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On sensorimotor function and the relationship between proprioception and motor learning

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Abstract

Research continues to explore the mechanisms that mediate successful motor control. Behaviourally-relevant modulation of muscle commands is dependent on sensory signals. Proprioception – the sense of body position – is one signal likely to be crucial for motor learning. The present thesis explores the relationship between human proprioception and motor learning.

First we investigated changes to sensory function during the adaptation of arm movements to novel forces. Subjects adapted movements in the presence of directional loads over the course of learning. Psychophysical estimates of perceived hand position showed that motor learning resulted in sensed hand position becoming *biased* in the direction of the experienced load. This biasing of perception occurred for four different perturbation directions and remained even after washout movements. Therefore, motor learning can result in systematic changes to proprioceptive function.

In a second experiment we investigated proprioceptive changes after subjects learned highly accurate movements to targets. Subjects demonstrated improved acuity of the hand's position following this type of motor learning. Interestingly, improved acuity did not generalize to the entire workspace but was instead restricted to local positions within the region of the workspace where motor learning occurred. These results provide evidence that altered sensory function from motor learning may also include sensory acuity improvements.

Subsequently the duration of acuity improvements was assessed. Improved acuity of hand position was observed immediately after motor learning and 24h later, but was not reliably different from baseline at 1h or 4h. Persistent sensory change may thus be similar to retention of motor learning and may involve a sleep-dependent

component.

In the fourth study we investigated the ability of proprioceptive training to improve motor learning. Subjects had to match the position and speed of desired trajectories. At regular intervals during motor motor learning, subjects were presented with the desired trajectory either only visually, or with both vision and passive proprioceptive movement through the desired trajectory using a robot. Subjects who received proprioceptive guidance indeed performed better in matching both velocity and position of desired movements, suggesting a role for passive proprioceptive training in improving motor learning.

Keywords

Co-authorship statement

A version of Chapter 2 has been published: Ostry DJ, Darainy M, Mattar AA, Wong J, Gribble PL (2010). Somatosensory plasticity and motor learning. J Neurosci, 30(15): 5384-93. A subset of the experiments were performed in Montreal Quebec, where data collection and analysis were performed by AAM and MD. Writing of the manuscript was performed in collaboration with (principally) DJO and AAM, and also with the remaining authors. This author collaborated in the experimental design of motor learning tasks, sensory tests, and control experiments, and was responsible for all data and analysis collected for Experiment 2.

A version of Chapter 3 has been published: Wong JD, Wilson ET, Gribble PL (2011). Spatially selective enhancement of proprioceptive acuity following motor learning. J Neurophysiol, 105(5):2512-21. ETW assisted with experimental design, data collection and manuscript revisions. PLG assisted in experimental design, data collection and manuscript writing.

S Climans assisted with data collection and analysis of chapter 4.

DA Kistemaker assisted with the experimental design and manuscript revision of chapter 5. PLG assisted in experimental design and manuscript revision.

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My family, Ann, Larry, Darren and Andrew, have been supportive and thoughtful throughout. Crucial to this work, my parents engendered (environmentally and genetically) both a broad curiosity that drives a desire to understand (and do/fix) things that most people leave to those directly trained (occasionally there are real limits), and a specific interest in human psychology via fascinating discussions about (anonymous) patients. They have been generous to their children to a degree that is rather unmatched to my knowledge. My brothers have always been a source of ideas and support. I envy how quick-thinking and thoughtful they are, and growing up with them continues to influence me.

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Chapter 1

Introduction

Investigations into the neural control of movement frequently feature human adaptation to novel movement contexts. These adaptive changes are often characterized in terms of kinematic, electromyographic and dynamic measures, such as movement kinematics, muscle activation, and delivered force and torque.

1.1 Overview

The studies presented in this thesis explore the relationship between motor learning and proprioceptive function, using the paradigm of human reaching movements made with the upper limb. This relationship has been measured by assessing movement kinematics, and psychophysical estimates of human proprioceptive threshold. Both motor learning tasks (sometimes in the presence of external, perturbing forces) and psychophysical tests were undertaken using a graspable robotic manipulandum (inMotion Technologies).

The studies described in **Chapter Two** assess the degree to which proprioception systematically varies during the adaptation to novel external loads. During the learning of novel movements it is often observed that subjects make specific and systematic changes to motor commands to adapt to novel perturbations. It is not known if these motor changes occur as a result, or in the presence of, similar changes to our sensory system. Indeed it may be that sensory changes are an integral part to the motor adaptation process.

We performed a series of empirical studies that examined if the sense of hand position was systematically varied during the production of reaching movements made in the presence of a directional load. Subjects were observed to compensate for the

perturbing loads and reduced the kinematic deviations made along the force-field's direction. We performed psychophysical estimates of proprioception before and after learning, and found that subjects' perceived location of their hand was systematically altered in a consistent fashion across subjects experiencing the same force-field. After learning, subjects were more likely to perceive the position of their hand as being located in the direction of the experienced external load. We explored the generality of the effect on altered perception by measuring both static and dynamic psychophysical estimates, and found that subjects demonstrated perceptual changes in both instances, data which support the notion for a generalized shift in perceptual estimates. We also tested if this effect was related to motor learning itself by estimating sensory function in subjects who did not perform active movement but were instead passively moved by the robot through pre-recorded movements made by other subjects. We found that these subjects did not demonstrate any sensory changes, which supports the notion that sensory changes are related to motor learning.

In **Chapter Three**, we further explore the idea that motor learning might change sensory function, specifically in the context of motor tasks requiring high precision. Many tasks require the motor system to generate precise motor commands to bring the hand accurately from one location to another. Little is known about how this change in motor ability relates to perceived hand position, leaving open the question of perceptual function following training in these tasks.

Again using the robotic manipulandum, we provided subjects with the task of accurately positioning their hand within targets arrayed randomly in a small patch (10×10 cm square) of the arm's workspace, for approximately 10 minutes. Sensory function was measured with psychophysical tests before and after the motor task.

Perceptual acuity – the slope of the psychophysical threshold, and a measure of how consistently stimuli were perceived by a subject – was improved after motor learning, relative to baseline. This increase in perceptual acuity was shown also to depend on the location of motor learning, as subjects who performed accurate reaching movements in a location 25 cm away from the perceptual testing location did not demonstrate the same improvements to sensory function. Again, we tested if this perceptual effect depended on active movement by measuring sensory changes for subjects who passively experienced pre-recorded movements made by other subjects. Proprioceptive acuity improvement was not observed for these subjects, a finding that supports the idea that active movement is required to mediate change in perceptual function.

Lastly we attempted to test whether learning itself was the cause of sensory perceptual change. To do this, we provided new subjects with a motor task that required active movement, but which reduced the possibility of learning of accurate movements. To do this, targets were presented open-loop to subjects, and no visual information was provided about subjects' hand position. We observed no reliable increases in movement accuracy for these subjects, and also found no changes to sensory function. Taken together, changes to the perceptual acuity of hand function depend on *spatially-specific*, *active*, *learning* of novel accurate movement.

The experiment in **Chapter Four** explores the extent to which the improvements to sensory sensitivity observed in Chapter Three persist following motor learning. It has previously been shown that learned motor commands may persist for long periods of time post-learning. In Chapter Two, we observed 24 hour persistence of sensory bias following motor learning of directional loads. Thus, a natural question arises

about the persistence of the perceptual acuity change observed in Chapter Three.

We measured proprioceptive sensitivity at baseline and then again at 0, 1, 4 and 24 hours following the motor task requiring accurate movement described in Chapter Three. Perceptual acuity was again shown to be significantly improved relative to baseline immediately following motor learning. Subsequent tests revealed that acuity was again improved 24 h following learning, relative to baseline measures. No-movement control subjects did not show the same sensory improvements at any time after motor learning. Taken together, these results support the notion that proprioceptive changes as a result of motor learning have some persistence greater than immediately following movement itself, and perhaps suggest that motor learning and sensory processes have similar retention characteristics.

In **Chapter Five** we invert the relationship between proprioceptive function and motor learning, and ask whether proprioceptive training might improve motor learning. It remains an open question if proprioceptive information about desired movement can be used by the motor system to generate more accurate movements.

To address this question, we provided subjects with a motor learning task composed of two kinds of trials – demonstration trials where subjects were shown the desired movement, and active movements where subjects were asked to perform the desired arm movement themselves. Demonstration trials were interleaved throughout learning, and either featured only visual information (control subjects) or both visual and proprioceptive information (experimental subjects) about the desired trajectory to determine the effect of proprioceptive information on motor learning. Subjects performed arm movements over three days. Subjects were provided with feedback about their performance on each trial, and showed clear improvement at replicating

this movement over time. Notably, experimental subjects receiving proprioceptive information on demonstration trials showed improved ability to reproduce desired movement. This improvement was measured in terms of matching desired movement velocity, where subjects showed significantly greater performance, and also in terms of positional error, where subjects were better able to reduce positional error. Interestingly, experimental subjects demonstrated greater benefit from training than an additional group of subjects who received an active form of proprioceptive training: during demonstration trials these subjects actively attempted to move along the desired trajectory. These results support the idea that proprioceptive information provided to a passive arm can assist in the learning of novel movements.

1.2 Literature Review

1.2.1 Motor adaptation in the upper limb

Studies in motor learning have investigated the extent to and means by which the motor system adapts to changes in the dynamical behaviour of the human body. Tool use is an oft-cited paradigm in which human motor control is exceptional. A hand-held object, with its own unique dynamic properties, changes the relationship between muscle force and limb movement. Despite this fact, we are capable of effortlessly interfacing with myriad objects with considerable skill, and seemingly without effort. How this adaptive behaviour is achieved is not understood. A broad research aim in motor control is to understand how the brain adapts muscle commands to compensate for perturbing forces both from the environment (of which gravitational and frictional forces are two examples), and also from the complex dynamics of the human body

that result from interaction torques between connected limb segments. The principal goal of motor control might be defined as the investigation of adaptations made by the human motor system to compensate for these perturbations and thereby obtain successful movement.

One well-studied avenue of motor adaptation has been the application of externally generated forces to the human arm. These forces are typically applied via a handle grasped in the subject's hand (or in some cases directly to the shoulder and elbow joints) and are commonly termed *force-fields*. An early study of motor control observed adaptations to reaching movements, the characteristics of which are illustrative of and relevant to current motor control studies. In Shadmehr and Mussa-Ivaldi (1994), subjects generated reaching movements to targets in the presence of a velocity-dependent force-field. Movements first made in the force-field were shown to be curved, as these external forces pushed the limb away from a regular, approximately straight trajectory. Throughout the training phase, subjects learned to adapt muscle forces to counteract the robot forces, and therefore regained the straight reaching movements made in baseline trials (also called *null* trials to denote zero applied force). The curvature during special after-effect trials – trials presented infrequently at randomized intervals, in which the force-field was removed entirely – illuminated the specific nature of adaptation, because these movements were mirror-reflected images of early, perturbed movement. Therefore, subjects had learned to apply forces to precisely counteract external loads. Finally, the concept of generalization was also addressed in this paper (although limited in scope), by investigating how other movements were affected by the force-field training. Deviations in hand-path were observed for reaching movements made to untrained targets, thereby suggesting that

motor adaptations resulted in changed motor commands to a subset of movements, rather than to a single specific reach. These concepts of *magnitude* and *generalization* of motor adaptation continue to be investigated, and both are addressed in some capacity in the experiments contained in succeeding chapters.

Neural correlates of arm movements

It is known that the region of cortex identified as *primary motor cortex* (MI) is involved in reaching movements, based on the results of lesion, electrical stimulation, and single cell recording experiments (Porter and Lemon, 1993). Thus some neurally-implemented calculation that occurs in this area is important for reaching movement, but the nature of this calculation continues to be poorly understood. The prior hypothesis might be simply that MI neural activation directly results in muscle activation, and therefore muscle force (given that neurons in this area project directly to motor neurons via the corticospinal tract), and this indeed was an early finding of monkey neurophysiological preparations (Evarts, 1968). In a subsequent influential study, Georgopoulos et al. (1982) attempted to determine if neural firing is related to movement direction. By measuring mean neural firing activity during the reaction time (RT, from cue presentation to non-zero hand velocity), movement time (MT, non-zero velocity) and total time (RT+MT), the authors were able to determine that neural activity in 75% of all cells was directionally tuned to movement direction in either or both of RT and MT, and that the activity of many cells showed well-behaved cosine tuning functions featuring peak activation for a specific reach direction of the hand, a cell's so-called *preferred direction* (this cosine tuning also results in smooth reduction of activation with increased angular deflection away

from the direction of maximal activity). Thus a reasonable argument was made for the idea that MI activity is also related to movement direction.

Recent studies about cortical activity during reaching movements have more fully explored two aspects of this early work. First, Georgopoulos et al. (1982) does not address whether motor neurons in fact *encode* direction itself or some other covariate; despite references made to the earlier Evarts study, no attempt was made to determine the degree to which correlations with direction would appear if MI activity simply coded for the open-loop activation of muscles. Other studies have gone on to show significant correlations between MI activity and movement velocity, arm position, acceleration, movement preparation, target position, distance to target, muscle coactivation, serial order, visual target position, and visual target position (see Todorov 2000; Mussa-Ivaldi 1988 for a review of these correlated parameters), presumably because kinematic parameters are related by physical laws. Indeed, it has been shown that an artificial neural network of MI implemented such that neurons send muscle activation commands to a simulated two-joint arm will feature activation in the simulated neurons that correlates with these movement parameters (Todorov, 2000). Moreover, changes in the activity of MI neurons have also been observed when joint configuration (but not direction of hand movement) is altered for reaching movements (Scott et al., 1997). Errors in preferred-direction-based representations of MI activity have even been shown to be correlated with the rate of work done at a joint (Scott et al., 2001), evidence for MI activity related to muscle activation itself.

Second, the conclusions in Georgopoulos et al. (1982) were not based on time-varying correlations of movement direction with neural firing but rather mean firing rate over the entire movement duration. Subsequent studies have explored the degree

to which this coarse analysis holds for the precise temporal variation of MI activation during movement. In fact, collapsing data across time obscures important aspects of MI activation which cast doubt on such simplification. Most basically, neural activation is significant before movement (even accounting for transmission delays from neural conduction and the activation dynamics of muscle). The accepted theory for this activation is that this activity is merely *sub-threshold* activation of preferred-direction-tuned neurons (Bastian et al., 1998; Riehle and Requin, 1989; Cisek, 2006). This hypothesis is testable: if MI neurons encode movement direction, neural activity both before and during movement should be well-correlated. However the preferred direction of a given MI neuron can change substantially between preparatory and movement epochs (see Churchland et al. 2010 for review) such that, on a population level, only weak correlations exist for neural activity between epochs.

At least four posterior hypotheses might be made about the relationship between pre-movement neural activity and movement activity: neural activation is not related to the same parameter at each epoch; neural activation is related to the same parameter but the (directional) preference changes between epochs; neural activity before movement is epiphenomenal; and finally it might be that they are related in a non-obvious manner at the level of single neuron activation. This issue continues to be unsolved. Recent proposals have employed powerful mathematical techniques to represent neural activity at different epochs as linear dynamical models of neural activity over time (Churchland et al., 2010). In such models, activity at a given neuron for (discretized) time-points is linearly related to firing of other neurons in the population. These models have been proposed as mechanistic models of neural activity – the activity of such a model over time putatively represent MI cortical activity. Using

such an approach, these models can match two important aspects of empirical data: population activity at each epoch is well captured, while activity of a given neuron at each epoch (preparatory vs movement times) is only weakly correlated. The degree to which this approach succeeds in fact due to the power of linear dynamical models remains to be quantitatively assessed (though argued against in the above paper).

Among regions of the brain considered as a whole, activity in MI is most commonly associated with the execution of movement. A number of other brain regions have been implicated in the computation of various aspects of movement. Proposed roles for these contributing brain regions are briefly outlined here. Ipsilateral cerebellum may be involved in generating precise commands to control grasping and tool-use movements (Imamizu et al., 2000). Pre-motor dorsal area neurons respond in a similar fashion to primary motor cortical neurons (and when activation is represented with preferred-direction vectors, demonstrate similar encoding), while pre-motor ventral neurons may encode information about target position and reach directions in visual space, motor space, or both (for review see Hoshi and Tanji, 2007). Supplementary motor area neurons have been associated with self-generated (as opposed to externally triggered) movement, the coding of movement sequences, and abstract cognitive control of movement (Nachev et al., 2008, for review). Posterior parietal cortical neurons may be specifically involved in coordinating looking and reaching movements (Dean et al., 2012). Regions of the cerebellum have been proposed as sites of plastic changes for the learning of internal models of novel dynamics (Diedrichsen et al., 2005) including tool use (Imamizu et al., 2000), and a role in motor learning of motor sequences has been proposed for territories of the basal ganglia (Lehéricy et al., 2005).

