint position sense improved after training for seven right-handed young adults with additional vibro-tactile feedback. The observable improvements in proprioception facilitate sensorimotor learning [27]. The somatosensory discrimination training focuses on the ability to discriminate between two somatosensory stimuli using intrinsic proprioceptive feedback. A study has shown that a 14-week *stimulus-specific training* (SST), was successful for trained texture and proprioceptive discriminations in 3 stroke patients. The texture grid or flexion-extension stimuli were trained over ten treatment sessions. Patients showed improvements in touch discrimination and wrist proprioception based on the increasing scores of the *tactile discrimination test* (TDT), the *fabric matching test* (FMT), and the *wrist position sense test* (WPST) [28]. Based on the above studies, it is clear that various types of intrinsic feedback play an important role in sensorimotor learning. This sensorimotor learning results in both behavioral improvements observed in the form of enhanced proprioceptive and motor function and physiological improvements manifested as cortical plasticity.

The role of extrinsic feedback for sensorimotor learning

Extrinsic feedback enhances sensorimotor learning [3]. Extrinsic feedback can be provided by a human expert or a technical display using external sources through vision, verbal, haptic, or multimodal feedback [3, 8]. Behavioral improvements after the use of extrinsic feedback in sensorimotor learning have been documented. In a study, 14 healthy adults took participate in a robot-aided wrist proprioceptive training with extrinsic visual feedback. The task required to finish 45 training trials to move the ball to a circular target and to hold there for 5 seconds. The level of task difficulty changed by increasing a balanced wrist position of either 10°, 15° or 20° flexion. All participants showed improvements in the JND threshold by about 34%. Wrist movement accuracy evaluated in terms of JPME improved by 27% in 13 participants [29]. Other studies revealed corticomotor facilitation by observing hand actions as a function of extrinsic visual feedback provided in sensorimotor learning [30-33]. In one study, the hand action depicted by a video displayed the hand action of a male cutting a piece of material with scissors. 11 healthy adults imitated the same hand action after viewing the video and had shown a significant increase in amplitude of *motor evoked potentials* (MEP) in muscles of the right hand (*first dorsal interosseous*: FDI; and *abductor digiti minimi*: ADM) compared to the rest condition (eyes closed and instructions to relax for 10s) [30].

Verbal extrinsic feedback can also be applied in sensorimotor training. A study used a three-week specific training of standing up with verbal extrinsic feedback for 12 stroke patients. Verbal extrinsic feedback was about weight distribution provided by the *limb-load monitor* (LLM). This device can generate a proportional auditory signal which correlated with the amount of weight placed on the affected lower limb. The sound decreased in frequency with increasing loading and became silent when the loading goal was reached, or increased if actual loading did not match the intended loading. The loading goal was determined by recording the maximum amount of weight the subject can bear over 5 trials. Patients increased peak vertical force through their affected lower limb after training. This result indicated that verbal extrinsic feedback added on training can help improve muscle strength and muscle control [34]. Based on the above studies, it is clear that extrinsic feedback also plays an important role in sensorimotor learning.

Differential effects of intrinsic and extrinsic forms of feedback

The studies above all explored the effects of intrinsic feedback or extrinsic feedback independently. One study tried to investigate the sensorimotor learning effects of visual versus verbal extrinsic feedback training in dynamic postural control. Eighteen healthy young adults took a three-day task bringing the real-time *center of pressure* (COP) in line with a hidden target by body sway in the sagittal plane. The target moved in seven cycles of sine curves at 0.23 Hz in the vertical direction on a monitor. The visual or verbal extrinsic feedback were provided by the change of the magnitude of a visual circle and a sound, respectively, based on the distance between the COP and the target for reaching the target. The verbal extrinsic feedback group demonstrated a significant decrease in the distance between COP displacement and the target in both the spatial and temporal parameters ($p < 0.05$) compared with the visual extrinsic feedback group. It indicates verbal extrinsic feedback is more effective in motor learning of dynamic postural control [35]. However, this study only focused on the lower limb, not the upper limb. Thus, this study will investigate the interaction between intrinsic and extrinsic form of feedback and the differential effects of extrinsic verbal and visual feedback on proprioceptive learning, especially how acuity of the forearm position sense changes during sensorimotor learning under different conditions of feedback.

Summary

The important points derived from this review are the following: Sensorimotor learning improves both motor performance and proprioceptive accuracy [1]. First, feedback can be classified as intrinsic or extrinsic. Intrinsic feedback is inherent in our body obtained from proprioceptors or other somatosensory receptors [4]. Extrinsic feedback comes from the information that cannot be elaborated without an external source, such as seeing or hearing from a trainer or a display [3]. Both forms of feedback play an important role in sensorimotor learning [2]. Second, proprioceptive acuity is the ability to accurately sense a joint position in space in the absence of other senses. Accuracy has two components. *Bias* represents the systematic error and *precision* indicates random error [15]. Bias in proprioceptive acuity is usually evaluated in terms of *Just-noticeable difference* (JND) position sense thresholds and/or *absolute joint position matching* error (JPME) [19]. Third, there is converging evidence that sensorimotor training with proprioceptive intrinsic feedback can yield meaningful improvements in somatosensory and sensorimotor function [5, 23-28]. Fourth, extrinsic feedback, provided by a trainer or a display, such as visual or verbal, also effectively enhances sensorimotor learning [8, 28-32, 34]. Finally, most studies investigate a single type of feedback on sensorimotor learning or compared the effects of two extrinsic feedback on just lower limb [35]. This study aims to evaluate the differential effects of intrinsic and extrinsic feedback on sensorimotor learning, especially how acuity of the forearm position sense changes during sensorimotor learning under different conditions of feedback.

Aims and hypotheses:

The goal of this study was to compare the interaction between intrinsic and extrinsic forms of feedback and differential effects of extrinsic feedback on proprioceptive learning. The specific aims and hypotheses are as follows:

Aim 1: To determine the type of unimodal feedback or multimodal feedback combination that yields the highest gains in proprioceptive and motor function. Participants performed forearm flexion movements and learnt to actively match a previously experienced forearm position. Outcome measures of proprioceptive learning are the just-noticeable difference threshold (JND) and the absolute elbow position matching error (JPME). Participants in the three different groups will receive different combinations of intrinsic and extrinsic feedback in each training session: a) proprioceptive only, b) proprioceptive + visual, and c) proprioceptive + verbal. Using a custom-built 2-joint manipulandum, elbow position sense acuity will be evaluated using a passive position sense discrimination task and an active ipsilateral matching task before and after training. Showing a significant decrease in both or one of JND and JPME before and after training in one of the three groups will verify this aim.

Hypotheses 1: Proprioceptive + visual feedback condition will be the most effective to improve proprioceptive and motor function. In comparison to the two other feedback conditions, it will show a significantly higher reduction of JND (passive position sense acuity), and/or a significantly larger decrease in JPME (active position sense acuity).

Aim 2: To determine the retention effects of each sensorimotor training condition after proprioceptive learning. Participants of each group will be retested approximately 24 hours after the post-test. Showing a significant decrease in both or one of JND and JPME at the posttest and after 24 hours in one of the three groups will verify this aim.

Hypotheses 2: Retention effects will be most pronounced after training with proprioceptive + verbal feedback condition. Both or one of JND and JPME in the verbal group will show a significant decrease at retention.

Method

Participants

Thirty 18-35 years old healthy adults were recruited for the study (Table 1). The rationale of this sample size was based on the power analysis during the pilot testing, at least n=28 was required to achieve a significant difference between proprioceptive only and proprioceptive + visual feedback condition ($p < 0.05$, a power of 0.8), the effect size was 0.423. The research protocol was reviewed and approved by the Institutional Review Board (IRB) at the University of Minnesota. All participants were informed about the experiment and voluntarily consented to participate in the study. *Inclusion criteria:* 18-35 year-old healthy young adults. *Exclusion criteria:* any history of musculoskeletal, neurological and/or orthopedic impairments that currently affected movement control in the upper arm as determined by self-report. Individuals currently pregnant would also be excluded. All participants completed a modified Edinburgh handedness inventory to determine their dominant upper limb [36].

Table 1 Research participant characteristics

	Proprioceptive only (n = 10)	Proprioceptive + Visual (n = 10)	Proprioceptive + Verbal (n = 10)
Age (in yrs.)	24.5 ± 3.0	25.6 ± 4.9	25.8 ± 4.2
Gender	5 male	5 male	4 male

Study design

This study employed a pretest-posttest design with three feedback conditions during the learning of a forearm pointing task (see Figure 1). Participants were randomly and equally assigned to one of the three different groups, each receiving different combinations of feedback: a) proprioceptive only, b) proprioceptive + visual, and c) proprioceptive + verbal. Each participant completed the pretest, the training, the post-test, and a 24-hour retention test.