Motor learning: observational learning

A powerful mechanism by which the motor system links motor control with action observation has been identified in visual observational learning. When we observe the actions of others, there is measurable activation of the same neural circuitry involved in executing the action ourselves (Gallese et al., 1996). Thus, so-called mirror neurons show similar activation when performing an action, or when observing it. In a recent study the authors proposed that such observations are capable of informing low-level information about the dynamical properties of a task. In this study by Mattar and Gribble (2005) the authors had subjects watch videos of other subjects performing reaching movements with a robotic manipulandum as they learned to adapt to a a force-field that depended on movement velocity (termed *viscous*) and exerted a force perpendicular to object motion (termed *curl*). Subjects (both movie watchers and controls) were then required to perform reaching movements themselves in the force-field. Observers of the learning videos demonstrated a performance improvement over the first eight movements, at the beginning of the motor learning phase, compared to control subjects who had not undergone observational learning, and also to controls who had watched videos of subjects only making movements in a null field (and who therefore acquired no novel motor commands). Interestingly, subjects who observed the opposite force-field showed poorer initial performance. Additional groups of subjects who were actively engaged in a motor task during video observation did not show modifications to their own performance as strongly, a fact that argues for this effect requiring engagement of the motor system itself. Taken together these results support the idea that visual observation of a motor learning task being learned can significantly influence and improve how we learn new motor tasks.

1.2.2   Proprioception

Signals underlying proprioception

Historically the sense of body position has been considered to be the composite of several distinct anatomical sensors. Four primary classes of receptors - joint receptors, skin afferents, Golgi tendon organs, and muscle spindles - are all proposed to provide information about the body. The functional roles of each primary receptor has been debated.

It is currently held that muscle spindles serve a primary role for position sense of the body. Muscle spindles are situated in parallel with extrafusal (force-generating) muscle fibres, and have been characterized as sending afferent signals about the kinematic properties of muscle - position, velocity, and acceleration, in some nonlinear relationship. Signals from these receptors are known to reach somatosensory cortex (Oscarsson and Rosen, 1963), respond during muscle lengthening across a wide range of joint angles (Prochazka and Gorassini, 1998b; Dimitriou and Edin, 2008a,b), and can be entrained during sinusoidal stretching (and vibration) of the tendon (Brown et al., 1967). Tendon vibration, when applied externally, has been shown to provide an illusory sense of motion when performed on humans. (Goodwin et al., 1972; McCloskey et al., 1983).

Golgi tendon organs may also play a role in proprioception. These sensory organs are placed in series at the junction of muscle and tendons. Their afferent behaviour has been differentiated from muscle spindle afferents in a critical way during the above vibration preparations: Golgi tendon organs have been observed to be very insensitive to vibration in the absence of efferent, descending signals to the extrafusal

muscle fibres (Brown et al., 1967). Partly as a result, Golgi tendon organs have been traditionally proposed to signal muscle force (Appenteng and Prochazka, 1984).

It has however been observed that in the real musculoskeletal system, the existence of spring-like tendons means that tendon-length itself must be known (or calculated) for the motor system to in turn know the current state of the body. Given the fact that tendons are passive structures and exhibit nonlinear spring-like behaviour, force at the muscle-tendon junction is proportional to the product of tendon stiffness and (a power law relation of) tendon length. Therefore an alternative interpretation of tendon signals considers Golgi tendon organs as in fact signalling tendon length. This role has been proposed explicitly in a recent modelling study (Kistemaker et al., 2012).

Joint receptors were originally thought to fulfill the role now ascribed to muscle spindles, that is to provide necessary information about joint angle change across the entire range of a joint. However, subsequent studies identified that in fact joint receptors signal identically for opposite ends of the joint range, and also feature low/absent mid-range responses (Burgess et al., 1982). In addition, both temporary and permanent disruption of receptor function via anaesthesis (Clark et al., 1979) or surgically-mediated destruction (Grigg et al., 1973) have been shown to leave movement perception and generation relatively unimpaired. Thus joint receptors have been relegated to subsidiary roles, perhaps as limit detectors signalling extreme joint angles (Ferrell et al., 1987).

Behavioural experiments of proprioception

Investigating human proprioception has typically been performed by measuring both the mean and variance of behavioural responses to stimuli. In fact, a wide variety of

experimental methods have been employed.

Perhaps the most direct attempt to assess proprioception as a source of sensory information in arm movements was performed by van Beers et al. (1998). The authors began with the following assumption: in bimanual visually-guided reaching movements, there are 3 principle sources of information necessary for movement planning: 1) proprioception of the left arm, 2) proprioception of the right arm, and 3) visual information. While it might be argued that proprioception in a stationary arm is qualitatively different than proprioception of a moving arm, the authors argued that by allowing very slow movements (and even corrective movements), errors from movement itself were minimal, and thus assumed that variability was the same for a stationary arm used as a target, or a moving arm used as an indicator (the right arm was used as both target and indicator, while the left arm was always only used for indication). Therefore, the authors attempted to quantify the bias and variance of each of the three information sources. Estimates were made by fitting a model of pointing accuracy during reaching to several pointing locations. Subjects performed three sets of pointing movements: 1) to visual targets with an unseen left hand, 2) to visual targets with the unseen right hand, and 3) to the right hand with the left hand, without vision. In each case one of the sources of information was therefore removed, and regression coefficients were computed for each information source. The authors demonstrated that proprioception was more accurate in radial (shoulder) directions rather than azimuthal directions. Proprioception was also shown to be higher for targets closer to the body (in particular near the ipsilateral shoulder). Both of these patterns can be understood by the geometry of the arm - greater total angular displacement occurs during radial and proximal movements. This geometric result

has been observed again in several recent studies (Wilson et al., 2010; Fuentes and Bastian, 2010).

A number of studies have targeted inter-hemispheric differences in proprioception (Goble et al., 2006; Goble and Brown, 2008a; Sainburg, 2002). Some evidence exists that proprioception of the non-dominant left arm benefits from superior position sense to that of the right arm. Differences in proprioception between limbs were reported in Goble et al. (2006) in a task in which subjects were required to return their limb to a remembered joint angle. Limb matching was better for the non-preferred left arm. A subsequent study by the same lab replicated this finding and also observed better performance for remembered visual matching with the preferred right arm (Goble and Brown, 2008a), which supports a recent hypothesis proposing that the non-preferred arm has a specific role for stabilizing an object based on proprioceptive feedback, while the preferred arm uses visual guidance for motor control (Sainburg, 2002; Goble and Brown, 2008a).

Other studies have investigated proprioception in the context of sensorimotor integration in visuomotor tasks. The use of proprioceptive signals might be particularly important in movements where proprioceptive signals are superior to visual signals. This has been observed to indeed be true for movement directions where relatively low visual information exists, such as radial movements away and toward the body (van Beers et al., 2002, 1998).

Misalignment of proprioception and vision has been shown to occur in a number of instances (Brown et al., 2003; Wolpert and Kawato, 1998; Wann and Ibrahim, 1992). Brown et al. (2003) showed that when subjects make reaching movements between two visual targets but without vision of the hand, start and end positions of the

hand drift gradually over time from their original positions, while other movement parameters – movement direction and amplitude – remained constant. Brown et al. (2003) note that this is paradoxical because of two seemingly inconsistent facts: first, there is evidence that the motor system has a *poor* estimate of the arm's position since the hand is no longer successfully reaching the desired stationary targets (apparently unbeknownst to subjects); second however, there is evidence that the motor system has in fact a very *good* estimate of the hand's position, since very accurate information about the arm's position is required to make movements that maintain the same length and direction of the original goal movement. Drift between proprioceptive arm position and visual target has also been shown by Wann and Ibrahim (1992) who had subjects make unseen reaches every 15 seconds to visual targets. Drift has not always been observed: Desmurget et al. (2000) did not find any decrease in accuracy in a hand-position-matching task over 20 seconds. It remains unclear what constitutes the perceptual estimate of drift. Desmurget et al. (2000) suggest one potential culprit. The authors note that both sensory and efference copy signals about recent movement – as distinct from perception of static position – are typically included in the experiments for which drift has been reported, and in fact it is the differential use of these signals over time that may be the source of observed drift.

Isolating proprioception

A general difficulty in the interpretation of proprioceptive studies is the separation of proprioception from other methodological components. Seldom have these methods clearly disentangled proprioception itself from coordinate transformations implicit in perceptual responses. Such variations have included responses to visual targets, re-

sponses that require a motor or active movement aspect, responses that require require inter-hemispheric transfer of information for contralateral limb-matching, memory of remembered positions, and/or a combination of the above. Therefore, any measurement of proprioceptive threshold may be confounded with other sources of variation: sensory noise in the visual and/or motor systems themselves, or higher level variations from transformation of different sensory sources to a common coordinate system.

These methodological variations are of particular importance for the studies included in this thesis because we are interested in measuring proprioception in the presence of motor learning. We carefully chose particular aspects of our sensory testing paradigm to avoid confounding estimates of proprioception with other aspects potentially affected by motor learning. Three major methodological variations in recent behavioural studies of proprioception serve as useful categorizations of the remaining literature, and identify components of sensory testing to be avoided in the psychophysical estimation procedure we employ in Chapters Two, Three, and Four.

Active motor responses

A number of methods have required that subjects indicate sensed position by performing an active movement (van Beers et al., 1998; Wann and Ibrahim, 1992; Chieffi et al., 2004; Goble et al., 2006; Goble and Brown, 2008a). Active movements here have included pointing to an unseen hand, or matching a target limb position or joint angle deviation. Naturally, any difference between the planned movement endpoint and the actual movement endpoint (resulting from an error in the computed motor command, or noise in efferent neural signals to muscles) will contribute to the observed net error, and may mistakenly be attributed to perceptual variation.

One aspect of active movement that can affect proprioceptive estimates is movement velocity of active responses (Adamovich et al., 1998; Chieffi et al., 2004). For example, in the former study, the authors observed that when subjects attempted to replicate an imposed passive movement of the limb, overshooting of the passive movement was observed when replication movements were performed with greater movement speed.

Muscle activation has also been shown to influence proprioceptive accuracy. In studies of proprioception of previously visited arm positions, accuracy to those locations held with active muscle contraction was greater than locations made via passive movements (Adamovich et al., 1998).

It has also been suggested that proprioception might share some aspect of the (anatomically-derived) what/where dichotomy in the visual system, a fact that would support the notion that fundamental differences exist between proprioception for active movement and proprioception for perception (Volpe et al., 1979; Paillard et al., 1983; Rossetti et al., 1995; Dijkerman and Haan, 2007). Using specific neuroanatomical case studies, a dissociation has been observed separating two different kinds of responses to tactile stimuli: conscious reporting of, and directed movement to different positional stimuli. In two case studies analogous of blindsight (Paillard et al., 1983; Rossetti et al., 1995), experimenters observed in each case a patient able to move accurately to a tactile stimulus, despite a complete lack of conscious awareness (i.e. as indicated by verbal reporting) of the proprioceptive testing site. Lesions were identified to exist in the left posterior cortical area and ventral posterior nucleus of the thalamus, respectively. This contrasts with other case studies reporting neurological patients who were unable to accurately locate stimuli that they could

successfully detect (Head and Holmes, 1911; Rapp et al., 2002), which when taken together with the previous study suggest that detection and location are doubly-dissociable processes. Recently, however, the double-dissociation hypothesis for the sense of touch was tested directly in a vibrotactile experiment (Harris et al., 2004). In this experiment, experimenters fit responses of normal subjects to different signal detection models to determine whether psychophysical responses could be explained by independent parallel processes, or serial processes. Only the serial model successfully described subject responses, leading the authors to conclude that somatosensation for action and perception are not mutually independent processes but rather localization is subsequent to detection. The authors speculate that somatosensory blindsight analogs may well be confounded by different response characteristics in yes-no as opposed to forced-choice psychophysical paradigms (for an exception to measures of true blindsight with controlled psychophysical estimates, see Azzopardi and Cowey 1997).

Vision in proprioception

Visual presentation of stimuli has been used in a number of proprioception experiments, either as a means of presenting targets, or as a response method itself (Desmurget et al., 2000; Sittig et al., 1985; Smeets et al., 2006; Vindras et al., 1998). Responses made to or with some visual reference involve coordinate transformations into a common space (van Beers et al., 1998), meaning that 1) determining proprioception distinct from vision is not straightforward, and 2) errors in coordinate transformation implicit in any perceptual judgment might again be attributed to sensory variation. In previous studies, experiments have found both that visual positions might be bet-

ter remembered than blinded (and passive) positions (Goble and Brown, 2008b) and also the reverse (Darling and Miller, 1993). In Darling and Miller (1993), matching movements to targets presented either visually (visible before movement onset) or kinaesthetically (blind guidance of the hand to a tactile object), subjects were better at moving toward kinaesthetic targets.

Inter-hemispheric transfer

Another method used for proprioceptive assessment is via joint matching either between limbs, or with the same limb (to remembered positions). Joint matching is more accurate when made to ipsilateral remembered positions than to contralateral positions either remembered or simultaneously presented (Adamo and Martin, 2009; Goble et al., 2006), thereby supporting the simple hypothesis that there is a cost of integrating two sensory signals that is greater than comparing a remembered signal to a current signal from the same sensor.

Psychophysics and proprioceptive sensitivity

The psychophysical estimation of sensory threshold is the measurement of subjective responses at various levels of stimulus intensity. The mapping between perception and stimulus intensity provides estimations of both perceptual acuity – the range of stimuli for which changes in perception occur – and also perceptual threshold: the stimulus intensity at which subjects detect with 50% probability. This is the method we employ for the estimation of proprioception in subsequent chapters.

By choosing to perform psychophysical estimates we diverge somewhat from the majority of proprioceptive estimation experiments, including the majority of the lit-

erature cited above. The most important reason for this choice has been because the use of two-alternative, forced-choice psychophysical tests is a good way of measuring proprioception while avoiding movement and visual components that would confound hypothetically observed changes in proprioceptive function following motor learning. It is known that motor learning certainly results in altered movements, and motor learning also systematically enhances vision (Brown et al., 2007), and thus such components must be avoided in estimates of sensory function.

Measuring the sense of human proprioception is slightly different from other psychophysical estimation procedures. At a basic level, estimates of human psychophysics require the delivery of stimuli across an input range; psychophysics of human vision or audition involve presenting sensory stimuli of sound or light inputs of varying amplitude or wavelength via precision display and acoustic equipment. Estimation of proprioceptive threshold faces a unique challenge by the obvious fact that the human apparatus must be physically moved across any range. Where other perceptual judgments require the stimuli at particular wavelengths/amplitudes to be systematically (Laming and Laming, 1992) or algorithmically (Taylor and Creelman, 1967) varied, in proprioceptive measurements the transitions *between* each stimuli must also be constrained. A robotic apparatus for stimulus presentation is useful for such tasks.

Additionally, the dimension along which stimuli might be varied is also open for consideration: in which coordinate system should the stimuli be varied? Cartesian distance (perhaps relative to some initial location), joint angle, or muscle length, are all potential domains (likewise with their time derivatives). The benefit of a given coordinate system might depend on how proprioception is of interest. Joint angle is most logical when comparing perceptual variation across different parts of

the body; Cartesian perturbations are useful for considering perceptual differences that might be use-dependent, or for interpreting the functional relevance of such perceptual differences. Ultimately, proprioceptive signals are believed to be mediated at a muscle level, the length of which however cannot be directly known without knowledge of or assumptions about additional states of the system, including muscle activation and tendon length (see Dimitriou and Edin 2010).

1.2.3 Perceptual changes resulting from motor learning

Several recent investigations have focused on the degree to which movements modify our perceptual abilities, particularly in the context of motor learning. Does learning new motor commands to generate novel movement result in changes in human perception?

In the visual system, developmental findings suggest that this effect of movement on perception may be a feature of normal development. It has been shown in infant studies that accurate reaching movements to objects are made early at 5 months of age (von Hofsten and Spelke, 1985). Prediction of visual motion happens slightly later, at 7 months (Kim and Spelke, 1992). Visual motion prediction was assessed by measuring the duration infants spent gazing at objects accelerating at appropriate or inappropriate rates, the authors inferred the degree to which infants were habituated to different visual accelerations. Seven month olds, but not five month olds, demonstrated a habituated response to objects accelerating appropriately under gravity, and spent longer time observing visual motion. Therefore, long-term visual adaptation occurs a few months later than the time during which which infants learn appropriate arm movements in the presence of gravity. The temporal sequence of motor and

visual adaptations thus allows for the possibility that reaching movements play a role in the natural development of visual perception.

Other investigations have been made into altered visual sensitivity directly from motor learning itself. After subjects learned a novel gait, subjects demonstrated increased visual sensitivity to the visual perception of such gait patterns (Casile and Giese, 2006). Subjects were required to learn novel phase differences between hands (180 degrees normally separate the contralateral limbs) of either 225 or 270 degrees. These tasks were learned blind-folded, and only with the assistance of verbal instructions and haptic guidance from experimenters. Following this motor learning period subjects were given a visual discrimination task in which two point-light displays were shown of human walking. The experimenters specifically altered the degree of phase difference between the two displays, and subjects were required to respond in a forced-choice paradigm whether the two point-light displays of visual motion depicted identical gait patterns. It was observed that subjects who had learned the motor task showed lower detection thresholds for gait phase differences – and, further, subjects who were better able to learn the novel movement patterns were also better at detecting visual differences. Importantly, because subjects were blindfolded during their own learning of movement, the increased sensitivity to visual gait differences after learning was not confounded by subjects simply training their visual system on processing (their own) novel gait patterns. This study demonstrates an effect of motor learning on visual processing in a restricted sense: altered visual perception was restricted to vision of that movement itself.