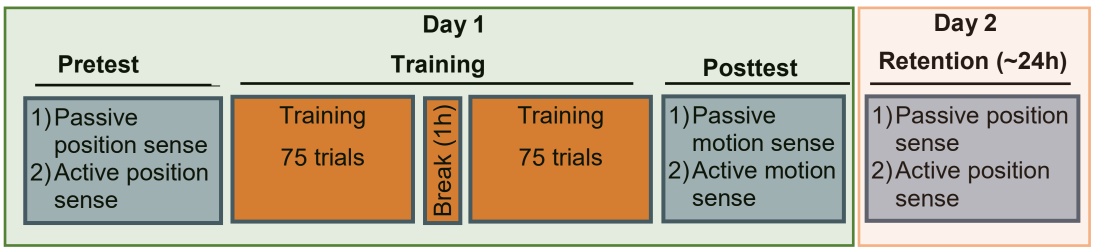
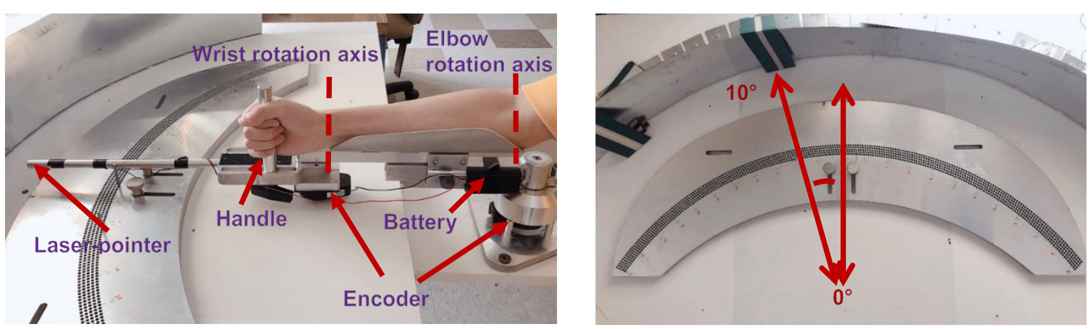


Figure 1 Research protocol

Apparatus

A custom-built 2-joint manipulandum (Figure 2) was used to deliver elbow movements in the horizontal plane. Optical encoders were embedded in the rotation axis of each segment and recorded the instantaneous joint position at a sampling frequency of 200 Hz.



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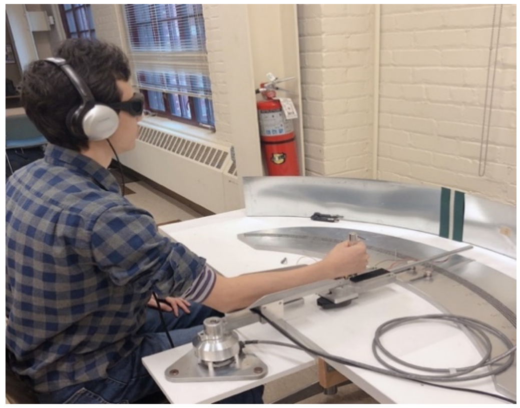


(c)

Figure 2 The 2-joint manipulandum used in the study. (a) Left view of the 2-joint manipulandum. The wrist motion was blocked. Participants only performed joint rotations around the elbow in the horizontal plane. A laser attached to the front of the device indicated the current arm position for the proprioceptive + visual feedback condition training session. (b) Top view of the manipulandum. The starting position was at the center (0°), the target position was 10° of internal rotation of the forearm in the horizontal plane (depicted here for a right-handed individual). When the participants did the training in the proprioceptive + visual condition, the position error was presented in the form of a laser pointer against a target white line over a green paper background. When the laser pointer pointed the target white line, the forearm position was at 10° from the start position. (c) An overall view of the manipulandum. The arm was placed on the splint of the manipulandum and the participant gripped the handle. The manipulandum was able to swing freely in the horizontal plane

Procedure

Proprioceptive acuity assessment

To control for the effects of hand dominance and hemispheric lateralization on proprioceptive acuity, the dominant arm will be tested for all participants. During testing, the participants wore a pair of opaque glasses and headphones to block the vision and auditory background noise. Prior to following assessments, participants completed the Edinburgh Handedness Inventory [36] to identify the participant's dominant hand.

Assessment of passive position sense

This assessment involved passive movement to sense position and response verbally. Sensing position is proprioceptive function. Participants were seated in the height-adjustable chair at a comfortable height placing his/her arm on the armrest of the manipulandum. Pink noise was played via headphones to obscure any sounds generated by the movement to prevent additional information about elbow position. The participant's elbow was displaced from the resting position (0°) by the experimenter moving the participants' arm at a slow speed towards the target. The rationale for moving the arm slowly and deliberately was that the participant could have ample time to begin to concentrate on the final displacement. This approach was similar to the approach described by Bhanpuri [37]. Two position stimuli were presented in each trial. Reference stimulus position was set at 10° elbow flexion. Comparison stimulus was always greater than the reference stimulus position. The order of the two stimulus positions was randomized. In each trial, the experimenter passively moved the participant's elbow to a 10° flexion position (reference), stayed for 2 seconds, moved back to the starting position and then moved to the comparison position which was greater than 10° elbow flexion for 2 seconds, then moved back to the rest/start position. After each trial, participants verbally responded to the question, *"Which position was farther from the starting position, first or second?"* (Figure 3). The stimulus difference between the reference position and the comparison position for each trial was selected by the *psi-marginal adaptive method* based on the participant's response [7]. A correct response was followed by a smaller stimulus difference than the previous trial. In each test, there were 20 trials, breaks were allowed every 10 trials, or when the participant felt tired or their attention was lost.

"Which of the two stimulus positions moved farther away from the starting

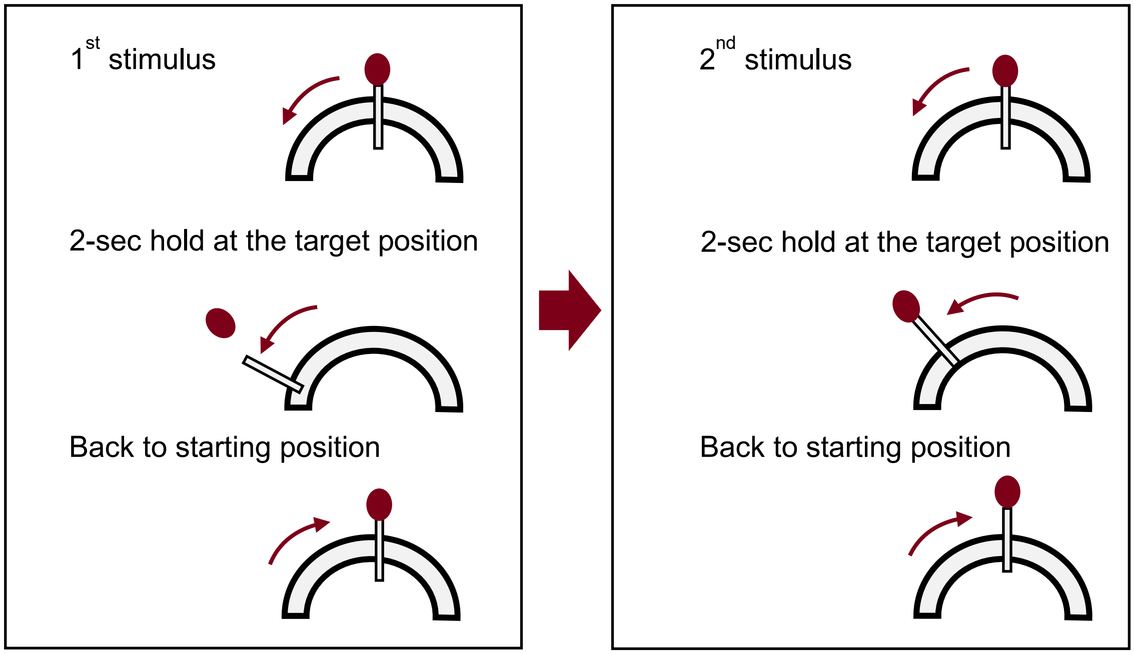


Figure 3 Description of the assessment of passive motion sense

Assessment of active position sense

This assessment involved both passive and active movement to sense position and do the voluntary movement. Sensing position is proprioceptive function and movement response is motor function. Participants rested their dominant forearm on the movable splint of a custom-built 2-joint manipulandum while being seated in an upright position (Figure 2). They were instructed to hold the handgrip in a relaxed manner. The armrest had a stopper to ensure the same starting position for all the trials (0°). In each trial, the examiner moved the splint on each participant's dominant side by 10° from the starting position toward the body. The experimenter verbally informed the participants when the desired target position was reached. Their forearm was then passively moved back to the starting position. Next, the participants actively moved their forearm to the remembered target position. They were instructed to stop their movement and provide verbal notification when they feel they had reached the same forearm position as the target. The participants held the position for about 2 seconds to allow for collecting a solid sample of angular data through the encoder. In each test, 10 trials were administered. The participants were allowed a few practice trials before the start of the task for familiarization. During the whole task, all participants wore a pair of opaque glasses that block the vision of the arm position. The angular positions were recorded for

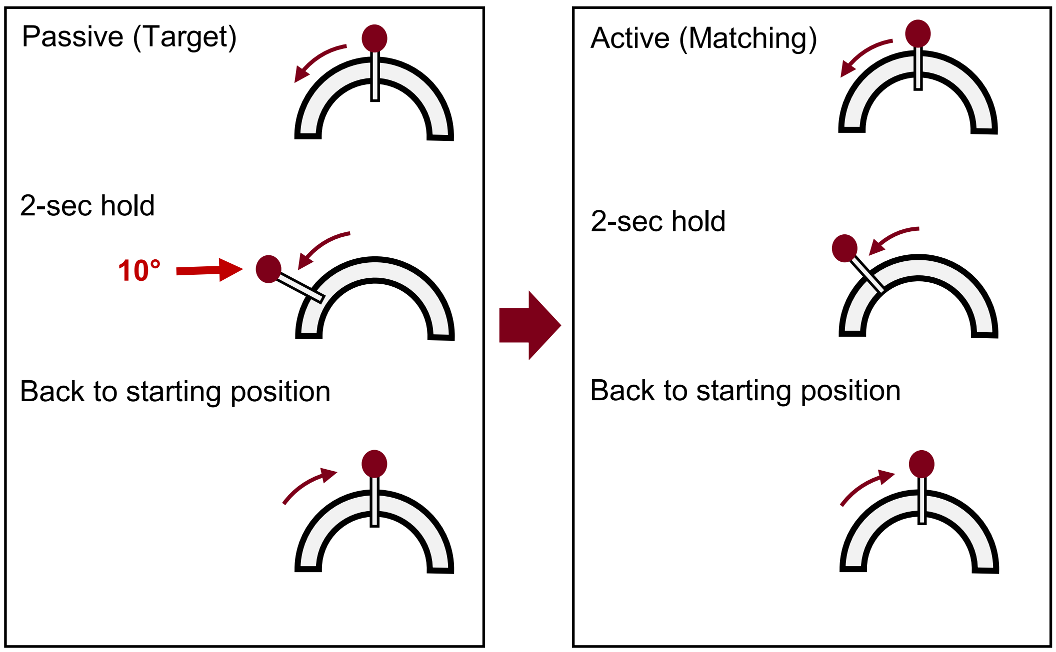


Figure 4 Diagram outlining the procedure for assessing active motion sense

both target and matched positions, which were used to compute the absolute angular difference between these two values, indicating a joint position error for the ipsilateral matching (Figure 4).

Training

During training, participants rested their dominant forearm on the movable splint of custom-built 2-joint manipulandum while being seated in an upright position. They were instructed to hold the handgrip in a relaxed manner. The armrest had a stopper to ensure the same starting position for all the trials (start position = 0°) which meant the arm pointing straight ahead (in the sagittal plane), the targets towards the midline of the body doing the elbow flexion. Participants wore a pair of opaque glasses to block the visual information about the arm position. In each trial, the examiner moved the splint on the participant's dominant side by 10° from the starting position toward the mid-line of the body (passive movement experienced by the participant). The experimenter verbally informed the participant when the desired target position was reached and held this position for two seconds. The participant memorized the target position of his/her elbow before being passively returned to the start position. Then, the participant actively moved the arm from the start position to the memorized target position in a single movement without any correction. The participant held the arm at this end position. At this point, the experimenter provided proprioceptive, visual, or verbal feedback (see below for the description of feedback) to the participants to reach the target. After experiencing the correct target position for two seconds, the participant's arm was moved back to the start position and the next movement can start (Figure 5). Two sessions of 75 trials were administered. The participants had an hour break in between the sessions. The participants were allowed 5 practice trials before the start of the task for familiarization.

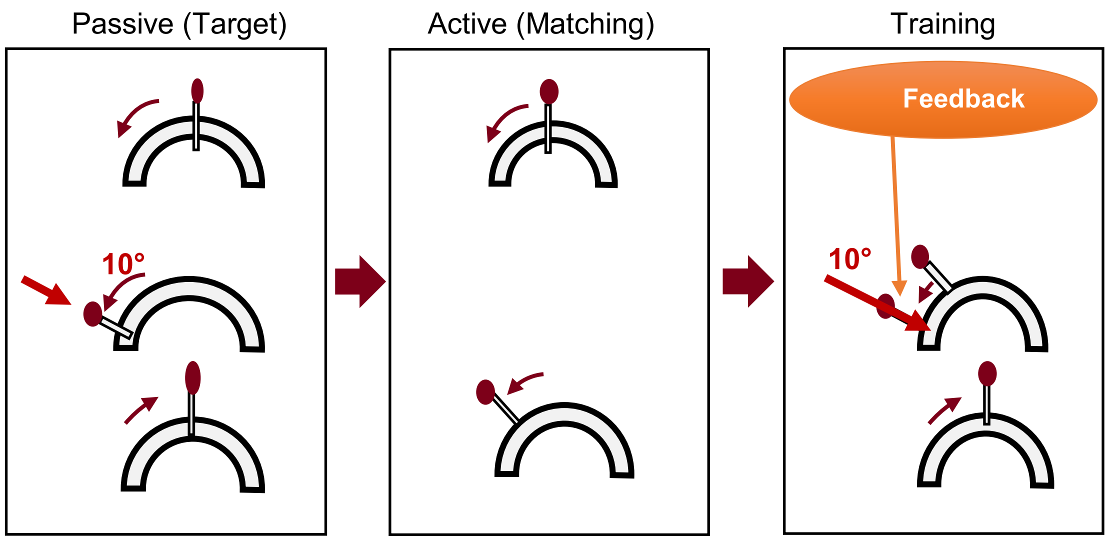


Figure 5 Diagram outlining the training procedure.

Three types of feedback conditions

Proprioceptive only: After the participant moved their dominant forearm to the remembered target position in each trial, the investigator provided proprioceptive feedback by manually correcting the arm position by moving the forearm to the target. After experiencing the correct target position for two seconds, the participant's arm was passively moved back to the start position in preparation for the next trial.

Proprioceptive + visual: After the participant moved their dominant forearm to the remembered target position in each trial, the participant was allowed a visual feedback of their performance. The position error was presented in the form of a laser pointer attached at the end of the forearm splint against a target white line over a green paper background. When the laser pointer pointed the target white line, the forearm position was at 10° from the start position. Any deviation from the target represented the position error (see Figure 6). After observing the error, participant actively corrected the error by actively moving to the target in the presence of visual inputs. Upon reaching the target for two seconds, participant closed their eyes and his/her arm was moved back to the start position and the next trial begun.

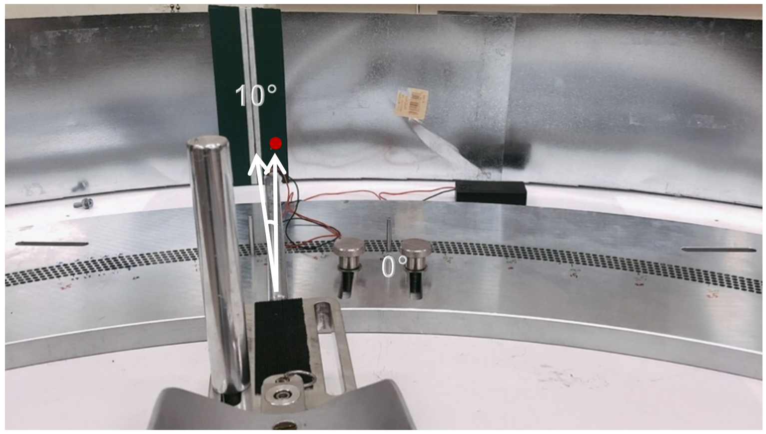


Figure 6 Description of the proprioceptive + visual feedback condition. 0° was the starting position. The target was 10° in the center of the white line. The position error was presented in the form of a laser pointer attached at the end of the forearm splint against a target white line over a green paper background. The deviation from the target represented the position error.