One recent study investigated motor learning effects on visual processing, and in this case focused on whether alterations to visual perception of object motion oc-

curred more generally (Brown et al., 2007), and not specifically restricted to vision of learned movements as in the previous study. Subjects performed reaching movements with a robotic manipulandum and the robot was programmed such that the force at the hand was constant and unidirectional. One group of subjects received a force-field pushing their hand leftward, another group experienced a rightward force-field, and a final group of subjects experienced a null force-field (0 output force). First, subjects learned to make straight reaches to targets while in the presence of the force-field. Next, with the force-field still turned on, subjects were required to reach out and intercept visual targets that moved left-to-right across the display, with constant acceleration. Therefore, the visual motion of these targets was carefully chosen to be either congruent, or incongruent, to the experienced force-field. The authors hypothesized that motor learning of a force-field systematically alters visual prediction: subjects who have learned reaches in a rightward force-field will also predict visual objects to accelerate rightward, as though the objects are moving under the same force-field.

Indeed, subjects whose force-field experience was congruent to visual object motion were significantly better at successfully intercepting the visual targets. This benefit was observed to be independent of interception behaviour in two ways. First, subject groups showed no reliable differences in interception kinematics. Second, a control experiment showed that changes to visual perception were not tied to reaching movements alone. In a task that required subjects to make button-press responses to indicate the position of moving objects, the timing (early, accurate, or late) of these button presses depended on the direction of the force-field experienced during previous reaching movements. Therefore, directional force-field learning is capable of

systematically altering how the brain perceives visual motion.

Increased visual sensitivity can also develop near the functional end of learned tools (Brown et al., 2011). After learning to move a novel pointer-like tool ballistically to targets, subjects performed a visual detection experiment in which they were asked to respond as soon as they saw a cursor appear near the tip of the tool. Only subjects who performed these active, ballistic movements showed an increase in visual sensitivity, as indicated by reduced response times. No visual sensitivity improvements were observed for control subjects who made no movements with the tool, nor for subjects who received passive guidance of their arm through reaching trajectories.

Proprioceptive changes resulting from motor learning

While motor effects on the visual system have been studied more frequently, recently some studies have investigated the effects of motor learning on the proprioceptive system. One such study investigated perceptual changes following the motor adaptation to a visuomotor rotation (Cressman and Henriques, 2009). In this study, subjects performed a set of point-to-point reaching movements while the visual representation of hand position (the arm itself was not visible) was gradually altered such that the represented position appeared rotated from actual hand position. Before and after this learning phase, subjects performed a psychophysical test session during which they reported the perceived position of their hand as being left or right of a displayed visual cursor. After learning a visual rotation field, subjects demonstrated that the perceived position of their hand was directly related to the rotation magnitude applied to reaching movements. Since the psychophysical test measured the difference

between perceived hand position and visual cursor, the observed change represents a change in the calibration between vision and proprioception: neither vision nor proprioception are uniquely implicated in this change.

Evidence for long-term changes to proprioceptive function as a result of motor learning might be observed by assessing proprioception in different locations of the arm's workspace, thereby probing for differences dependent upon arm use. Relatively few studies have been reported that assess how proprioception may vary across the workspace of the limb (Fuentes and Bastian, 2010; van Beers et al., 1998; Wilson et al., 2010), and no perceptual differences (beyond those admitting of a simple geometric explanation) have been observed. In contrast, we know a great deal about other sensory systems that are characterized by differential anatomic sensor density, resulting in greater visual (Wald, 1945), acoustic (Davis and Kranz, 1964), and haptic sensitivity (Bolanowski et al., 1988; Verrillo, 1963; Weinstein, 1968) across a subset of the input domain.

1.2.4 Physiological bases for proprioceptive changes from motor learning

Central plasticity of sensory areas

Neuroplasticity is central to the development of human motor function and, likewise, to skill acquisition in the mature motor system. Work to date on motor learning has focused almost exclusively on plasticity in motor systems: on how motor systems acquire new abilities, how learning occurs during motor development, and how learning is compromised by trauma and disease. The extent to which these changes in motor

function affect the somatosensory system is largely unknown. Numerous studies have shown central activity of sensory neurons during movement, presumably since activity in somatosensory cortex neurons varies systematically changes with body position. In area SI 3b of monkey somatosensory cortex, approximately 50% of neurons with tactile receptive fields of skin have been reported to modulate their activity during reaching movement (Prud'homme and Kalaska, 1994; Cohen et al., 1994). These neurons fired most strongly to tactile manipulations but still showed activity during reaches without direct tactile stimulation. The probability of task-related activity was related to particular response properties of given neurons, in particular sensitivity to direct stretching of the skin, implying that movement-induced skin stretch is the mechanical event resulting in cortical signals.

Neurons in primary somatosensory cortex (SI) vary systematically with movement. This conforms with a priori expectations about cortical areas that appear to wire directly to peripheral sensors (Oscarsson and Rosen, 1963). Interestingly however, these neurons did not seem to reflect only the kinematics of the arm, since neural activity was not only affected by current limb kinematics; instead, these neurons showed strong hysteresis effects. This was observed in a task where monkeys made reaching movements to a common central target. Neuronal activity seemed to reflect previously-experienced movement. It could be that somatosensory cortex indeed reflects sensory history; indeed the authors note that hysteresis effects observed in a particular neuron were often larger when previous movements included the neuron's preferred direction. A different earlier study found that activity for many of the neurons in somatosensory areas (1, 2, and 5) changed firing while the arm was stationary, but before activation of arm muscles, in the range of 60 to 100 ms *be-*

fore changes in electromyographs (Soso and Fetz, 1980; Nelson, 1987; Lebedev et al., 1994).

Finally, it is also well known that sensory representations can be heavily modulated by training. Several studies have investigated adaptations to vibrotactile sensory learning (Recanzone et al., 1992), precision grasping (Xerri et al., 1999) and even simple tactile stimuli from maintained contact between finger and object surface (Jenkins et al., 1990). Each of these studies observed rather similar changes to tactile representations in area 3b of somatosensory cortex. The most recent paper Xerri et al. (1999) required monkeys to make precision grasps to apprehend small banana-flavoured food pellets placed in wells, over a period of 3 months. The monkeys demonstrated change in prehensile behaviour over the course of learning to feed on the pellets, often switching number of grasping fingers (typically reducing number of involved fingers) and ultimately resulting in a greater proportion of successful grasps. In 3b, representation of a given glabrous skin area nearly doubled (on average; relative to untrained fingertips or contralateral fingertip areas); receptive fields for individual neurons in the area simultaneously decreased to less than half original size. These findings demonstrate the nature and extent of cortical plasticity that may occur during the acquisition of a motor skill.

Segmental basis for changes to proprioceptive function during movement

Sensory sensitivity is modulated dynamically via descending signals from the brain, and this may provide one mechanism by which the motor system mediates functional sensory change during movement. Efferent innervation of sense organs occurs in many human sensory systems, including those associated with proprioception. Efferent in-

nervation of semicircular canals (Purcell and Perachio, 1997; Warr, 1975) and retinal cells (Honrubia and Elliott, 1970) modulate the signals about head orientation and the visual field. Muscle spindles, widely regarded to be the primary source of information about the position of the limbs, also receive modulating efferent signals. It has been proposed that such signals may account for the sensory consequences of self-generated action (Bays et al., 2005; Blakemore et al., 1998; Wolpert and Flanagan, 2001) and augment the functional dynamic range of the sensor (Scott and Loeb, 1994; Windhorst, 2007).

Models of spindle afferent signals designed to infer what property is encoded by spindles during movement itself have had only partial success. In one study of chronic-recordings of normal stepping in cats (Prochazka and Hulliger, 1998), the key variable achieving good prediction of afferent signals was muscle velocity, with power law functions being the best fit (spindle firing rate being approximately proportional to the square root of muscle velocity). These data were collected from hamstring muscles - a muscle that is not significantly recruited during the stepping phase. When the experiment was repeated with a heavily-recruited muscle - triceps surae - it was shown that this relationship between muscle length and encoded signal does not hold well (Prochazka and Gorassini, 1998a). In humans, spindle afferent signals recorded during finger tapping and grasping studies have found muscle velocity and acceleration may be encoded by spindles (Dimitriou and Edin, 2008a,b).

Spindles are significantly innervated by descending signals that functionally modify the behaviour of the sensor. Gamma fusimotor drive is putatively responsible for changing the mechanical properties of the muscle spindle and thereby altering spindle feedback (Kuffler et al., 1951). It has recently been suggested that a significant

component of learning novel movement may in fact be learning appropriate fusimotor signals to control our sensory apparatus (Dimitriou and Edin, 2010).

Gamma fusimotor efferents have been classified into two types: static and dynamic (for a review, see Hulliger 1984). Descending activation from these differing fibre types has been differentiated based on the ability to either increase or decrease sensitivity during the ramp phase of ramp and hold movements.

In humans there has been some evidence that afferent signals may be modulated by efferent commands. In Hospod et al. (2007), experimenters tested the hypothesis that spindle signals might change systematically when subjects were required to attend to that part of their body. Interestingly researchers observed a variety of changes to spindle afferents, including increased discharge variability, changes in spontaneous (baseline) activity, and decreases in depth of signal modulation. The authors speculated that since muscle EMG was zero (and subjects were told to remain passive during these imposed movements), that fusimotor drive is responsible for modulation of afferent signals.

A separate study has found further evidence that spindle sensitivity can be modified based on movement context (Davis et al., 2011). In this study it was hypothesized that a stressful movement context would affect spindle reflex amplitudes. Subjects were asked to stand at the edge of a platform either during a low stress condition (less than 1 metre from the ground), or high stress condition (suspended 3 m from the floor). During quiet standing at these differing heights, subjects received reflex-inducing achilles tendon taps, while both reflex amplitude and cortical evoked potentials were recorded. Reflex amplitude was shown to increase during the high stress condition, while cortical-evoked potentials did not differ across the two conditions.

This suggests that either spindle afferents themselves, or spinal reflex gains, are modulated during the maintenance of stance under stressful conditions. A recent subsequent study by the same research group replicated the experiment but in addition to the tendon-tap reflex measures, H-reflex magnitude was also recorded (Horslen et al., 2011). H-reflexes are elicited by surface-electrical stimulation of afferent neurons, causing a monosynaptic motor reflex. By essentially sending artificial sensory input to the spinal cord and measuring the resulting reflex magnitude, changes to spinal reflex gains themselves may be inferred. No change in H-reflex magnitude was observed, which suggests that modulation of the afferent sensory signal occurs at the level of the spindle itself.

The literature cited above shows that anatomic substrates of perception support differential sensitivity, efferent neural signals provide top-down modulation of sensitivity, and behavioural context may play a role in this descending modulation.

1.3 Summary

In this chapter we have reviewed issues related to the motor system's capacity for motor adaptation, and provided an outline for the current characterizations of human proprioception. We also highlighted recent research investigating the how sensory function might be altered with motor learning, and explored current knowledge about the central and segmental bases for sensory plasticity.

Proprioception and its relationship to motor learning has not been completely studied. While other work has explored sensory integration of vision and proprioception, and a number of studies have investigated changes to the visual system following

motor learning, the effect of motor learning on proprioception itself remains an open question. Indeed it may be that the nature of changes in the perceived position of the hand after motor learning depend on the nature of the type of motor adaptation itself. Nothing is known about changes to the perceived position of the hand in the presence of external load, or even following the simple task of increasing movement accuracy to targets in the absence of an external load.

Similarly, it is not known if proprioceptive information can assist motor learning. While the ability of the motor system to adapt movements has been shown to benefit from visual information, it is not known if proprioceptive information about a desired novel movement is able to inform the motor system about learning motor commands.

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Chapter 2

Somatosensory plasticity and motor learning

2.1 Introduction

Neuroplasticity is central to the development of human motor function and, likewise, to skill acquisition in the adult nervous system. Here we assess the possibility that human motor learning also alters somatosensory function. We show that after brief periods of movement training, there are not only changes to motor function but also persistent changes to the way we perceive the position of our limbs.

Work to date on motor learning has focused almost exclusively on plasticity in motor systems, that is, on how motor systems acquire new abilities, how learning occurs during motor development, and how learning is compromised by trauma and disease. The extent to which these changes in motor function affect the somatosensory system is largely unknown. An effect of motor learning on sensory systems is likely since activity in somatosensory cortex neurons varies systematically with movement (Soso and Fetz, 1980; Chapman and Ageranioti-Bélanger, 1991; Ageranioti-Bélanger and Chapman, 1992; Cohen et al., 1994; Prud'homme et al., 1994; Prud'homme and Kalaska, 1994) and also because of the presence of ipsilateral corticocortical pathways linking motor to somatosensory areas of the brain (Jones et al., 1978; Darian-Smith et al., 1993). It is also likely since sensory experience on its own results in structural change to somatosensory cortex (Recanzone et al., 1992b,a; Jenkins et al., 1990; Xerri et al., 1999). Indeed there are a number of pieces of evidence suggesting perceptual change related to movement and learning. These include proprioceptive changes following visuomotor adaptation in reaching movements and in manual tracking (van Beers et al., 2002; Simani et al., 2007; Malfait et al., 2008; Cressman and Henriques, 2009) and visual and proprioceptive changes following force-field learning (Brown et al., 2007; Haith et al., 2008).

Here we describe studies involving human arm movement that test the idea that sensory function is modified by motor learning. Specifically, we show that learning to correct for forces that are applied to the limb by a robot results in durable changes to the sensed position of the limb. We obtain estimates of sensed limb position before and after motor learning, using two different techniques. We find that following periods of training as brief as 10 min, the sensed limb position shifts reliably in the direction of the applied force. We obtain a similar pattern of perceptual change for both leftright movements and forward back movements. The change is also similar following perceptual tests conducted in statics and during movement. The perceptual shifts that we observe are squarely grounded in motor learning. Subjects show no evidence of sensory change when the robot is programmed to passively move the hand through the same kinematic trajectories as subjects who actually experience motor learning. Moreover, we find that the perceptual shifts are reflected in subsequent movements. Following learning, movement trajectories deviate from their prelearning path by an amount similar in magnitude and in the same direction as the perceptual shift.

2.2 Materials and Methods

Subjects and tasks In total, 91 subjects were tested: 30 in experiment 1, 36 in experiment 2, and 25 in three different experiment 1 control studies. The subjects were all right handed and reported no history of sensorimotor disorder. All procedures were approved by the McGill University and The University of Western Ontario Research Ethics Boards.

Subjects performed reaching movements while holding the handle of a two degree-of-freedom planar robotic arm (InMotion2, Interactive Motion Technologies). Subjects were seated and arm movements occurred in a horizontal plane at shoulder height. An air sled supported the subject's arm against gravity, and a harness restrained the subject's trunk. Vision of the arm was blocked by a horizontal semisilvered mirror, which was placed just above the hand. During reaching movements, visual feedback was provided by a computer-generated display that projected target positions and a cursor representing hand position on the mirror. This resulted in a visual image that appeared in the same plane as the hand. Hand position during the experiment was measured using 16-digit optical encoders (Gurley Precision Instruments) located in the robot arm. A force-torque sensor (ATI Industrial Automation) mounted below the robot handle measured forces applied by the subject. *Experiment 1.* Subjects were tested on 2 separate days. The first day was used only to familiarize subjects with the experimental procedures, and the data were not included in our analyses. The first day of the experiment was divided into two parts. In the first part, subjects were trained to make straight reaching movements to a visual target in the absence of load. In the second phase, subjects' perception of limb position was estimated using an iterative algorithm known as parameter estimation by sequential testing (PEST) (Taylor and Creelman, 1967), which is described below.

The second day involved the experimental manipulation. It was divided into several parts in which tests of sensed limb position were interleaved with different phases of a standard dynamics-learning task 2.1A. Day 2 began with an initial baseline estimate of sensed limb position. Subjects then made 150 movements during which the robot applied no force to the hand (null condition). Immediately following
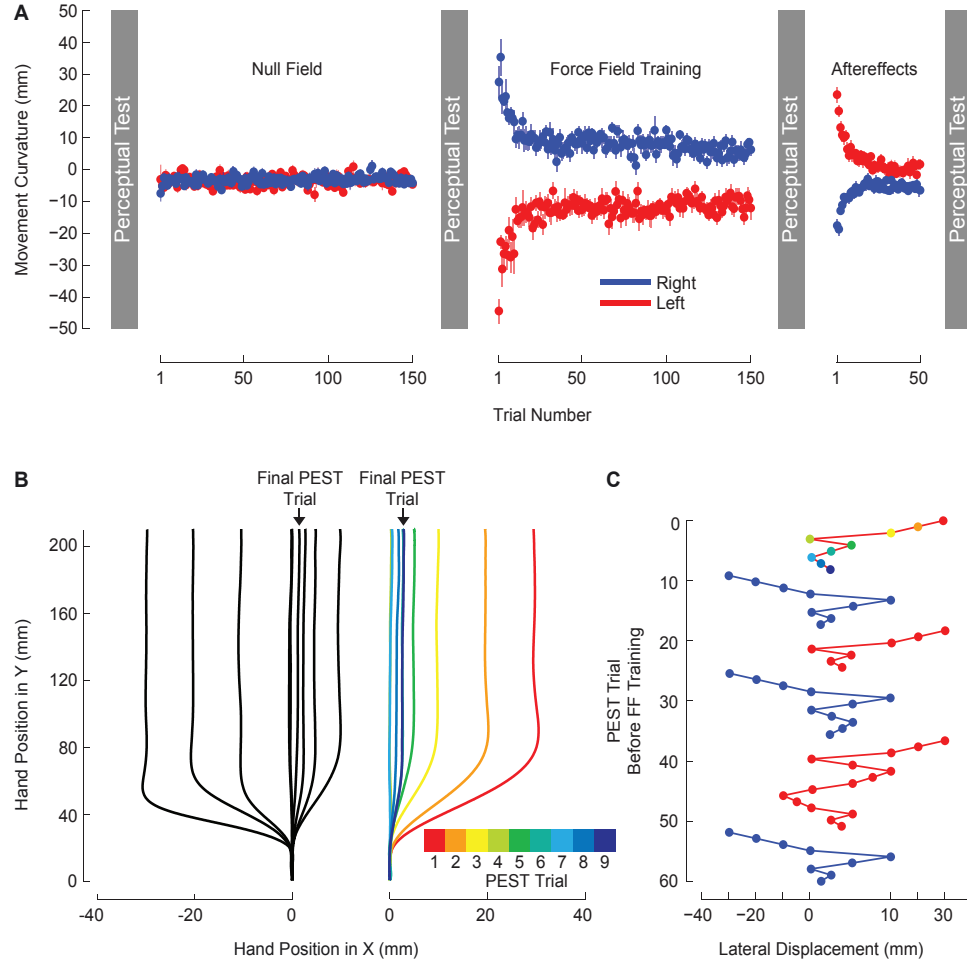
Figure 2.1: A, Subjects adapt to mechanical loads that displace the limb to the right or the left in proportion to hand velocity. Perceptual tests (gray) that estimate sensed limb position are interleaved with force-field training. Average movement curvature $\pm$ SE is shown for null-field, force-field, and aftereffect phases of the experiment. B, The perceptual boundary between left and right is estimated using an iterative procedure known as PEST. The limb is displaced laterally by a computer-generated force channel, and subjects are required to indicate whether the limb has been deflected to the right. Examples are shown of individual PEST runs starting from left and right, respectively. The sequence beginning to the right is color coded to indicate the sequence of trials. C, A sequence of six PEST runs (starting from the top) with the lateral position of the hand shown on the horizontal axis and the PEST trial number on the vertical. The colored sequence of positions shown at the top is the same as that shown on the right side of B. PEST runs alternately start from the right and the left and result in similar estimates of the perceptual boundary. Note that the horizontal axis highlights lateral hand positions between 0 and 10 mm.

null-field training, a second baseline estimate of sensed limb position was obtained. Subjects then began the training phase, during which they made 150 movements in a velocity-dependent force-field. An estimate of the sensed limb position was obtained immediately after force-field learning. Subjects then made 50 movements in a null field, to measure aftereffects and to wash out the kinematic effects of learning. After these aftereffect trials, a final estimate of the sensed limb position was obtained. The design thus yielded two baseline estimates of sensed limb position, one estimate immediately after force-field learning and one following aftereffect trials.

In the dynamics-learning task, subjects made reaching movements to a single visual target. Two white circles, 1.5 cm in diameter, marked the movement start and end points. The start point was situated in the center of the workspace, 25 cm from the subject's chest along the body midline. The target was located 20 cm in front of the start position in the sagittal plane. A yellow circle, 0.75 cm in diameter, provided the subject with feedback on the hand's current position. Subjects were instructed to make reaching movements in 1000 ± 50 ms. Subjects were also asked to move as straight as possible. Visual feedback of movement speed was provided at the end of each movement. The feedback was used to help subjects achieve the desired movement duration, but no trials were removed from analysis if subjects failed to comply with the speed requirement. At the end of each trial, the robot returned the subject's hand to the start position. An interval ranging from 500 to 1000 ms, chosen randomly, was included between trials.

In the force-field-learning phase, subjects were randomly divided in two groups. For one group, the robot applied a clockwise load to the hand that primarily acted to deflect the limb to the right. The second group was trained in a counterclockwise

force-field that deflected the limb primarily to the left. The force-field was applied to the hand according to the following equation:

$$\begin{bmatrix} f_x \\ f_y \end{bmatrix} = D \begin{bmatrix} 0 & 18 \\ -18 & 0 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \end{bmatrix}$$

where x and y are the lateral and sagittal directions, f_x and f_y are the commanded force to the robot in newtons, v_x and v_y are hand velocities in Cartesian coordinates in meters per second, and D defines the direction of the force-field. For the clockwise force-field, D was 1; for the counterclockwise condition, D was -1.

Estimates of sensed limb position were obtained in separate experimental blocks by asking subjects to reach to the same visual target as in the motor-learning phase of the experiment. When the subject's hand was 0.5 cm beyond the start point, all visual feedback (the target location and the yellow dot representing the subject's hand location) was removed. The robot applied a force channel throughout the movement that determined the lateral position of the hand. The parameters of the force channel were similar to those used in Scheidt et al. (2000). The equation for the force channel was $f_x = 3000\delta_x + 90v_x$, where f_x is the force applied by the robot in newtons, δ_x is the difference in meters between the current lateral position of the hand and the center of the channel, and v_x is the lateral velocity of the hand in meters per second. Stiffness is in newtons per meter, and viscosity is in newton-seconds per meter. No force was applied in the y direction. The force channel was programmed to be straight for the initial 1.5 cm of the outward movement. At 1.5 cm, the force channel was programmed to shift laterally over 300 ms and remain at the new lateral position until the end of the movement. The change in the lateral position occurred according to a

minimum jerk profile. Subjects were instructed not to oppose the lateral deflections and to continue the outward movement until a virtual soft wall at 20 cm indicated the end of movement. When subjects reached the haptic target, they were asked to maintain the position of the limb. At this point, subjects answered the question Was your hand pushed to the right? Subjects had been briefed previously that if they felt the hand had been deflected to the right they should respond yes, and otherwise they should respond no. Following a response, the limb was returned to the start location by the robot.

The PEST procedure (Taylor and Creelman, 1967) was used to manipulate the magnitude of the lateral deviation of the hand for purposes of estimating the perceptual boundary between left and right. PEST is an efficient algorithm for the estimation of psychophysical thresholds. Each PEST run begins with a suprathreshold displacement and, based on the subject's response, progressively decreases the displacement until a threshold displacement is reached. Based on a pilot study, we used 3 cm as an initial lateral deviation, which all subjects could correctly identify. On the next trial, the deviation was reduced by 1 cm, and this was repeated until the subject detected a change in the direction of lateral deviation. At this point, the step size was reduced by half, and the next displacement was in the opposite direction. The algorithm terminated whenever the upcoming step size fell below 1 mm.

Each block of perceptual tests had six PEST runs that yielded six separate estimates of the rightleft boundary. Three of the six PEST runs started from the right (3 cm to the right as a first lateral displacement and −1 cm as the first step size), and three runs started from left (3 cm to the left and 1 cm as the first step size). Figure 2.1B shows two sets of PEST runs for one representative subject, one starting

from left and the other starting from the right.

The data from all six PEST runs in each phase of the experiment were used to estimate the perceptual boundary between left and right. The entire set of measured lateral deviations and associated binary responses were fitted on a per-subject basis with a logistic function that gave the probability of responding yes, the hand was deviated to the right as a function of the lateral position of the hand. We used a least-squared error criterion (glmfit in Matlab) to obtain the fit. The 50% point of the fitted function was taken as the perceptual boundary and used for purposes of statistical analysis. Measures of the perceptual boundary, based on the lateral position of the hand in the final trial of each PEST sequence, gave results similar to those derived from the fitted psychometric functions.

We verified that the force channel produced the desired displacements by comparing the difference between the actual and commanded positions of the limb. We focused on the largest commanded displacement, the 3 cm deviation that occurs at the start of each PEST run. The absolute difference between actual and commanded displacements was 0.46, 0.42, 0.77, and 0.40 mm for the two sequences of PEST trials that occurred before learning and the sequences following force-field training and following aftereffect trials, respectively. These values are averaged over subjects, over PEST runs that began from the left and the right, and over force-field directions.

Experiment 2. Subjects were tested in a 1-h-long session. Each subject completed tests of sensed limb position, using the method of constant stimuli, before and after force-field learning. In the dynamics-learning phase of the study, subjects were asked to make side-to-side movements between two 2 cm targets. The targets were placed on a lateral axis 25 cm in front of the body and centered on the subject's midline. The

total movement distance was 20 cm. A small filled circle 0.8 cm in diameter indicated the position of the subject's hand during the movement. The start of each trial was indicated visually by the appearance of the target circle. Subjects were instructed to make straight movements between targets in 600 ± 100 ms. Visual feedback of movement speed was provided at the end of each trial. The feedback was not used to exclude any movements from analysis.

Subjects completed 400 movements in four experimental blocks. In the force-field-learning phase, subjects were assigned at random to one of two groups. One group trained with a load that pushed the hand outward during movement, away from the body. The other trained with a field that pushed the hand inward, toward the body. The force-field was defined by the following equation:

$$\begin{bmatrix} f_x \\ f_y \end{bmatrix} = D \begin{bmatrix} 0 & 0 \\ -17 & 0 \end{bmatrix} \begin{bmatrix} |v_x| \\ v_y \end{bmatrix}$$

where x and y are the lateral and sagittal directions, f_x and f_y are the commanded force to the robot in newtons, v_x and v_y are hand velocities in Cartesian coordinates in meters per second, and D defines the direction of the force-field. For the outward force-field, D was 1; for the inward condition, D was -1.

In perceptual tests, subjects were required to compare the felt position of their right hand with that of their left index finger. The subject's left index finger was fixed in position 0.5 cm to the left of the moving right hand. On each perceptual trial, the right hand was positioned by the robot at a location along the subject's midline in the sagittal plane. Subjects were instructed to indicate whether their right hand was closer or farther from their body relative to the left index finger. The hand was not

moved directly between test locations, since information related to the sequence of hand positions might be used as a basis for their perceptual decision. Instead, for each successive hand position in the perceptual test, the robot moved the right hand first away and then back to the next test position in sequence. This distractor movement was used between all perceptual judgments. The movement away and back followed a bell-shaped velocity profile, and was randomized in terms of the distance traveled (14 ± 2 cm SD), duration (1000 to 1600 ms), and direction (away from or toward the body).

Perceptual judgments were collected for each subject before and after motor learning. Seven fixed locations on a sagittal axis were used for perceptual testing. The test points were all at the midpoint of the lateral movement axis and differed in their inward outward position. Relative to the left index finger, which was held at 0.0 cm, the right hand was positioned at $-3.0, -1.3, -0.7, 0.0, 0.7, 1.3$, and 3.0 cm along the sagittal axis. Each position was tested multiple times, 6, 12, 12, 14, 12, 12, and 6, respectively. The locations farthest from the midpoint were tested less often because subjects performed at almost 100% at these locations. The ordering of test locations was randomized. The direction of the distractor movement between judgments (outward or inward) was pseudorandomly ordered such that each position was approached from each of the two directions an equal number of times. As in experiment 1, the actual positions of the right limb (as measured by the encoders of the robot) and subjects' binary verbal responses were fit with a logistic function (glmfit in Matlab) for each subject separately to produce psychometric curves. The position on the curve at which the subject responded close and far with equal probability determined the perceptual boundary.

Data analysis. In experiment 1, hand position and the force applied to the robot handle were sampled at 400 Hz. In experiment 2, the sampling rate was 600 Hz. The recorded signals were low-pass filtered at 40 Hz using a zero phase lag Butterworth filter. Positional signals were numerically differentiated to produce the velocity estimates. The start and end of each trial was defined as the time that hand tangential velocity went above or fell below 5% of maximum velocity. The maximum perpendicular deviation of the hand (PD) from a straight line connecting movement start and end of movement was calculated on a trial-by-trial basis and served as a measure of motor learning.

To statistically quantify our data, our general approach was to use repeated-measures ANOVAs. When appropriate, the ANOVA included a between-subjects factor that specified the direction of the force-field in which subjects were trained. ANOVAs were followed by Bonferroni-corrected post hoc tests. We applied this ANOVA approach to the following analyses. To quantify motor learning in both experiments 1 and 2, we analyzed the change in PD between the first 10 and the last 10 movements made in the force-field. To quantify perceptual shifts in experiment 1, we analyzed the change in perceptual boundary between the second baseline measurement and those that were subsequently obtained. The perceptual shift in experiment 2 was quantified as the difference between the prelearning and postlearning perceptual boundaries, and was evaluated using a one-way ANOVA. A repeated-measures ANOVA was used to show differences in the extent to which subjects showed after-effects in the passive control experiment. Changes in movement kinematics following learning were quantified as the difference in movement curvature between the final 10 movements in the aftereffect phase and the final 50 null-field movements before

motor learning. A repeated-measures ANOVA was used to compare the magnitude of the shift in kinematics with the shift in perceptual boundary following learning and after washout. ANOVA was used to determine how force production changed over the course of the experiment, and differed depending on the force-field direction. Lateral forces applied to channel walls were measured over the first 100 ms of the first movement in each sequence of perceptual testing.

We also performed analyses to determine whether motor learning led to a change in perceptual acuity. For these analyses, we quantified acuity on a per-subject basis using the distance between the 25th and 75th percentiles of the fitted psychometric function. For both experiments 1 and 2, we used ANOVA to assess changes between prelearning and postlearning acuity for the different force-field directions.

2.3 Results

We used two different techniques in two different laboratories to assess sensory change associated with motor learning. In experiment 1, we assessed the sensed position of the limb in the absence of visual feedback by having subjects indicate whether the robot deflected straight ahead movements to the left or the right. Experiment 2 used an interlimb matching procedure also in the absence of visual feedback to obtain estimates of the sensed limb position. In both cases, sensed limb position was assessed before and after subjects learned to reach to targets in the presence of a force-field that displaced the limb laterally in proportion to movement velocity. Experiment 1 involved outward movements along the body midline. Experiment 2 tested lateral movements. We varied the measurement technique and the movement direction to

assess the generality of the observed perceptual changes.

Figure 2.1A shows the experimental sequence for the study in which we obtained estimates of sensed limb position during movement. We interleaved blocks of trials in which we estimated limb position (shown in gray) with blocks of trials in a standard force-field-learning procedure. We also assessed whether the perceptual change persisted after the effects of motor learning were eliminated using washout trials.

Estimates of limb position were obtained in the absence of visual feedback using an iterative procedure known as PEST (Taylor and Creelman, 1967), where on each movement the limb was displaced laterally using a force channel (Scheidt et al., 2000) Figure 2.1B. At the end of each movement, the subject gave a binary response that indicated whether the limb had been deflected to the left or the right. The magnitude of the deflection was adaptively modified based on the subject's response to estimate the sensed boundary between left and right (Taylor and Creelman, 1967). Figure 2.1B shows PEST runs for a representative subject before force-field learning. The left panel gives trials in which the testing sequence began with a deflection to the left. The right panel shows a sequence for the same subject that started from the right. Figure 2.1C shows a sequence of six PEST runs. Each run converges on a threshold for the perceived leftright boundary that remains stable across successive estimates.

In the motor-learning phase of the study, subjects were trained to make movements in a clockwise or a counterclockwise force-field, whose main action was to push the hand to the right (blue) or the left (red) during movement. Performance over the course of learning was quantified by computing the maximum PD from a line joining movement start and end. Values for PD in each phase of the experiment are shown in Figure 2.1A, averaged over subjects. It can be seen that movements are straight

under null conditions. They are deflected laterally with introduction of load and reach asymptotic levels at the end of training that approach null-field levels. A repeated-measures ANOVA found that the reduction in curvature was reliable for both directions of force ($p < 0.001$ in each case). Curvature in aftereffect trials is opposite to that observed early in learning and reflects the adjustments to motor commands needed to produce straight movements in the presence of load. Curvature at the end of the washout trials differs from that under null conditions; movements remain curved in a direction opposite to that of the applied force.

Perceptual performance was quantified for each subject separately by fitting a logistic function to the set of lateral limb positions and associated binary responses that were obtained over six successive PEST runs in each phase of the experiment. For example, the entire sequence in Figure 2.1C would lead to a single psychometric function relating limb position to the perceptual response. Figure 2.2A shows binned response probabilities, averaged across subjects, and, for visualization purposes, psychometric functions fit to the means for the rightward and leftward force-fields. Separate curves are shown for estimates obtained before and after force-field learning. It can be seen that following learning, the psychometric function and hence the perceptual boundary between left and right shifts in a direction opposite to the applied load. Thus, if the force-field acts to the right (Fig. 2.2A, right), the probability of responding right increases following learning. This means that the hand feels farther to the right than it did before learning.