Proprioceptive + verbal: After the participant moved their dominant forearm to the remembered target position in each trial, the investigator informed the participant verbally about the error, indicating in the extent of the error to the right or left of the target. The extent of the error was demonstrated by the investigator as “move a little” and “move more”. After actively moving to reach the target using the verbal feedback and holding for two seconds, the participant’s arm was passively moved back to the start position in preparation for the next trial.

Measurements

Just-noticeable difference (JND) threshold

Based on the participants' verbal responses for each trial, the number of correct responses per stimulus size was computed. The response from the participant to discriminate the reference stimulus position from the comparison stimulus position went into the adaptive algorithm [38] which generated the next comparison stimulus position.

After 20 trials, a logistic Weibull function was used to fit stimulus size difference and the probability of correct response for each participant [39]. Based on the fitted function, 75% of correct response for a participant to discriminate the reference stimulus position from the comparison stimulus position was served as *Just-noticeable Difference* (JND) threshold [19]. In this study, JND threshold for each participant was determined as the minimum difference in elbow flexion position required to discriminate a stimulus from the reference stimulus of 10° elbow flexion. This JND threshold served as a measure of passive position sense acuity.

Joint position matching error (JPME)

During the assessment of active position sense acuity, elbow flexion angles were recorded at the target position and the matching position. Absolute angular difference between the matching and target angular position were calculated for each trial. Mean absolute angular difference across 10 trials were computed for each participant. This mean of absolute angular difference across 10 trials served as *joint position matching error* (JPME) for each participant.

Statistical analysis

Statistical analysis was performed using R-Studio [40]. All variables were tested for normality using Shapiro-Wilk test [41] and found to be normally distributed. The modified Levene's test confirmed the homogeneity of variance in all variables [42].We tested for between group differences using one-way Analysis of Variance (ANOVA) procedures [43] and within-group differences using paired t-test [44]. The three feedback conditions served as independent variables and the JND and JPME served as dependent variables. In order to verify the **Hypotheses 1,** the differences between pretest and posttest of JND and JPME in each of the three different conditions served as dependent variables. For **Hypotheses 2,** the differences between posttest and retention of JND and JPME in each of the three different feedback conditions served as dependent variables. The significance level was set at a value of $p < 0.05$. Furthermore, we evaluated effect size. Cohen's d was calculated as $d = \mu_1 - \mu_2 / SD_{pooled}$, where $SD_{pooled} = \sqrt{\frac{SD_1^2 + SD_2^2}{2}}$ [45]. Conventionally, d = 0.20 is considered as a small effect, d = 0.50 as medium and d = 0.80 as large [46]. Post-hoc power analysis was performed in G*Power 3.1 [47].

Results

Elbow passive proprioceptive acuity as measured by JND

None of feedback conditions led to significant gains in passive position sense acuity after training

JND measures were not significantly different at the baseline among the three feedback conditions ($F_{2, 27} = 0.577$, $p > 0.05$). This meant there was no recruitment bias across all participants. Changes in JND as a function of training at post-test were not significantly different among the three feedback conditions ($F_{2, 27} = 0.647$, $p > 0.05$). It indicated that the three feedback conditions had no differential effects in improving passive proprioceptive acuity after training. No significant decrease of JND before and after training was found in each feedback condition (Proprioceptive only: $p > 0.05$, Proprioceptive + Visual: $p > 0.05$, Proprioceptive + Verbal: $p > 0.05$). These results showed that no feedback condition led to significant gains in passive position sense acuity after training (Figure 7 and Figure 8).

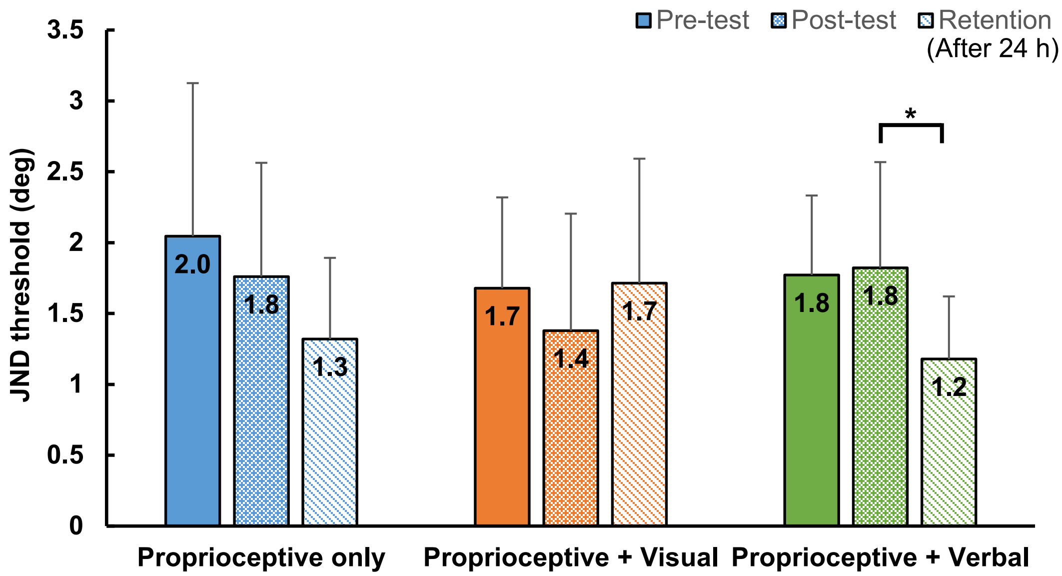


Figure 7 Mean just-noticeable difference (JND) thresholds among the participants in each feedback condition at the pretest, posttest, and retention. Error bars indicate standard deviation. * - p < 0.05.

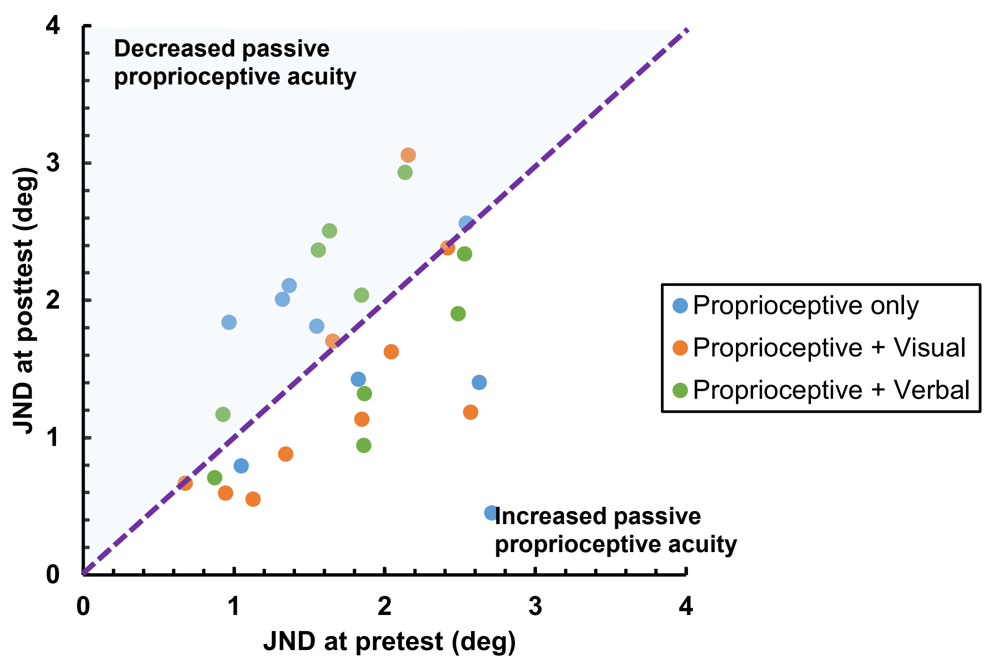


Figure 8 Just-noticeable difference (JND) thresholds in all participants at pre- vs. post-testing. The purple dotted line represents the line of equality indicating no change due to training.