Figure 2.2 B quantifies perceptual performance at various stages of learning. The dependent measure for these analyses is the 50% point on the psychometric function that was obtained by fitting the curve to the set of binary responses. This is the

limb position associated with the perceived leftright boundary, that is, the position on the lateral axis at which the subject responds left and right with equal probability. Figure 2.2 B shows mean values for this perceptual measure over the course of the experiment. Perceptual estimates are seen to be similar for the two prelearning measures (labeled baseline 1 and baseline 2). The sensed position of the limb shifts following force-field training, and the changes persist following aftereffect trials.

We evaluated changes in sensed limb position as a consequence of learning by computing the perceptual shift on a per-subject basis (Fig. 2.2C). We computed the shift in the perceptual boundary as a difference between the final null condition estimate and the estimate following training. We computed the persistence of the shift as the difference between the final null condition measure and the estimate following aftereffect trials. A repeated-measures ANOVA found that immediately after force-field learning, there was a shift in the sensed position of the limb that was reliably different from zero ($p < 0.01$). The shift decreased ($F(1,28) = 5.063$, $p < 0.05$) following washout but remained different from zero ($p < 0.05$). The magnitude of the shift was the same in both directions ($F(1,28) = 0.947$, $p = 0.3$). Thus force-field learning is associated with changes in the sensed position of the limb that persist even after washout trials.

To examine the persistence of the perceptual change, we tested 15 new subjects in a procedure that was identical to the main experiment with the addition of another perceptual test 24 h after motor learning. As in the previous analyses, we calculated the perceptual shift as the difference between the final baseline estimate and each of the estimates following training (Fig. 2.2C). A repeated-measures ANOVA found that the force-field resulted in a reliable shift in the perceptual boundary that was
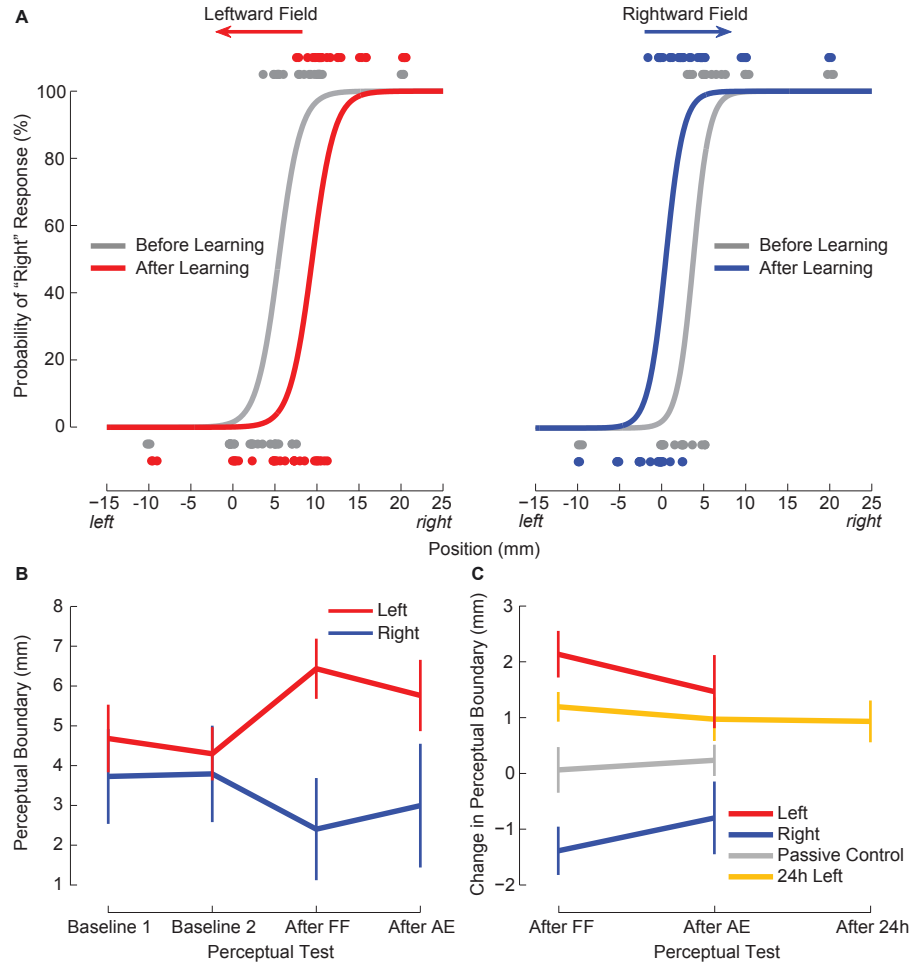
Figure 2.2: Following motor learning, the perceptual boundary shifts in a direction opposite to the applied force. A, Binned response probabilities averaged over subjects ± SE) before (gray) and after (red or blue) learning and fitted psychometric functions reflecting perceptual classification for each force-field direction. B, Mean estimates of the perceptual boundary between left and right ± SE) are shown for baseline estimates (Baseline 1 and Baseline 2) and for estimates obtained following force-field learning (After FF) and following aftereffect trials (After AE). The sensed position of the limb changes following learning, and the change persists following aftereffect trials. C, The perceptual shift depends on the direction of the force-field (left vs right). The change in the perceptual boundary persists for at least 24 h (24 h Left). A perceptual shift is not observed when the robot passively moves the hand through the same sequence of positions and velocities as in the left condition such that subjects do not experience motor learning (Passive Control).

similar for the three time points ($F(2,28) = 0.298$, $p > 0.7$). Moreover, at each of the time points, the mean shift was reliably different from zero ($p < 0.05$ in each case). Thus, brief periods of force-field learning result in shifts in the perceptual boundary that persist for 24 h.

We quantified the magnitude of the perceptual change in relation to the extent of learning. For this analysis, we took measures of perceptual change from the data shown in Figure 2.2C. We obtained estimates of the magnitude of learning by measuring lateral deviation on aftereffect trials following training. We used both maximum PD and the average perpendicular distance for each movement as measures of learning. Averaged over subjects and force-field directions, we found that the perceptual shift was 33% as large as the extent of learning based on average PD for the first three aftereffect trials, and 11% as large as the extent of learning using maximum PD on these same trials.

In a control analysis, we assessed the possibility that the estimated perceptual shift might differ depending on whether testing began from the right or the left. For purposes of this analysis, we computed estimates of the perceptual shift separately for PEST runs that began from the left and the right using the final position of each PEST run in each condition. A repeated-measures ANOVA found that there were no differences in the perceptual shift for PEST runs beginning from the left or the right ($F(1,28) = 0.03$, $p > 0.85$). None of the interactions between force-field direction, the phase of the experiment at which perceptual shifts were measured, and whether PEST runs began from the left or the right were significant ($p > 0.2$ or more in all cases).

Psychometric functions shown in Figure 2.2 A can be characterized by two pa-

rameters. One parameter represents the sensitivity of the subject's response to the lateral position of the limb (slope), and the other parameter gives the position on the lateral axis at which the subject responds left and right with equal probability (left-right boundary). We tested whether learning resulted in differences in the slope of the psychometric function, using the distance between the 25th and 75th percentiles as a measure of perceptual acuity (or sensitivity). We assessed possible differences in sensitivity following force-field learning and following aftereffect trials in both left-ward and rightward force-fields using a repeated-measures ANOVA. We observed no differences in sensitivity in measures obtained following force-field training or after washout trials ($F(1,28) = 0.7$, $p > 0.4$), nor for leftward versus rightward force-fields ($F(1,28) = 0.28$, $p > 0.85$). None of the individual contrasts assessing possible inter-actions was reliable by Bonferroni comparisons ($p > 0.1$ or more in all cases). This suggests that dynamics learning modified the sensed position of the limb in space without modifying perceptual acuity.

We conducted a separate experiment involving 10 subjects to determine the extent to which the observed perceptual change is tied to motor learning. The methods were identical to those in experiment 1 except that the force-field-learning phase was replaced with a task that did not include motor learning. In the null and aftereffect phases of the control experiment, subjects moved actively as in experiment 1. The force-field phase of the experiment was replaced with a passive task in which the robot was programmed to reproduce the active movement of subjects in the leftward force-field condition of experiment 1. We used this condition for the passive control because it resulted in the largest perceptual change following motor learning. We computed on a trial-by-trial basis the mean movement trajectory experienced by

subjects during the training phase in experiment 1. The robot produced this series of movements under position servo control in which the subject's arm was moved along the mean trajectory for each movement in the training sequence. As in the active movement condition, the hand path was also displayed visually during the passive movement. Thus, subjects experienced a series of movements that were the same as those in experiment 1, but they did not experience motor learning. As in experiment 1, perceptual tests were conducted before and after this manipulation.

To ensure that subjects in the passive control experiment were attending to the task, we randomly eliminated visual feedback during either the first or the second half of the movement in 15 of 150 movements in the passive condition. Subjects were instructed to report all such instances after the trial ended and to indicate whether the first or the second half of the movement had been removed. Six of the ten subjects tested in this condition missed none of these events, two subjects missed one, and two subjects missed two. This suggests that in the passive control experiment, subjects attended to the task.

Figure 2.3 (top) shows the mean movement curvature (PD) of the hand for subjects tested in the passive control experiment (yellow) and for subjects in the original experiment (red). Figure 2.3 (bottom) shows the average difference between PD measured in the passive control experiment and PD as measured in the original leftward force-field condition. Note that a value of zero indicates an exact match in the PD measures of the two experiments. The subtraction, given in the bottom of Figure 2.3, shows that movement kinematics were well matched in the null phase, when subjects in both experiments made active movements. In the force-field phase of the experiment, the near-zero values in the bottom indicate that subjects in the passive control

experienced kinematics that closely matched the mean trajectory in the original experiment. The nonzero values at the start of the aftereffect phase indicate that the passive control condition resulted in aftereffects that were smaller than those in the main experiment. A repeated-measures ANOVA based on the first 10 and last 10 trials in the null field and aftereffect phases showed that PD differed depending on whether subjects actively learned the force-field or were tested in the passive control experiment ($F(3,69) = 14.194$, $p < 0.001$). Differences in PD were reliable on initial aftereffect movements; subjects trained in the force-field showed more curvature on initial aftereffect movements than subjects in the passive control ($p < 0.001$). Curvature on initial aftereffects for passive control subjects was no different from curvature on initial or final null-field movements ($p > 0.2$ for both comparisons). Thus, there was no evidence of motor learning in the passive control experiment.

We measured perceptual change in the passive control study in exactly the same manner as in experiment 1. Figure 2.2C shows measures of perceptual change in both the original active learning condition and comparable measures taken from the passive control. A repeated-measures ANOVA compared the perceptual shifts in the two experiments. Perceptual shifts differed depending on whether or not subjects experienced motor learning ($F(1,23) = 5.619$, $p < 0.05$). As described above, subjects in the original experiment who learned the leftward force-field showed perceptual shifts that were reliably different from zero both immediately after learning and after washout trials as well ($p < 0.05$ in both cases). In contrast, subjects tested in the passive control experiment showed shifts that were not different from zero at either time point ($p > 0.7$ in both cases).

The passive control experiment rules out the possibility that the shifts in the per-

ceptual boundaries that we observed are due to the movement kinematics experienced during training. The passive control also argues against the idea that the perceptual shifts depend on the forces experienced during training and not on motor learning. Under passive conditions, it is not possible to equate fully both trajectory and force simultaneously. Thus, forces at the hand during the passive control study differed from those experienced during learning in the main experiment. On average, subjects in the passive condition experienced a maximum lateral force at the hand of 2.44 N, whereas during active force-field learning, the maximum lateral force averaged 5.14 N. However, if the perceptual shift that we have observed was linked to experienced force, then a nonzero perceptual change should have been seen in passive control manipulation, since subjects experienced nonzero forces. As reported above, this was not the case. Instead, the passive control experiment suggests that the perceptual shifts depend on motor learning.

We found that following learning, subsequent movements were modified in a fashion that was consistent with the perceptual change. The modification can be seen in Figure 2.4, which gives movement curvature (replotted from Fig. 2.1) during null-field movements before and after motor learning (note that the force-field learning phase is not shown in this figure). It can be seen that relative to movements before learning, which were straight, movements after learning are more curved. The difference in curvature between null-field movements before learning and the final 10 aftereffect movements was reliable for both force-field directions (p < 0.01 in both cases). This suggests that following learning, movement trajectories do not return to their prelearning values.

We compared the change in movement trajectory to the observed shift in the per-
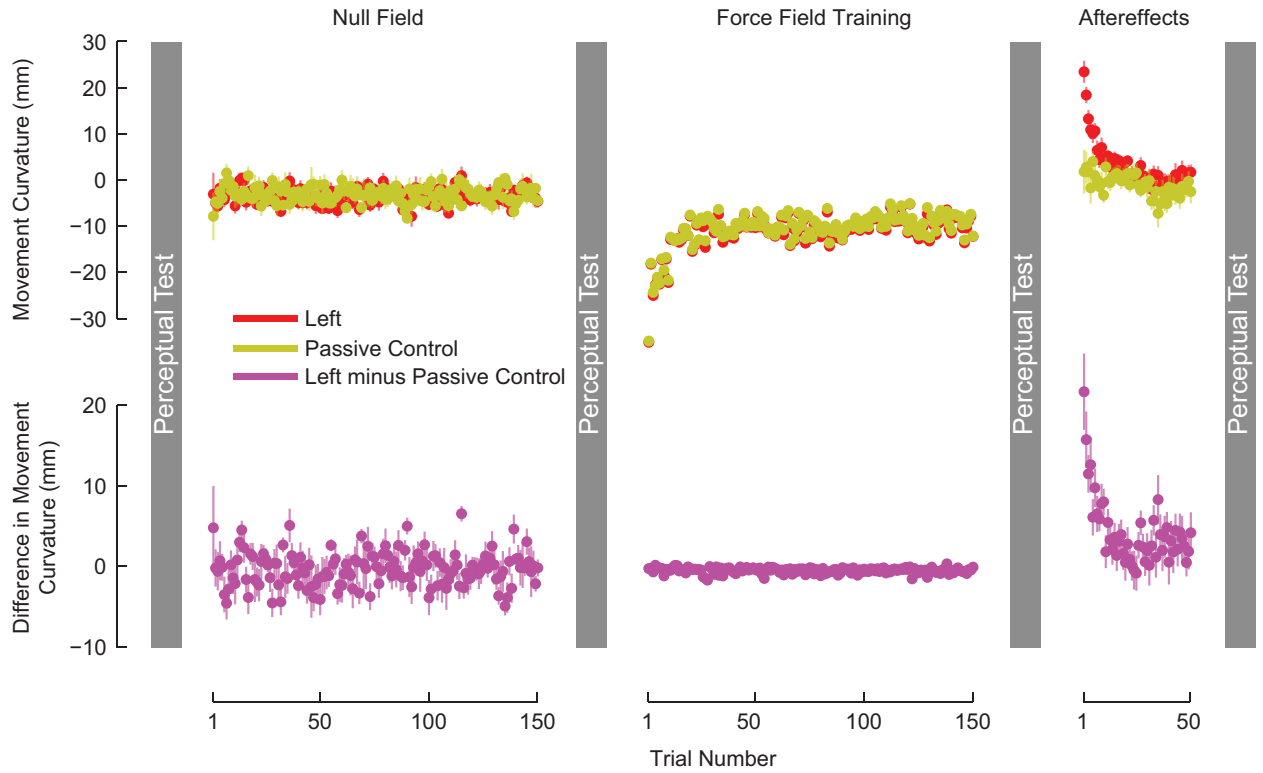
Figure 2.3: In a control experiment, subjects experience the same trajectories as individuals that display motor learning. Subjects make active movements in the null and aftereffect phases of the study. In the force-field training phase, they are moved passively by the robot to replicate the average movement path experienced by subjects in the leftward condition that show motor learning. The top shows mean movement curvature $\pm$ SE) over trials for subjects in the original active learning condition (red) and the passive control condition (yellow). The bottom (magenta) gives the difference between active and passive movements. Movement aftereffects are not observed in the passive condition (yellow), indicating there is no motor learning.

ceptual boundary (shown in red and blue in Fig. 2.4, replotted from Fig. 2.1). We performed a repeated-measures ANOVA and found that depending on the force-field direction, there were differences in the kinematic and perceptual measures ($F(2,56) = 8.35$, $p < 0.01$). For the rightward field, Bonferroni-corrected comparisons found no differences between the kinematic change and the perceptual shift, following learning ($p > 0.35$) and following aftereffect trials ($p > 0.10$). For the leftward field, the kinematic change was no different from the perceptual shift immediately following learning ($p > 0.20$) but was marginally greater than the perceptual shift following aftereffect trials ($p = 0.054$). Nevertheless, despite the marginal statistical effect, it can be seen that the perceptual shift is somewhat smaller in size. Thus, we performed two further analyses to assess whether the movement trajectories shown in Figure 2.4 were similar to the perceptual shifts or whether indeed there was a difference. In these analyses, we computed two different kinematic measures and repeated the statistical comparison between the lateral shift in the movement trajectory and the shift in the perceptual boundary. One measure was the perpendicular deviation at maximum velocity. The second was the average perpendicular deviation throughout the movement trajectory. We performed separate repeated-measures ANOVAs using these new variables and found that lateral changes in the perceptual boundary, following learning and also following aftereffect trials, did not differ from the lateral shift in movement kinematics measured over the final 10 aftereffect trials ($F(2,56) = 0.25$, $p > 0.75$ for perpendicular deviation at maximum velocity, $F(2,56) = 0.72$, $p > 0.9$ for average perpendicular deviation). Thus, based on these analyses, postlearning movements follow trajectories that are no different from shifted perceptual boundaries.