Learning effects on passive proprioceptive acuity was retained after 24 hours of training in the proprioceptive + verbal feedback condition

Changes in JND after 24 hours of training were significantly different across the three feedback conditions ($F_{2, 27} = 4.0361$, $p < 0.05$). This meant the three feedback conditions showed differential effects in improving passive proprioceptive acuity after 24 hours of training. A significant decrease of JND between the posttest and after 24 hours was found in the proprioceptive + verbal feedback condition (Proprioceptive only: $p > 0.05$, Proprioceptive + Visual: $p > 0.05$, Proprioceptive + Verbal: $p < 0.05$) (Figure 7). This indicated the improvement in JND threshold persisted 24 hours after training in the proprioceptive + verbal feedback condition. As seen in Figure 9, most of the participants in the proprioceptive + verbal feedback condition improved in passive proprioceptive acuity at retention-test. In relative terms, the average improvement in passive proprioceptive acuity after 24 hours of training was 35% across all participants in the proprioceptive + verbal feedback condition. These results indicated that learning effects on passive proprioceptive acuity were retained after 24 hours in the proprioceptive + verbal feedback condition (intrinsic + extrinsic).

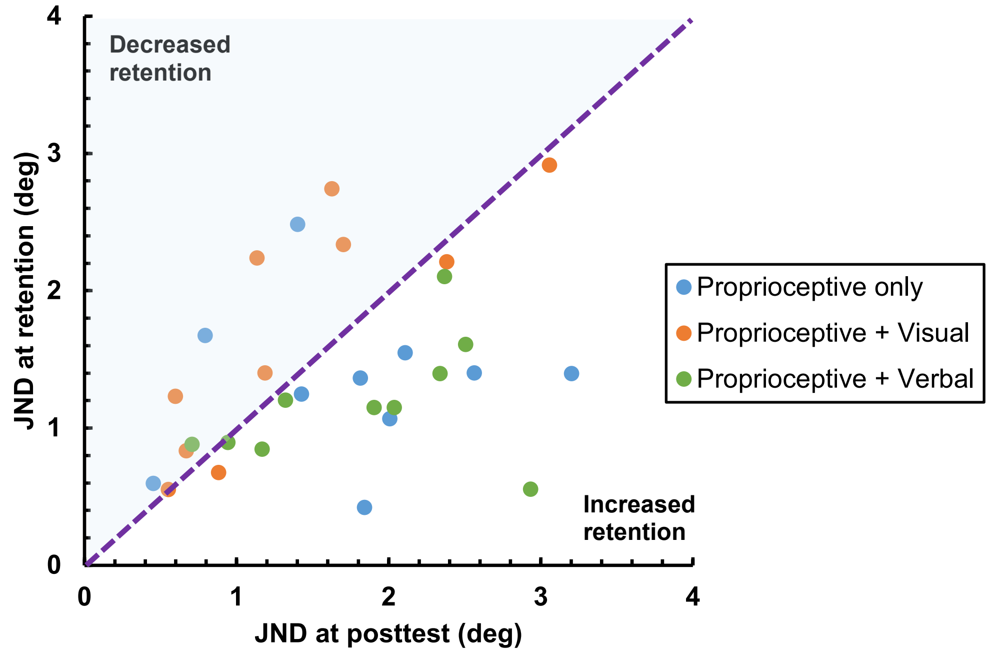


Figure 9 Just-noticeable difference (JND) thresholds in all participants at post- vs. retention-testing. The purple dotted line represents the line of equality indicating no change due to training. Most participants in the proprioceptive + verbal feedback condition are below the line of equality indicating improvements in passive position sense acuity at retention.

Elbow active joint position matching indicated by JPME

All three feedback conditions improved active proprioceptive acuity with both the proprioceptive only *and* proprioceptive + verbal *feedback conditions showing the very large effect sizes*

The descriptive statistics for JPME at pre-test, post-test, and retention are shown below (Table 2 and Figure 10). JPME measures were not different at the baseline among the participants in the three feedback conditions ($F_{2, 27}$ = 0.480, p > 0.05). This indicated there was no recruitment bias across all participants. No significant differences among the three feedback conditions were found in JPME changes as a function of training at the posttest ($F_{2, 27}$ = 0.217, p > 0.05). This indicated that no feedback condition was more effective in improving active proprioceptive acuity than another. However, a significant decrease of JPME before and after training was found in each feedback condition (Proprioceptive only: $p < 0.001$, Cohen's d=1.62; Proprioceptive + Visual: $p < 0.05$, Cohen's d=0.77; Proprioceptive + Verbal: $p < 0.001$, Cohen's d=1.57) and indicating an improvement in active proprioceptive acuity of each feedback condition at the posttest. The large effect sizes were observed in the proprioceptive only feedback condition and the proprioceptive + verbal feedback condition (Figure 10). As seen in Figure 11, most of the participants in each feedback condition yielded gains in active position sense acuity. In relative terms, the average of improvement in active proprioceptive acuity after training across all participants in the proprioceptive only feedback condition was 66%, proprioceptive + verbal feedback condition by 54% and the proprioceptive + visual feedback condition by 44%. These results suggested that all three feedback conditions improved active proprioceptive acuity after training with both the proprioceptive only (intrinsic) and proprioceptive + verbal (intrinsic + extrinsic) feedback condition showing the very large effect sizes.

Table 2 Descriptive statistics for both Just-noticeable difference (JND) threshold and absolute joint position matching error (JPME)

		Proprioceptive only			Proprioceptive + Visual			Proprioceptive + Verbal		
		pre	post	retention (24h)	pre	post	retention (24h)	pre	post	retention (24h)
JND	Mean	2.05°	1.76°	1.32°	1.68°	1.38°	1.71°	1.77°	1.82°	1.18°
	(SD)	1.08°	0.80°	0.56°	0.64°	0.83°	0.75°	0.56°	0.75°	0.44°
JPME	Mean	1.19°	0.41°	0.90°	1.40°	0.79°	1.02°	1.30°	0.59°	1.14°
	(SD)	0.44°	0.17°	0.52°	0.58°	0.19°	0.41°	0.38°	0.19°	0.45°

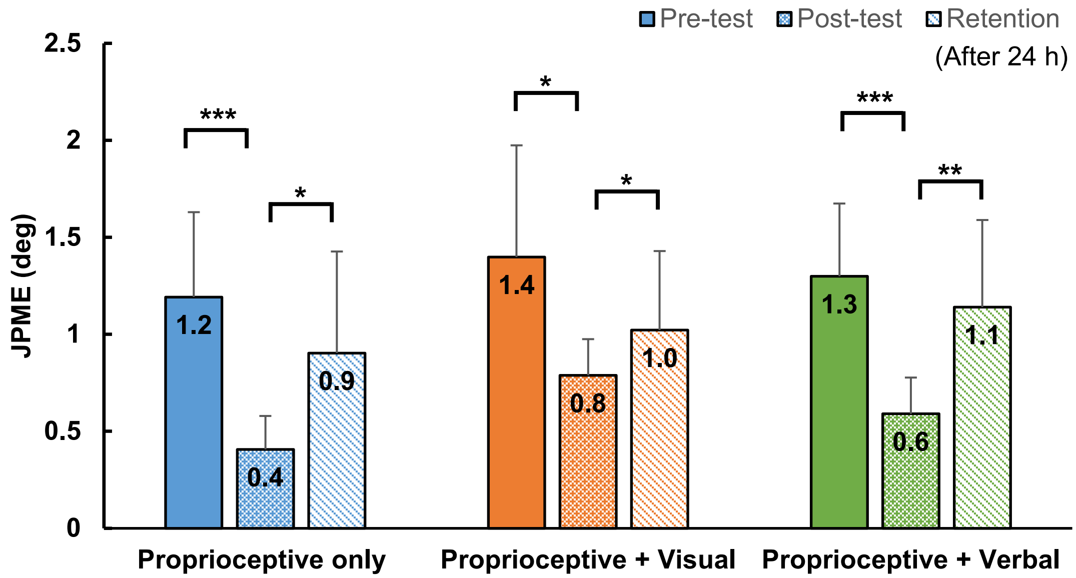


Figure 10 Mean absolute joint position matching error (JPME) among the participants in each feedback condition at pre-test and post-test, and retention. Error bars indicate standard deviation. Before and after training, the proprioceptive only feedback condition showed a significant decrease *** - $p < 0.001$, Cohen's d=1.62; the proprioceptive + visual feedback condition showed a significant decrease * - $p < 0.05$, Cohen's d =0.77; the proprioceptive + verbal feedback condition showed a significant decrease *** - $p < 0.001$, Cohen's d=1.57 and the effect sizes of both the proprioceptive only feedback condition and proprioceptive + verbal feedback condition were large. At the posttest and after 24 hours of training, the proprioceptive only feedback condition showed a significant increase * - $p < 0.05$, the proprioceptive + visual feedback condition showed a significant increase * - $p < 0.05$, the proprioceptive + verbal feedback condition showed a significant decrease ** - $p < 0.01$.

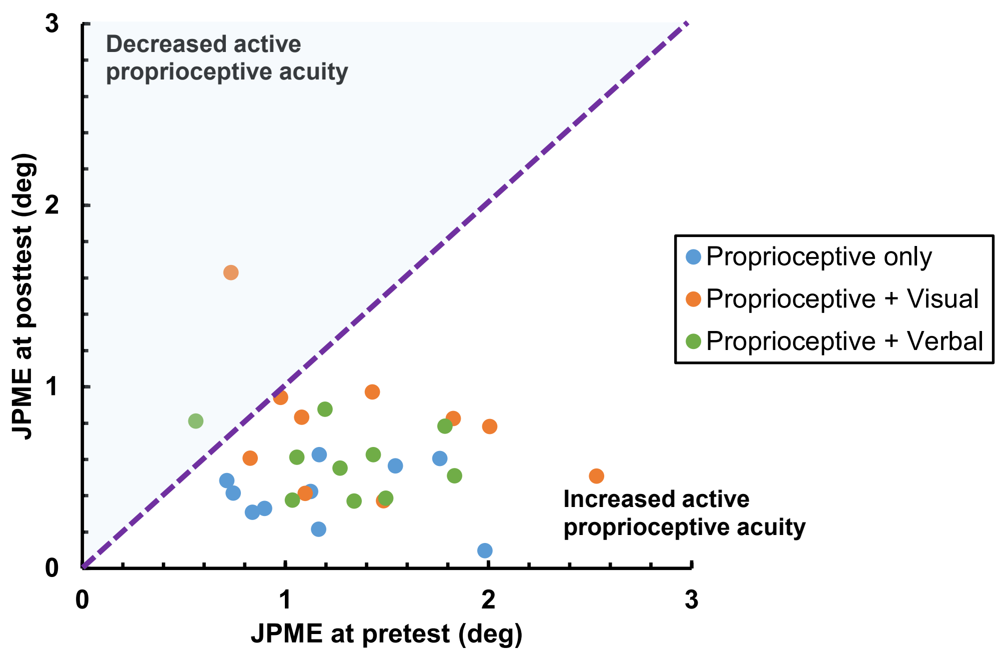


Figure 11 Joint position matching error (JPME) in all participants at pre- vs. post-testing. The purple dotted line represents the line of equality indicating no change due to training. Most of the participants in each feedback condition are below the line of equality indicating improvements in active joint matching.

Learning effects on active proprioceptive acuity was not retained after 24 hours

No significant differences in JPME changes between the posttest and after 24 hours of training were found among the three feedback conditions ($F_{2, 27} = 0.888$, $p > 0.05$). It indicated that there was no feedback condition showed more pronounced retention effects in improving active proprioceptive acuity after training than another. A significant increase of JPME at the posttest and after 24 hours of training was found in each feedback condition (Proprioceptive only: $p < 0.05$, Proprioceptive + Visual: $p < 0.05$, Proprioceptive + Verbal: $p < 0.01$). This meant the improvement in active proprioceptive acuity did not persist 24 hours after training in each feedback condition. As seen in

Figure 12, most participants across the three feedback conditions showed decreased retention in active proprioceptive acuity. These results indicated that learning effects on active position sense acuity was not retained in all three feedback conditions.

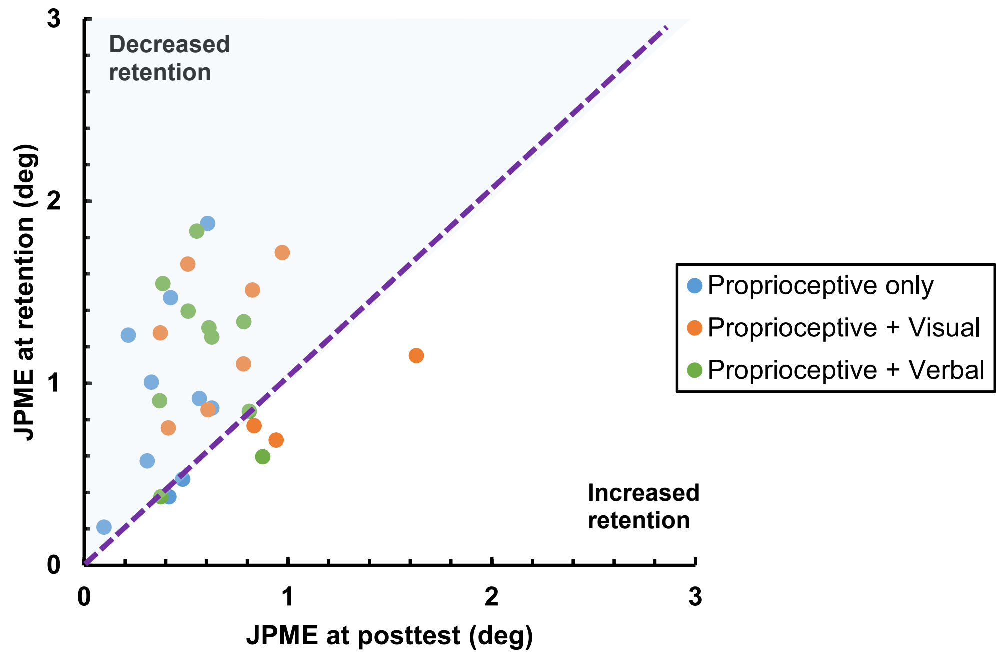


Figure 12 *Joint position matching error* (JPME) in all participants at post-test vs. retention. The purple dotted line represents the line of equality indicating no change due to training. Most participants in all three feedback conditions are above the line of equality indicating no improvements in active joint matching.

Post-hoc power analysis

An additional power analysis was performed to examine the number of sample size required for observing significant difference between the three feedback conditions. Changes in JPME as a function of training at post-test between the proprioceptive only and the proprioceptive + verbal feedback condition reached a small effect size (Cohen's d=0.17). To guarantee a power of 0.9, it was estimated that each feedback condition required 608 participants. It was found that n=242 for each feedback condition was required to achieve significant difference between the proprioceptive only feedback condition and the proprioceptive + visual feedback condition (Cohen's d=0.27).

Discussion

The purpose of the study was to examine changes in forearm position sense acuity as a result of training under different conditions of intrinsic and extrinsic feedback. The research objectives were: 1) to determine the type of unimodal or multimodal feedback combination that yields the highest gains in proprioceptive and motor function during proprioceptive learning (**aim 1**), and 2) to determine the retention effects of each sensorimotor training condition after proprioceptive learning (**aim 2**).

The main findings of this study are as follows: First, none of feedback conditions yielded gains in passive proprioceptive acuity after training. Second, participants in all three feedback conditions demonstrated improvements in active proprioceptive acuity after training showing large effect sizes in both the proprioceptive only and proprioceptive + verbal feedback conditions. However, no feedback condition was more effective in improving active and passive proprioceptive acuity than another. Third, the improvements in active proprioceptive acuity did not persist 24 hours after training.

Gains in proprioceptive and motor function after training

The sensorimotor training program required participants to experience a specific forearm position and then actively match this forearm position from memory. It challenged the ability of participants to sense a small-amplitude joint position and rely on memory for matching the target position accurately [22].

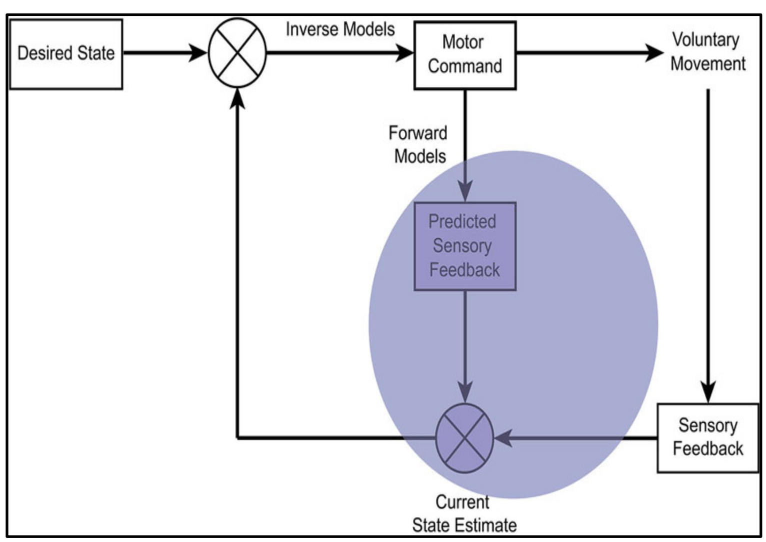
Why no effect on passive positions sense?