Above we show persistent shifts in the perceptual boundary between left and right.

The shifts were present following 50 washout trials and also 24 h later. One possible explanation for the persistence of the shifts is that there were too few washout trials for performance to return to asymptotic levels. To verify that performance on aftereffect trials had reached asymptotic values, we divided the 50 trials into 10 bins of 5 trials each (trials 15, 6 10, and so forth) and examined changes in movement curvature over successive bins. We repeated the analysis dividing the aftereffect trials into bins of 10 movements each and found similar results to those reported below. We conducted a repeated-measures ANOVA to compare how movement curvature changed over the course of the aftereffect trials. For subjects trained in the leftward field, we found no changes in movement curvature beyond the 16th aftereffect trial ($p > 0.7$ for 20 of 21 possible comparisons, $p > 0.05$ for the remaining comparison). The same was true for the rightward field ($p > 0.9$ for all 21 comparisons). This suggests that performance returned to asymptotic levels well before the end of the washout phase.

Our procedure for testing the effects of motor learning on the sensed limb position involved a series of movements in force channels (Scheidt et al., 2000) that deflected the limb laterally and allowed us to estimate the perceived left right boundary. The force channels were sufficiently stiff that they prevented lateral deflections of the hand and thus could be used to measure lateral forces applied by the subject following learning. This, however, raises the possibility that the changes in the sensed position of the hand following learning may have resulted from the production of isometric lateral force, as has been shown previously (Gandevia et al., 2006). The analyses described below rule out this possibility. Figure 2.5 shows the lateral force applied to the channel wall during perceptual testing. For purposes of this analysis, we used forces during the first 100 ms of movement, just before the force channel deviated the
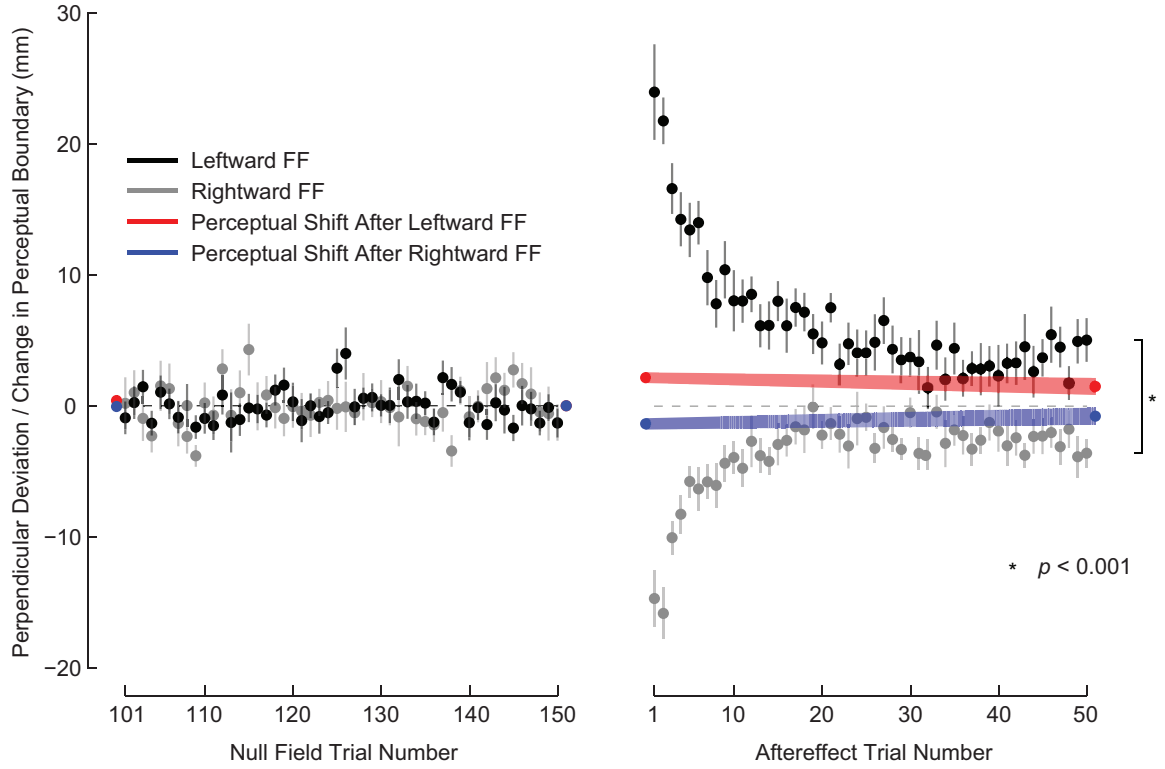
Figure 2.4: Mean movement curvature $\pm$ SE) is shown in gray (replotted from Fig. 2.1). The left side shows the final 50 null field movements before force-field training. The data have been shifted such that the mean movement curvature in the null field is zero. The right side shows curvature on the 50 aftereffect trials, plotted relative to curvature on the null field trials. Curvature during the final after-effect movements differs from baseline curvature. Changes in curvature following learning are not statistically different in magnitude and in the same direction as the shift in the perceptual boundary. The red and blue data points show the shift following force-field learning and aftereffect trials, replotted from Figure 2.3 $\pm$ SE shown in the red and blue bands).

hand to the left or right. For each subject, we measured lateral forces on the first channel movement in each of the four perceptual tests.

Figure 2.5A gives the mean force profile before motor learning (red), following learning (green), following aftereffect trials (blue), and in the perceptual tests conducted 24 h later (cyan). Figure 2.5B shows mean values for the force profiles shown at the left.

We performed a repeated-measures ANOVA to evaluate the extent to which lateral force production changed over the course of the experiment. We performed a single ANOVA to assess differences in lateral force production in perceptual trials that followed baseline, force-field training, aftereffects, and 24 h perceptual tests. ANOVA revealed that lateral force production differed for the four perceptual tests ($F(6,126)$ = 8.168, $p < 0.001$). Immediately following force-field training, subjects produced lateral forces during perceptual testing that were different from zero ($p < 0.05$ for the leftward, $p < 0.01$ for the rightward and 24 h subjects). For all other perceptual tests, lateral force production was not reliably different from zero ($p < 0.05$ for all comparisons). Thus, lateral force is observed immediately following learning but at no other time. Accordingly the observed changes in the sensed position of the hand are not due to lateral force production during perceptual testing.

To assess the generality of the perceptual changes that we observed, we conducted a second experiment in which movements were made in a different direction and perceptual estimates were obtained with the limb stationary, using a different procedure to assess sensed limb position. In experiment 2, subjects made movements in a lateral direction between two targets centered about the body midline. A velocity-dependent force-field displaced the limb, for one group of subjects toward the body, and for a

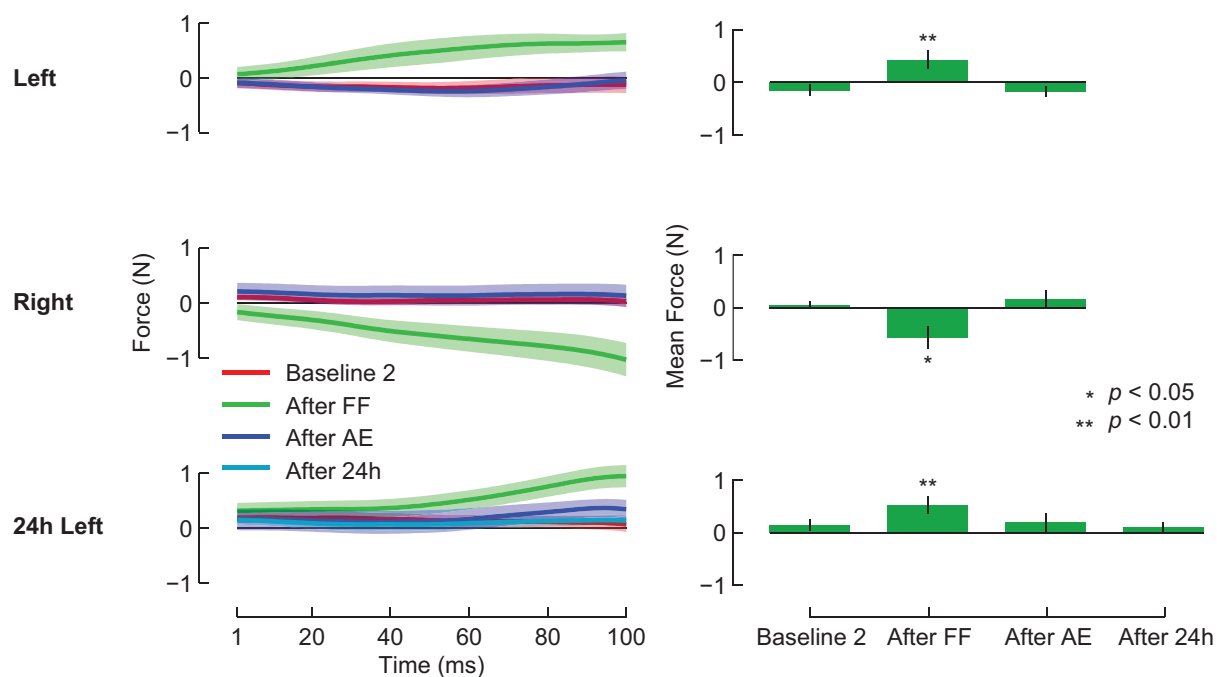Figure 2.5: In other phases of the experiment, lateral force during perceptual tests is not different from zero. Thus, perceptual measurements are not contaminated by active force production in a lateral direction. A, Mean lateral force applied to the force channel walls ± SE) in the first 100 ms of the first perceptual test movement. B, Summary plot showing mean lateral force production ± SE) on the four perceptual tests..

second group, away from the body. Sensed limb position was estimated before and after force-field training using an interlimb matching technique. Perceptual tests involved the method of constant stimuli in which the left hand was held in position midway between the two targets while the robot positioned the right hand that had been used for motor learning at a series of locations on a forward backward axis. At each position, the subject was asked to judge whether the right hand was located farther or closer to the body than the left hand.

We assessed motor learning by measuring movement curvature (Fig. 2.6 A). A repeated-measures ANOVA found that for both the inward and outward force-field, mean PD decreased reliably over the course of training ($p < 0.001$ in each case) indicating that subjects adapted to the load. The average perceptual performance associated with these training directions is shown in Figure 2.6 B. For visualization purposes, logistic functions were fit to the set of mean response probabilities (averaged over subjects) at each of the seven test locations. As in experiment 1, it can be seen that the perceptual boundary shifted in a direction opposite to the force-field. Thus, when the right hand was positioned coincident with the left, following training with an outward force-field, subjects were more likely to respond that their right hand was farther from the body than their left. A perceptual shift in the opposite direction was observed when the force-field acted toward the body.

Figure 2.6C shows the mean change in sensed limb position for each force-field direction. For statistical analysis, the sensed position of the limb was computed before and after learning for each subject separately. Figure 2.6C shows the mean change in sensed limb position for each force-field direction. The outward force-field moved the perceptual boundary closer to the body. The inward force-field shifted the boundary

outward. A one-way ANOVA found that outward and inward perceptual shifts were significantly different from one other ($F(1,35) = 16.092$, $p < 0.001$) and that each shift was reliably different from zero ($p < 0.01$ in each case).

As in experiment 1, the measured perceptual changes did not involve changes in perceptual acuity. Perceptual acuity was quantified on a per-subject basis using the distance between the 25th and 75th percentiles of the fitted psychometric function. A repeated-measures ANOVA assessed possible changes in acuity before and after force-field learning in both inward and outward force-fields. No changes were observed from before to after learning ($F(1,34) = 0.77$, $p > 0.35$), nor for inward versus outward force-fields ($F(1,34) = 1.52$, $p > 0.2$). Thus dynamics learning primarily affects the sensed position of the limb without affecting perceptual acuity.

2.4   Discussion

In summary, we have shown that motor learning results in a systematic change in the sensed position of the limb. The perceptual change is robust; we observe similar patterns of perceptual change for different movement directions, using different perceptual estimation techniques and also when perceptual estimates are obtained during movement and when the limb is stationary. The persistence of the perceptual change for 24 h and its presence under stationary conditions not experienced during training point to the generality of the perceptual recalibration.

The magnitude of the perceptual shift was between 11 and 33% of the estimated magnitude of learning. However, these calculations may well underestimate the magnitude of the perceptual effect. First, our measure of motor learning was based on
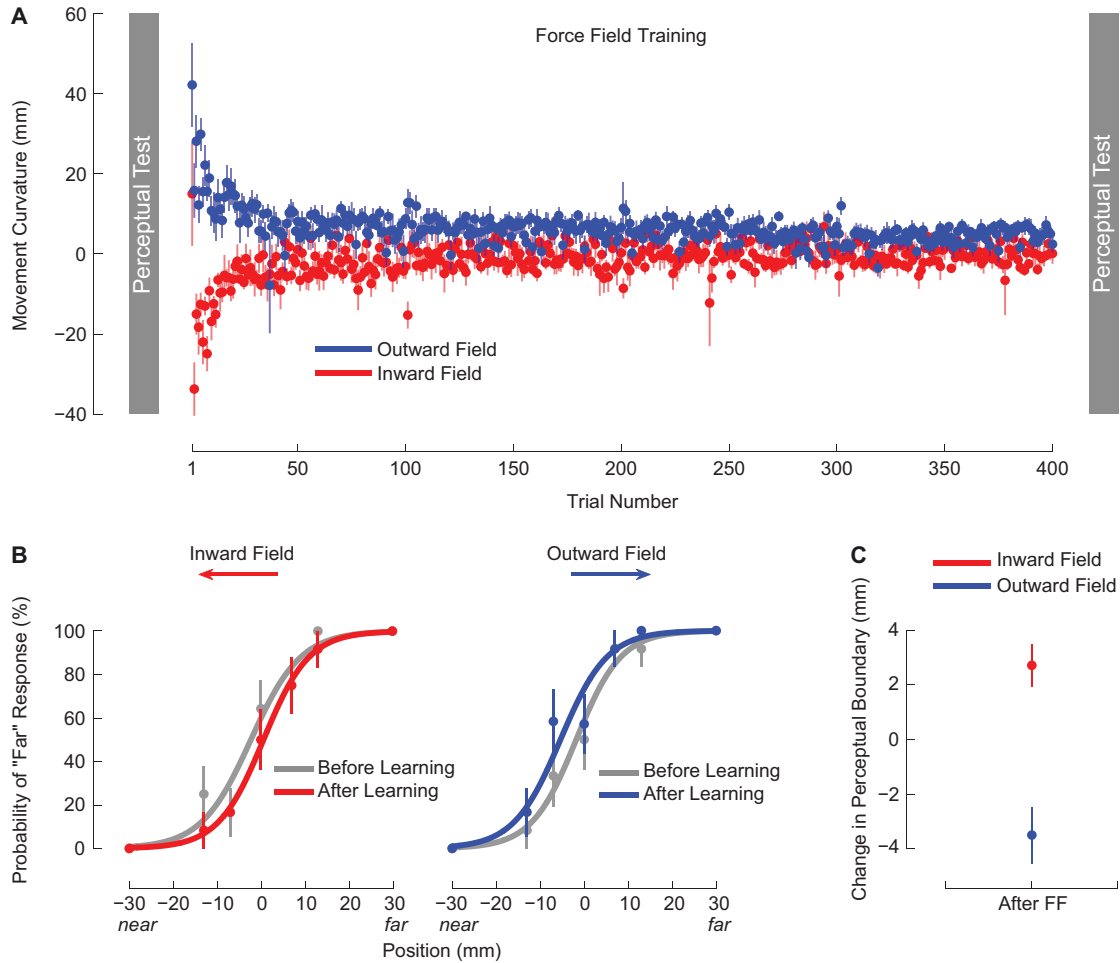
Figure 2.6: A, Mean perpendicular deviation over the course of training is shown for inward and outward loads. B, Binned response probabilities averaged across subjects $\pm$ SE) at each of the test locations and fitted psychometric functions show perceptual classification before (gray) and after (red or blue) learning force-fields that act toward and away from the body. As in experiment 1, following motor learning the perceptual boundary shifts in a direction opposite to the applied force. C, Mean perceptual change $\pm$ SE) following force-field learning (After FF) with loads that act toward or away from the body.

deviation measures that were obtained from the initial aftereffect trials. While these are standard measures of learning in experiments such as these, they are also measures that are particularly transient and dissipate rapidly over trials. A better measure for this purpose would be an estimate of motor learning that reflects more durable effects, such as one obtained at longer delays following training. We anticipate that perceptual change would constitute a larger proportion of a less transient measure of motor learning. A second consideration is that the perceptual change that we have observed is a measure that was taken after relatively little training. The measured perceptual change may constitute a more substantial portion of the estimated learning if more extensive training had taken place.

It is known that sensory experience in the absence of movement results in a selective expansion of the specific regions of somatosensory cortex that are associated with the sensory exposure and also leads to changes in sensory receptive field size that reflect the characteristics of the adaptation (Recanzone et al., 1992b,a). Structural change to somatosensory cortex is observed when sensory training is combined with motor learning in a task that requires precise contact with a rotating disk (Jenkins et al., 1990) and when animals are required to make finger and forearm movements to remove food from a narrow well (Xerri et al., 1999). In these latter cases it is uncertain whether it is the sensory experience, the motor experience, or both factors in combination that leads to remapping of the sensory system. The findings of the present paper help in the resolution of this issue. The sensory change observed here is dependent on active movement. When control subjects experience the same movements but without motor learning, perceptual function does not change. The present findings thus point to a central role of motor learning in plasticity in the sensorimotor

system.

We observed that movement kinematics change following motor learning. In particular, movement curvature in the absence of load is greater than that present before learning. Moreover, movements following learning deviate from their prelearning trajectories by an amount that is not statistically different in magnitude and in the same direction as the sensory recalibration. This suggests that, following learning, movements follow altered perceptual boundaries. The sensory change that we observe in conjunction with motor learning thus appears to have functional consequences in sensorimotor behaviors.

The findings of the present paper bear on the nature of adaptation in sensory and motor systems. Most approaches to neuroplasticity treat sensory and motor adaptation in isolation (Gomi and Kawato, 1993; Ghahramani et al., 1997; Wolpert and Kawato, 1998; Gribble and Ostry, 2000). An alternative possibility supported by the data in the present study is that plasticity in somato-sensory function involves not only sensory systems but motor systems as well (Haith et al., 2008; Feldman, 2009). Evidence in support of the idea that somatosensory perception depends on both sensory and motor systems would be strengthened by a demonstration that changes in perceptual function parallel changes in learning over the course of the adaptation process. Comparable patterns of generalization of motor learning and generalization of the associated sensory shift would also support this possibility. Other studies might use cortical stimulation to enhance (Reis et al., 2009) or suppress (Cothros et al., 2006) retention of motor learning, to show a corresponding enhancement or suppression of the change in somatosensory perception.

Other researchers have proposed that sensory perception depends on both sensory

and motor systems (Haith et al., 2008; Feldman, 2009). Learning can lead to changes in sensory perception via changes to motor commands, sensory change, or the two in combination. One possibility is that motor learning involves adjustments to motor commands that recalibrate the central contribution to position sense (see Feldman 2009 for a recent review of central and afferent contributions to position sense). In effect, signals from receptors are measured in a reference frame that has been modified by learning. A somewhat different possibility is that the learning involves a recalibration of both sensory and motor processes. Haith et al. (2008) propose that changes in performance that are observed in the context of learning depend on error-driven changes to both motor and sensory function.

The passive control experiment suggests that it is unlikely that sensory experience alone could contribute to the observed perceptual changes. However, prolonged exposure to lateral shifts in the position of the limb due to force-field learning might in principle lead subjects to modify their estimates of limb position and to interpret somatosensory feedback during subsequent perceptual testing in terms of this updated estimate (Körding and Wolpert, 2004). While the distribution of sensory inputs experienced during movement could play a role in subsequent perceptual measures, in the present study perceptual change is not observed in the context of passive movement. This suggests that active involvement of the participant in the context of movement production is required for the observed sensory shift.

The cortical areas that mediate somatosensory changes that accompany motor learning are not known. Changes to primary and second somatosensory cortex would seem most likely. However the involvement of primary motor cortex in somatic perception (Naito, 2004), and the involvement of premotor and supplementary motor

areas in somatosensory memory and decision-making processes (Romo and Salinas, 2003), suggests that sensory remodeling in the context of motor learning may also occur in motor or perhaps even prefrontal areas of the brain.

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Chapter 3

Spatially selective enhancement of proprioceptive acuity following motor learning

3.1   Introduction

The central nervous system receives information from a wide range of sense organs that are characterized by differential sensitivity across their respective domains. In this study we investigated changes to the sense of proprioception after spatially localized motor learning and found that estimates of limb position are flexibly improved in the region of motor learning. Relatively little is known about how proprioception changes with motor learning (Ostry et al., 2010), and indeed, few studies have been reported that assess how proprioception may vary across the workspace of the limb (Fuentes and Bastian, 2010; van Beers et al., 1998; Wilson et al., 2010). In contrast, we know a great deal about other sensory systems that are characterized by differential anatomic sensor density, resulting in greater visual (Wald, 1945), acoustic (Davis and Kranz, 1964), and haptic sensitivity (Bolanowski et al., 1988; Verrillo, 1963; Weinstein, 1968) across a subset of the input domain. Sensory sensitivity is modulated dynamically via descending signals from the brain. Efferent innervation of sense organs occurs in many human sensory systems, including those associated with proprioception. Efferent innervation of semicircular canals (Purcell and Perachio, 1997; Warr, 1975) and retinal cells (Honrubia and Elliott, 1970) modulate the signals about head orientation and the visual field. Muscle spindles, widely regarded to be the primary source of information about the position of the limbs, also receive modulating efferent signals. It has been proposed that such signals may account for the sensory consequences of self-generated action (Bays et al., 2005; Blakemore et al., 1998; Wolpert and Flanagan, 2001) and augment the functional dynamic range of the sensor (Scott and Loeb, 1994; Windhorst, 2007). Recent studies of human muscle spindle afferents have shown that attention can modify afferent signals. Directing

a subject's attention to the passive rotation occurring at a joint can cause changes to mean spike rate and range (Hospod et al., 2007). This suggests that proprioception may be modulated to provide greater acuity for changes in limb position that are behaviorally relevant. Such changes may accompany motor learning, to enhance proprioception for newly learned motor behaviors. The literature cited above shows that anatomic substrates of perception support differential sensitivity, efferent neural signals provide top-down modulation of sensitivity, and behavioral context may play a role in this descending modulation. In this study we further explored the nature of behaviorally relevant modulations of perceptual sensitivity and specifically test the extent to which motor learning is accompanied by changes in proprioceptive acuity. We did this by assessing changes to the psychophysics of proprioception following motor learning. We observed spatially selective improvements in proprioceptive acuity, which occurred only in limb positions experienced during motor learning. Additional experiments showed that this effect specifically depends on active, rather than passive, movement and does not occur for subjects who perform motor training without learning. Our results support the idea that proprioceptive acuity is tuned in a spatially selective manner during motor learning.

3.2   Materials and Methods

3.2.1   Subjects

One hundred eighty-six subjects between 17 and 40 yr of age (97 females; mean age = 20.9 yr) were randomly assigned to one of seven groups. All subjects reported no history of visual, neurological, or musculoskeletal disorder. Twenty-five subjects were

assigned per group, except for the two groups involving passive kinematics, which were composed of 18 subjects. Written informed consent was obtained from each subject before participation. The University of Western Ontario Research Ethics Board approved all procedures.

3.2.2 Apparatus

Subjects performed reaching movements and tests of proprioceptive acuity while grasping the handle of a robotic manipulandum (InMotion Technologies) in the right hand. A six-axis force transducer (ATI Industrial Automation, Apec, NC; resolution: 0.05 N), located inside the handle, measured forces at the hand. All subjects were seated at a desk and interacted with the experimental robot in the horizontal plane at shoulder height (see Fig. 3.1). A custom air sled, placed beneath the subject's right elbow, supported the arm against gravity and minimized friction between the arm and the desk. During motor learning, visual information was displayed via a mirror and LCD monitor display system (Kistemaker et al., 2010). The horizontal mirror was placed just below chin height and occluded the subject's view of his or her arm. Visual feedback of hand position was provided on the mirror in real time using the LCD display. Proprioception tests took place in the dark, and subjects were asked to close their eyes.

3.2.3 Experimental Protocol

At the start of each experiment we measured baseline proprioceptive acuity. This perceptual test was followed by motor learning (explained below), during which reaching movements were made to visual targets (except for control groups, as noted). Finally,
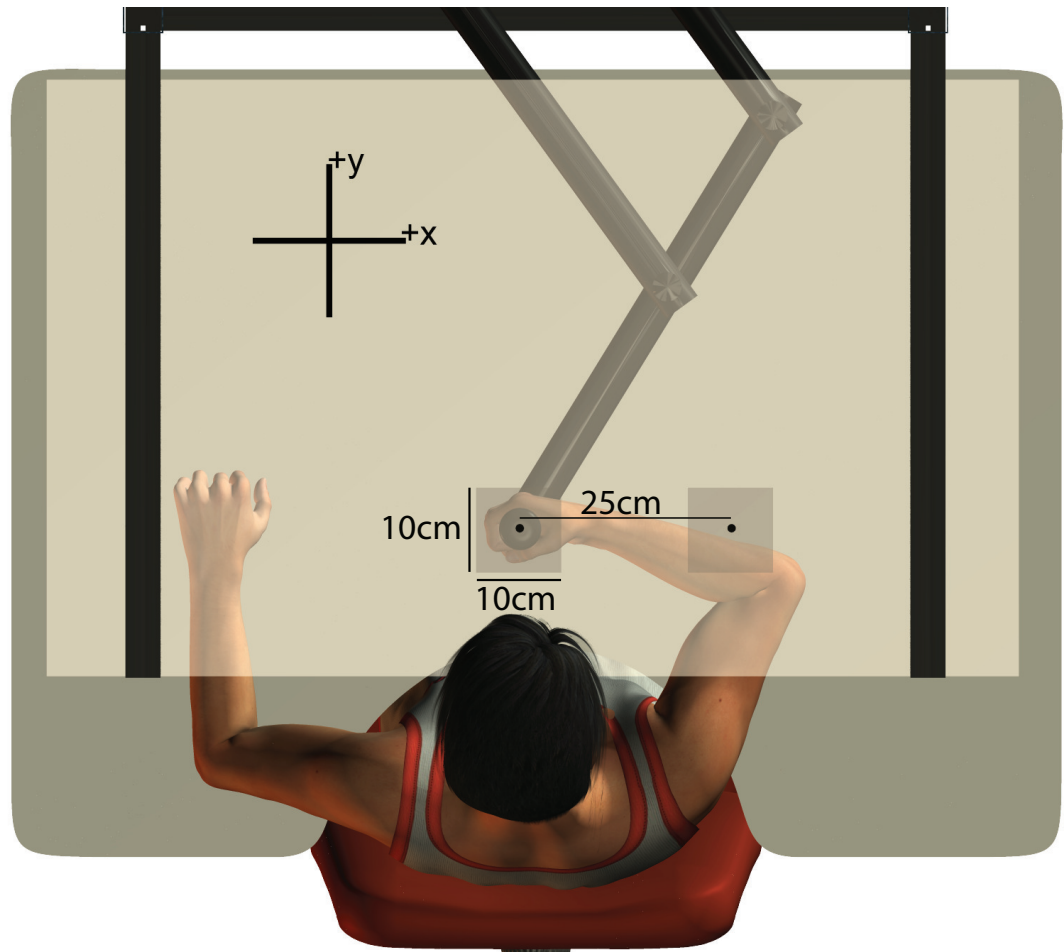
Figure 3.1: Subjects grasped a robotic linkage and per- formed perceptual tests and reaching movements while seated at a desk. Perceptual tests were performed in darkness, with the eyes closed. A semisilvered mirror and black curtains blocked vision of the arm and handle. The 2 shaded boxes indicate the 2 workspace regions in which subjects performed reaching movements during the motor task.

subjects performed a proprioception test immediately following learning. For control subjects, the learning phase was replaced with a control task (reading quietly) of the same duration.

3.2.4 Movement task

Subjects moved their hand to 5-mm (diameter; circular) targets presented pseudo-randomly, within a 10×10 cm workspace centered either on the location of proprioceptive testing or in a location 25 cm to the right (Fig. 3.1). A cursor (small filled circle, diameter 4 mm) was displayed in real time to represent the position of the hand. Motor learning consisted of 4 blocks of 100 movements (400 movements total). Subject instructions were told to "move your hand to the target as quickly and accurately as possible." Once the hand was within 2 mm of the target's center, the current target was extinguished and the next target appeared. A number of kinematic measures were computed to characterize learning (see RESULTS). Movement time was recorded for each trial, beginning when the target appeared and ending when the hand arrived within 2 mm of the target's center. Subjects were provided with their total movement time after each block and were encouraged to improve this time over the course of learning.

3.2.5 Proprioceptive Measurement

The proprioception measurement procedure was performed in the absence of vision with subjects' eyes closed and an opaque mirror resting at shoulder height to block vision of the hand and robot. The subject's unseen right hand was moved by the robot along a left-right axis, 18 cm in front of the body. Subjects made two-alternative

forced-choice judgments about whether they perceived their right hand to be left or right of a previous reference location. The reference location was in the center of the 10 × 10 cm movement area. Each perceptual judgment was composed of three phases: a 2-s hold phase during which the hand was held stationary at the reference position, a randomized passive movement that brought the hand indirectly to the test location, and the subject's response ("left" or "right"). During the passive movement phase, the subject's hand was moved along a line, first from the reference location to a peripheral location positioned at least 6 cm away from the reference, and then back to the test location (near the reference). To reduce the possibility that subjects might use cues related to passive movement speed or direction to aid their judgments of arm position, the passive movement between each reference and judgment position was randomized in terms of duration (between 1,000 and 1,600 ms, square distribution), total distance travelled (14 ± 2 cm, SD normal distribution), and direction (left/right). The passive movements were designed to be smooth, using a bell-shaped velocity profile. After the subject's response, the limb was again moved passively with random distance, speed, and direction to a peripheral location, before the hand was returned to the reference location to start the next trial. This passive movement prevented the subject from receiving any trial-to-trial feedback about the accuracy of their responses and hence minimized the possibility of adaptation over the course of perceptual testing. We used the method of constant stimuli to present subjects with proprioceptive judgment locations. Subjects were tested at 7 different distances (0 ± 0.7, 1.3, and 3.0 cm) from the reference location for a total of 74 judgments, requiring ∼ 8 min to complete. The test locations more distant from the reference location were tested fewer times because subjects performed at 100% accuracy on

these positions. Each judgment location was approached via leftward and rightward distractor movements an equal number of times.

A logistic function was fit to the set of binary response data across test locations. Proprioceptive acuity was quantified as the distance spanning the 25th and 75th percentiles of the logistic function (Fig. 3.2). This measure, sometimes called uncertainty range (Henriques and Soechting, 2003), is inversely related to sensitivity, and thus smaller values represent greater perceptual acuity. Statistical analysis of changes in proprioception and of kinematic measures were assessed using analysis of variance and Bonferroni or Tukey post hoc tests.

3.3 Results

We measured proprioceptive acuity at baseline and again following 10 min of motor learning. We examined a number of kinematic measures to characterize how subjects improved performances over the course of learning. Figure 3.3 (red line) shows total movement time recorded in each of four movement blocks. Clear decreases in total movement time were observed as subjects (n = 25) learned to reach the targets more quickly over the course of practice in blocks 1 through 4. An analysis of variance was performed with one within-subjects measure (block: levels 1:4). A significant effect of movement block was found on total movement time ($F(3,54) = 21.975$, $p < 0.0001$). Post hoc tests showed that movement time in block 4 was significantly less than in block 1 ($p < 0.001$);, thus subjects significantly improved performance on the reaching task over four blocks. Similarly, we also examined measures of movement speed and found reliable increases in tangential velocity across movement blocks (block 1: 19

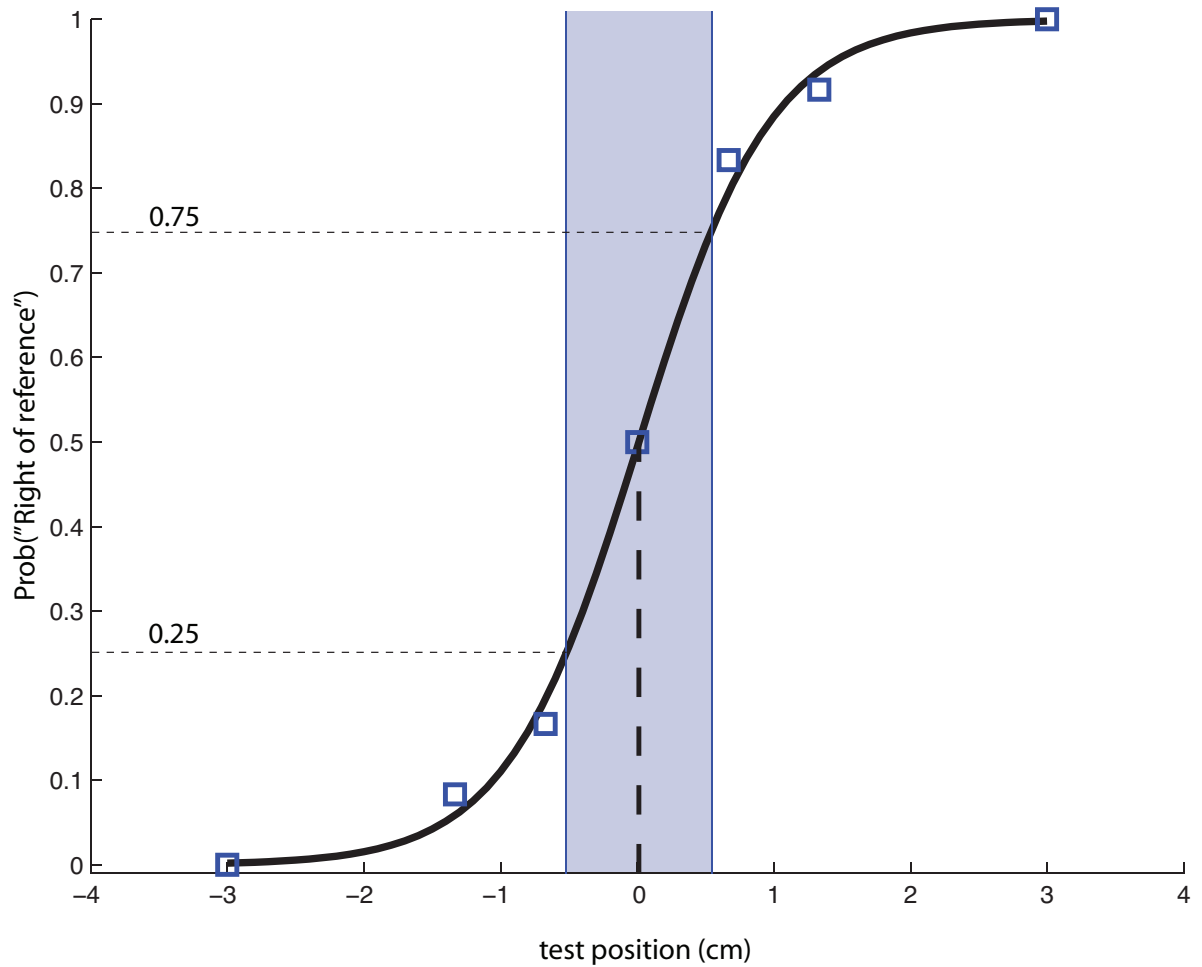Figure 3.2: Open squares denote the probability with which a subject reported a given hand position to be right of the reference location, as a function of the actual hand location. Subjects' responses were fit to a binomial model using a cumulative normal distribution function. The shaded region represents the uncertainty range of the fit, and the vertical dashed line denotes the perceptual bias.