Proprioceptive training-related improvements have been evaluated by various measures, such as somatosensory measure [19, 28, 48], somatosensory-motor measure [49, 50], balance [25, 51], and neurophysiological [24, 52, 53]. The somatosensory measure which included JND during passive movement. In the current study, we used this established measure to evaluate passive position sense acuity [19, 28, 48]. However, we did not find gains in passive position sense with any condition. This was inconsistent with some studies which found enhancement in proprioceptive acuity measured by JND after proprioceptive training [5, 29, 54, 55]. These studies evaluated JND were as small as 1-2 degrees when the target was 10 degrees [19, 22, 29]. My measures were in approximately same range. The lack of significance in JND measures was not due to the sensitivity of the measurement. Compared with the participants, one study found that a robot-aided sensorimotor training can improve proprioceptive function in sub-acute and chronic stroke survivors [55]. It would be easier to trigger proprioceptive learning for participants with proprioceptive deficits than healthy people. But some studies found the enhancement of proprioceptive acuity in healthy adults [29, 54]. One of these studies, a robot-aided sensorimotor training was delivered for 40 minutes. The task required to finish 45 training trials to move the ball to a circular target and to hold there for 5 seconds. The level of task difficulty changed by increasing a balanced wrist position of either 10°, 15° or 20° flexion. If the participant was successful in every single trial, he/she would have experienced 15 levels of difficulty [29]. Comparing with this study, the training program in our study was a simple matching task with 150 trials. The rationale of choosing 150 trials was based on the pilot testing. All participants showed the decrease in JPME after 150 trials. The participants were passively moved to the same target of 10° elbow flexion by a manual manipulandum. The complexity of training task, and the difference in device technology may affect the result in not showing JND reduction.

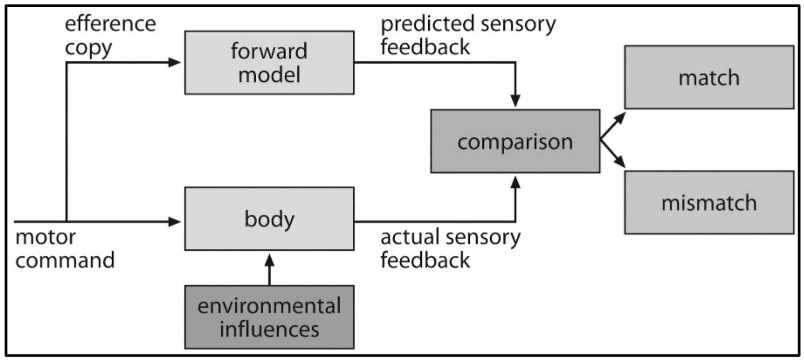
Improvements in active position sense in all feedback conditions

In our study, participants in all three feedback conditions demonstrated improvements in active proprioceptive acuity. The average of improvement in active proprioceptive acuity after training across all participants in the proprioceptive only feedback condition was 66%, proprioceptive + verbal feedback condition by 54% and the proprioceptive + visual feedback condition by 44%. This was comparable to the results from previous studies focused on upper limb active reaching or grasping movements with an average improvement of 39% as described in a systematic review [5].

The JND measures involved passive movements and participants were only required to discriminate two different positions. This was a pure processing of the somatosensory (proprioceptive) inputs and no motor commands generated [19]. The process included the transmission of proprioceptive signals and a cortical activation of regions in the contralateral somatosensory cortex [56]. While JPME measure involved both passive and active movements to match a given joint position [19]. It was not only position sens but also motor response. Our training was an active matching task which trained the motor. That is why we found the effect on active not passive. The active movement involved the internal models (Figure 13 (a)) to generate a voluntary movement which was matching the target in our study [57-60]. The passive movement first provided the target as desired state by external somatosensory feedback (kinematics such as forearm position). Then an internal inverse model converted the desired state to motor commands (kinetics such as torque) and the body generated the voluntary movement (motor outputs as kinematics) and sensory feedback (sensory outputs). In addition, the internal feedforward model transferred the copy of motor commands (efference copy) to predicted sensory feedback. The internal predicted sensory feedback was then compared with the actual sensory feedback (sensory outputs from the body combined with environmental influences) (Figure 13 (b)). This sensory discrepancy can be used to correct movement and also maintain the accuracy of the internal models [19, 58, 61]. It facilitates the gains in active proprioceptive acuity which can explain our result that all three feedback conditions showed improvements in active proprioceptive acuity but not passive after training. The active movements combined both external somatosensory feedback and internal predicted sensory feedback which was a process of sensorimotor integration. This sensorimotor integration not only activated the somatosensory cortices (the primary motor and premotor cortical regions) but also the subcortical regions (the ipsilateral cerebellum) [19, 62]. The gains in active proprioceptive acuity were as the result of not only proprioceptive function but also sensorimotor learning. Furthermore, if we want to understand a neurophysiological correlate of proprioceptive processing such as the study which reported somatosensory or motor evoked potentials (MEPs), or cortical activation [24, 52, 53, 63-65], the neurophysiological measure will be needed.



(a)



(b)

Figure 13 The Internal models for active movements involved in the assessment of active proprioceptive acuity. (a) The whole process including both inverse models and forward models [57]. (b) Part of the process including forward model [60].

Why no differential effect of extrinsic feedback?

Although all three feedback conditions demonstrated enhancement in active proprioceptive acuity after training, no feedback condition was more effective than another. The small sample size may contribute to this result. Nonetheless, even with a huge sample size suggested by the post-hoc power analysis, the effect sizes were still minor. It is true that the greater the sample size, the more likely a statistically significant difference between groups is observed. Such a difference, however, may have been caused by the law of large number and may not contain any practical meaning [66].

In summary, there was no effect on passive proprioceptive acuity with either form of feedback. All three forms of feedback conditions yielded significant improvements in active proprioceptive acuity. However, no feedback condition proved to be superior in improving active proprioceptive acuity

Retention effects on proprioceptive learning

We found learning effects on active position sense acuity was not retained in all three feedback conditions. This was inconsistent with some studies which showed that individuals were capable of retaining proprioceptive learning up to 24 h later [55, 67, 68].

For example, one study used a robot-assisted sensorimotor training program delivered in two days and found the improvements in proprioceptive acuity after 24 hours of training in stroke survivors. The training trial was to control the virtual ball on the board stayed in the target area for 5 seconds. The difficulty level increased after every 6 trials like increasing ball speed or decreasing the friction force on the board [55]. In our study, the training program was a matching task with 150 trials. The task kept the same target of 10° elbow flexion. It was insufficient to trigger retention effects on active proprioceptive acuity after 24 hours. However, we found learning effects retained by 35% on passive proprioceptive acuity across all participants in the proprioceptive + verbal feedback condition. This result was consistent with a study that evaluated the learning effects of dynamic postural control, which enhanced motor learning in the proprioceptive + verbal feedback condition would be sustained after 48 hours by nearly 20% under the no-feedback condition compared with visual feedback training [35]. A study used functional magnetic resonance imaging and demonstrated the brain activation with different extrinsic feedback provided. Brain activation increased in visual areas with extrinsic visual feedback. On the contrary, it decreased in auditory areas but increased in an interaction between auditory and proprioceptive areas with extrinsic verbal feedback [69, 70].Based on this study, extrinsic visual feedback increases dependence on visual information. On the other hand, the extrinsic verbal feedback facilitates dependence on proprioceptive information which enhances proprioceptive function. It is interesting to note that the presence of extrinsic verbal feedback did result in improvement after 24 hours of training but not immediately. This can be explained that memory consolidation happened in extrinsic verbal feedback condition [71]. The rationale of choosing 24 hours as the cut point for the retention test was the existence of sleep-dependent memory consolidation. An overnight sleep can enhance the memory consolidation [72]. Learning a motor skill (a target matching task in our study) involves a process of memory consolidation after training to improve the skill in the absence of any practice [73, 74]. The consolidation is the process to convert short-term memory into long-term memory. The sensory information is first stored in short-term memory. By rehearsing or recalling information over and over again, and then the information is transferred from a fragile to a permanent state stored in long-term memory [75, 76]. For my study, it took longer to show memory consolidation in the proprioceptive + verbal feedback condition. It is safe to say there was no retention effects on active proprioceptive acuity. Learning effect on passive proprioceptive acuity was retained after 24 hours in the proprioceptive + verbal feedback condition.

Limitation

Due to the consistent presence of the proprioceptive feedback on each individual, we could not purely compare the differential effects of proprioceptive, visual and verbal feedback. We just investigated the interaction of intrinsic and extrinsic feedback and the differential effects of extrinsic visual and verbal feedback. Although the manipulandum was a manual device moved by the investigators, we tried to keep consistency in maintaining a constant velocity for all participants during the assessments and training. Furthermore, increasing the level of training difficulty to improve motor performance at the same time needs to be considered. This study demonstrated behavioral improvements in proprioceptive function, neural correlates of training can be investigated in the future. Understanding such neurophysiological correlate of proprioceptive processing is helpful for rehabilitation to treat the patients with proprioceptive deficits. Addressing these limitations will help to choose an optimal training program to improve sensorimotor learning not only in the healthy population but also applied to the clinic.

Conclusion

This study compared the differential effects of intrinsic proprioceptive and extrinsic verbal and visual feedback on proprioceptive learning. We found no evidence that providing additional extrinsic feedback in a proprioceptive learning task can boost joint position sense accuracy. Proprioceptive training relying solely on proprioceptive signals is sufficient to induce measurable improvements of active position sense. However, such learning was not retained after 24 hours, indicating that repeated training over days is necessary to induce lasting improvements in proprioceptive function. These results provide a basis to develop optimal sensory feedback for the rehabilitation training programs of clinical populations.

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SUPPLEMENTARY MATERIALS

Pilot testing

We firstly conducted a pilot testing to decide the number of trials for the training (Figure 14). Three participants finished trainings with three different feedback conditions in three weeks. In each week, each person completed the training with one of three conditions. Using Ipsilateral matching method to be the assessment of the active position sense bias and the training method. 10° was chosen as the target. In day 1 and day 2, the process is shown in Figure 14. After a week, the next week pretest can be the retention test measured the relative improvements in active joint position matching. We want to figure out how many trials should we train.

Table 3 The arrangement of pilot testing

Participant	Training		
	Proprioceptive only	Proprioceptive + Visual	Proprioceptive + Verbal
1	Week 1	Week 2	Week 3
2	Week 2	Week 3	Week 1
3	Week 3	Week 1	Week 2

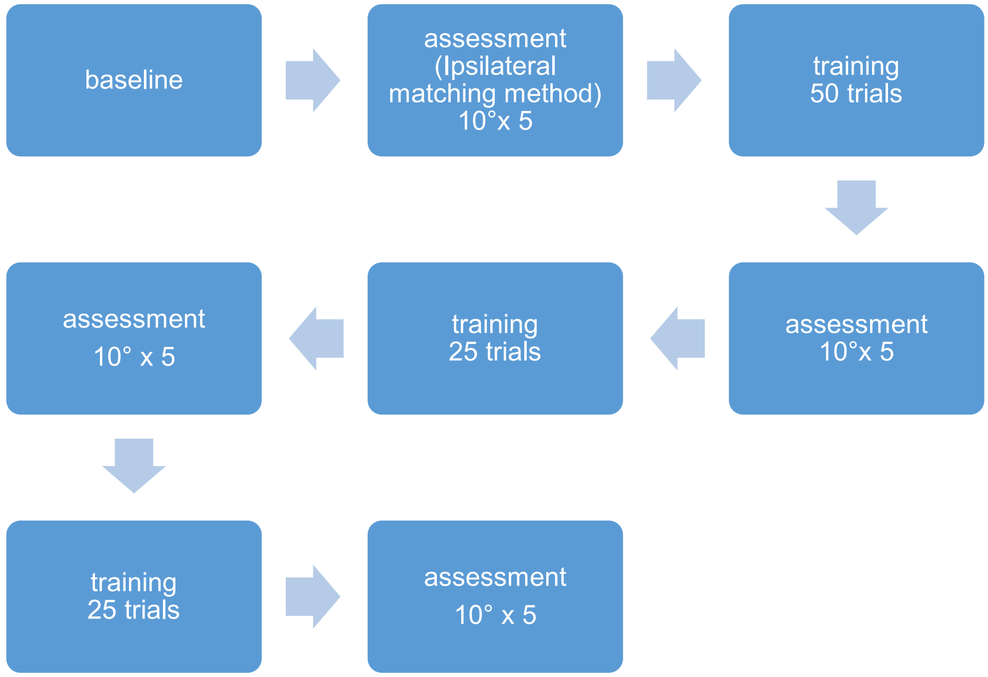

Figure 14 Overview of the process of pilot testing

Instruction:

Assessment task

a) I will move your forearm to the target position (10°) and remember this position, hold this position until I move you; (start-3 seconds-stop-save, save as\S_A_T_P)

b) I will then move your forearm back to the start position (0°);

c) You need to move your forearm to the position which you memorized, inform me when you feel you arrive the position and hold this position until I move you; (start-3 seconds-stop-save, save as\S_A_T_A)

d) I will move your forearm back to the start position (0°), next trial will begin.

Training task

Proprioceptive only feedback condition

a) You will wear a pair of opaque glasses and headphone to block the vision and auditory. I will move your forearm to the target position (10°) and remember this position

b) I will then move your forearm back to the start position (0°);

c) You need to move your forearm to the position which you memorized, inform me when you feel you arrive the position and hold this position until I move you (record the endpoint: start-3 seconds-stop-save, save as\S_T_);

d) I will manually move your forearm to the target position (10°) to correct the error and tell you “this is the target position”;

e) After experiencing the correct target position, I will move your forearm back to the start position (0°) and the next movement can start.

Proprioceptive + visual feedback condition

a) I will move your forearm to the target position (10°) and remember this position

b) I will then move your forearm back to the start position (0°);

c) You need to move your forearm to the position which you memorized, inform me when you feel you arrive the position and hold this position until I move you (record the endpoint: start-3 seconds-stop-save, save as\S_T_);

d) You can take off the opaque glasses and you can see the degree scale of the target to correct the error, move the forearm to the target position;

e) After experiencing the correct target position, I will move your forearm back to the start position (0°) and the next movement can start.

Proprioceptive + verbal feedback condition

a) I will demonstrate the deviation in the movement angle from 1˚ to 10°, starting at the target center at first.

b) I will move your forearm to the target position (10°) and remember this position

c) I will then move your forearm back to the start position (0°);

d) You need to move your forearm to the position which you memorized, inform me when you feel you arrive the position and hold this position until I move you (record the endpoint: start-3 seconds-stop-save, save as\S_T_);

e) I will tell you to move your forearm how many degrees right/left to the target position;

f) After experiencing the correct target position, I will move your forearm back to the start position (0°) and the next movement can start.

Handedness Questionnaire

University of Minnesota – Human Sensorimotor Control Laboratory
Handedness questionnaire

Study name: Assessment and training of elbow and wrist joint proprioception

Participant's ID: ______________________

Date: ______________________

Instructions: Place a check mark in the appropriate column(s) for each activity indicating which hand the participant prefers to use. If the participant has never performed the activity just leave the row blank.

	Which hand do you prefer?			Do you always use this hand?	
	right	left	no pref	yes	no
Writing					
Drawing					
Throwing					
Using scissors					
Using a toothbrush					
Using a knife without a fork					
Using a spoon					
Using a broom (upper hand)					
Opening a box (removing a lid)					
Items below are not in the standard inventory					
Holding a computer mouse (or using touchpad)					
Holding a key to unlock a door					
Holding a hammer					
Holding a brush or comb					
Holding a cup while drinking					

Subject Information Form

University of Minnesota – Human Sensorimotor Control Laboratory
Research Participant Information Form
GENERAL INFORMATION
Study Name: _______ __________________________________

Subject Category (e.g., control, patient): __________________________________

Subject Name:____________________________________ (first, last)

Subject Gender: Female / Male

Assigned Subject Number:___________________________

Testing Date:______________

Birthdate:_____________ Age:___________ (years, months)

Ethnic category (eg. Hispanic or Latino?): Racial category (Asian, Pacific Islander, Black, White not of Hispanic origin, etc.): Height: Education Level: Implanted metal devices: Currently pregnant: Y N

MEDICATION

Are you currently taking any medication? Y N

If so, list medication:

____

____

MEDICAL HISTORY

Do you have any history of:

Diabetes: Y N If so, since when: ________

Central Nervous System Disease: Y N If so, list approximate dates:

____

Describe:

Peripheral Nerve Disease: Y N If so, list approximate dates: ________

Describe:

Arm Fractures/Luxations: Y N If so, list approximate dates: ________

Right Upper Limb Pathologies (describe):

Describe:

Left Upper Limb Pathologies (describe):

Describe:

Subject accepted for study (investigator's initials):________