± 3.4 cm/s; block 4: 21.5 ± 4.1 cm/s; paired 2-tailed t-test, p < 0.01). A similar pattern was seen for a second group of subjects who were trained in a separate region of the workspace, 25 cm to the right (see *Spatial Sensitivity*).

3.3.1 Movement Accuracy

We also measured changes in the positional accuracy of reaching movements across motor learning. If subjects were learning to be more precise when reaching to targets, the perpendicular distance between the position of the hand and a straight line connecting the two targets might decrease across the motor learning period (Brashers-Krug et al., 1996; Caithness et al., 2004; Cothros et al., 2006a,b, 2008). Figure 3.4 displays measurement of absolute perpendicular deviation (PD) for each movement. Although this movement task does not include a perturbing force-field, the goal of reaching targets "as quickly and accurately as possible" still provides strong incentive to reduce PD, particularly as the hand nears the target, because deviations from a straight line would necessitate corrective movements to prevent missing, or even overshooting, the target, both of which represent considerable costs to task performance. Figure 3.5 shows absolute PD from a straight trajectory at 10% increments of the normalized movement distance between the previous target and the current target. Differences between initial (block 1) and final (block 4) motor performance are apparent. Deviations of the hand from the straight trajectory are reduced specifically where the hand approaches the target. To determine whether these differences are statistically reliable, we performed a split-plot repeated-measures analysis of variance (2 within-subjects factors: block, levels 1 and 4, and % movement length, levels 10:90; 1 between-subjects factor: group; see *Spatial Specificity*). Post hoc tests (Bonferroni
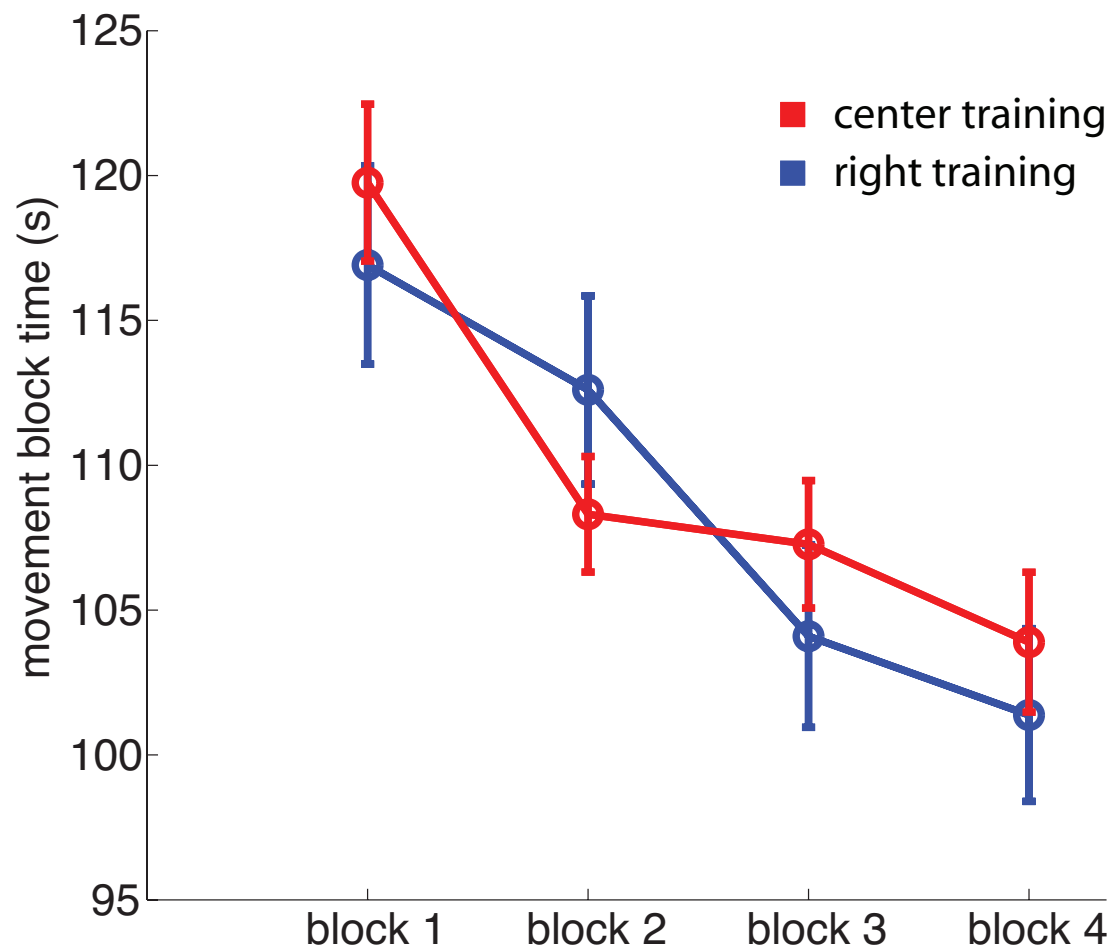
Figure 3.3: Mean ± SE) movement time to reach to 100 randomly placed targets within a 10×10 cm region in each of 45blocks is shown. The red line denotes subjects performing reaches in a central region aligned with the perceptual test location, 18 cm from the sternum; the blue line denotes subjects performing reaches in a region located 25 cm to the right of the center location.

corrected) revealed statistically reliable differences between blocks 1 and 4 at several points along the movement trajectory, including at 90% of movement length (see Fig. 3.5 for all pairwise comparisons). Thus subjects learned to move to the targets both more quickly and with greater accuracy.

3.3.2 Proprioceptive Acuity

To determine whether motor learning results in changes to proprioceptive acuity, we estimated uncertainty range at baseline and again following motor learning. To control for the possibility that observed changes in proprioceptive acuity might be due to the passage of time and not motor learning per se, we tested a second group of subjects (n = 25) who did not perform the motor learning task but read quietly for a matched duration of time. The uncertainty range (mean $\pm$ SE) for the control subjects who did not undergo learning was 10.27 ± 0.51 mm at baseline and 10.9 ± 0.56 mm on postlearning retesting (Fig. 3.6). In contrast, subjects who performed the motor learning task demonstrated uncertainty ranges at baseline of 10.53 ± 0.58 mm that decreased to 9.43 ± 0.56 mm following learning, representing an 11% improvement in acuity. To test for differences in proprioceptive acuity as a function of learning, we performed a split-plot repeated-measures analysis of variance on uncertainty range, with one between- subjects factor (learning: control vs. learning) and one within- subjects factor (time: baseline vs. postlearning). A significant interaction was found (p = 0.018). Post hoc Tukey tests revealed that the control group that did not experience motor learning and the group that did showed the same acuity at baseline (p = 0.95); however, subjects who underwent learning had significantly smaller uncertainty ranges post-learning (p < 0.05) relative to control subjects. These results
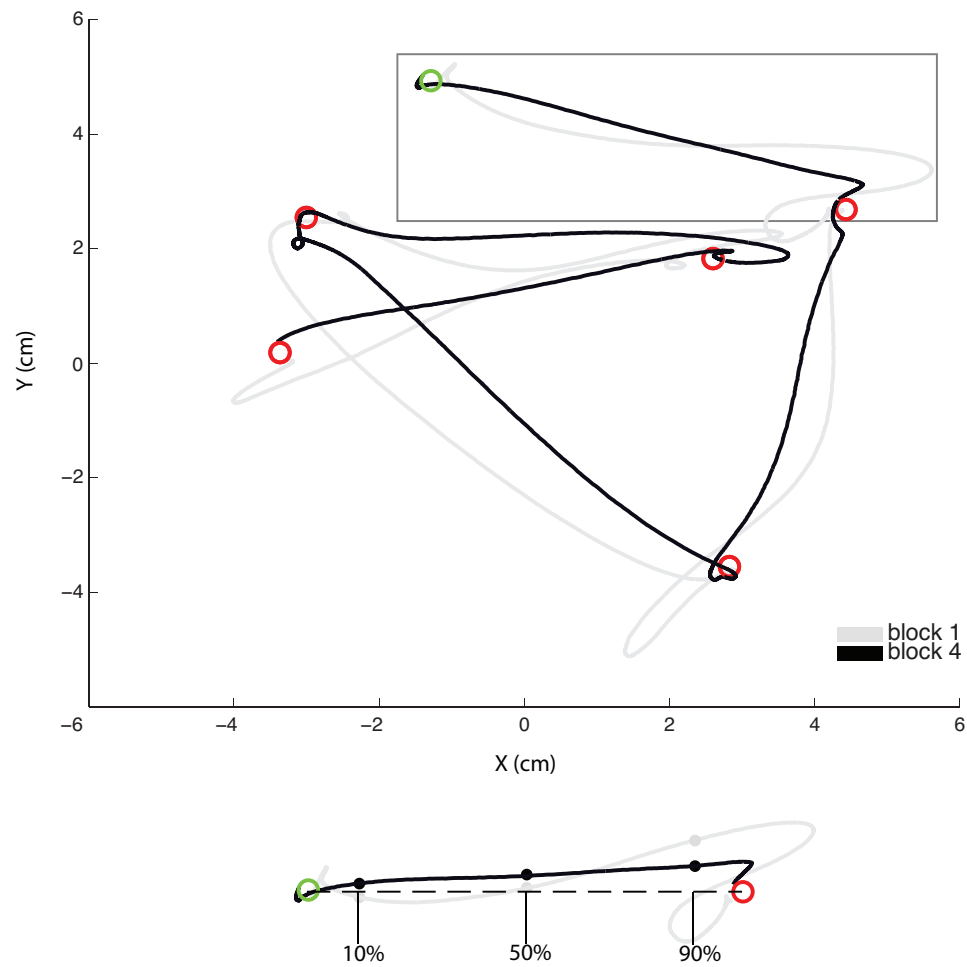
Figure 3.4: Overhead view shows 5 movements from an example subject, during blocks 1 and 4, depicting measurement of movement accuracy. Absolute perpendicular deviation (PD) from the straight trajectory was calculated for each movement, at 10% intervals of normalized movement length.
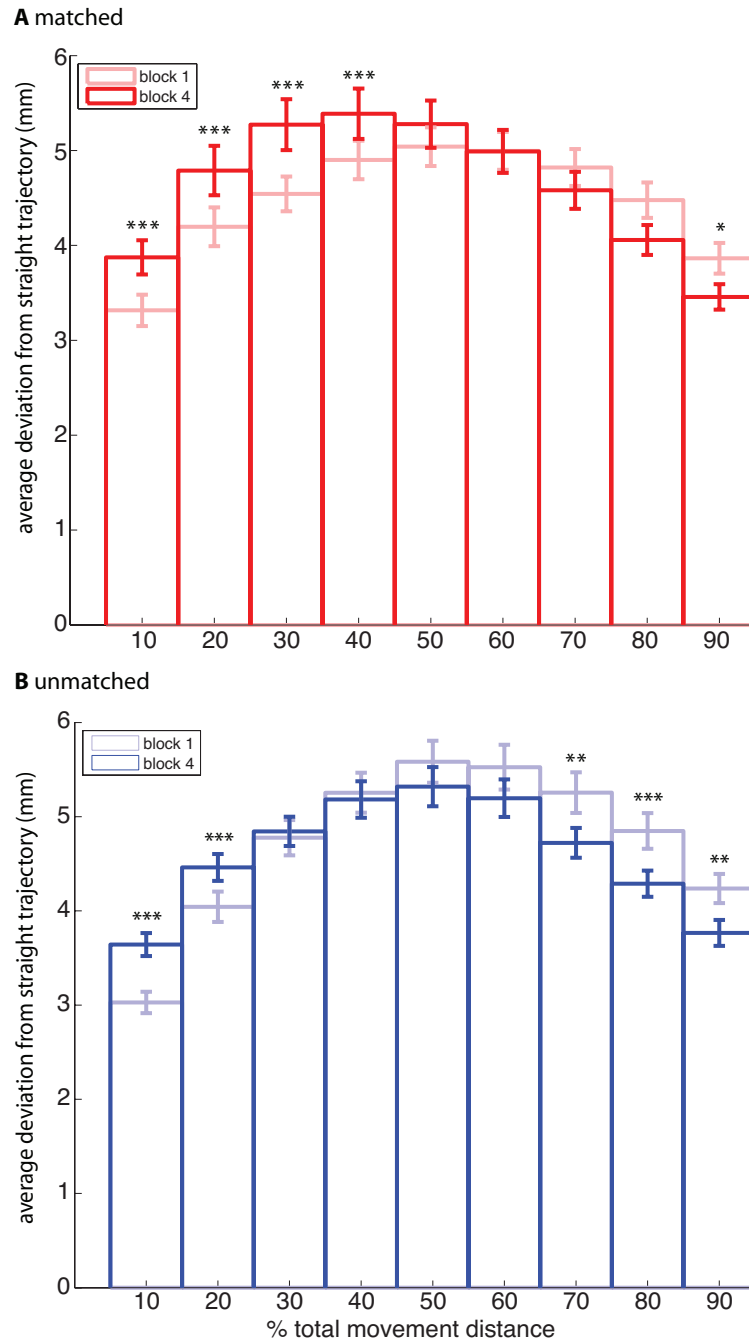
Figure 3.5: Mean ± SE) PD at 10% intervals along the straight line linking start and end targets is shown, averaged across subjects for movement blocks 1 and 4. A: matched group data (red). B: unmatched group data (blue). Bonferroni-corrected pairwise comparisons between blocks are noted for significance: *P< 0.05; **P< 0.01; ***P< 0.001.

suggest that motor learning results in an improvement in proprioceptive acuity.

3.3.3 Spatial Specificity

We next investigated the spatial specificity of this effect. Is the sense of limb position tuned locally, only in the region of motor learning, or is position sense improved more globally? To examine the degree of spatial generalization, we tested an additional group of subjects (n = 25) who performed motor learning in a different workspace location, positioned to the right of the position at which proprioceptive tests were performed. The same motor learning task as described above was performed in a 10 × 10 cm area, centered 25 cm to the right of the subject's midline. Proprioceptive tests were performed at the central workspace location as described above. Two additional groups of subjects were tested in the opposite configuration: one group (n = 25) had spatially matched motor learning (right location), whereas another (n = 25) had unmatched motor learning (center) and proprioceptive testing (right). We were also interested to see whether even more spatially focused motor learning results in a greater perceptual effect, and thus for these groups we restricted movements such that visual targets appeared only along a 10 cm left/right (transverse) line, rather than within a $100cm^2$ patch. Like the group of subjects trained and tested in the central workspace location (Fig. 3.3, red line, and Fig. 3.5A), the group of subjects undergoing unmatched training improved both movement speed (Fig. 3.3, blue line) and accuracy (Fig. 3.5B) over the course of learning. Figure 3.7 shows the change in proprioceptive acuity following learning for the two matched and two unmatched groups. Subjects receiving matched motor learning (red) showed decreased uncertainty range. In contrast, unmatched learning had apparently little effect on the
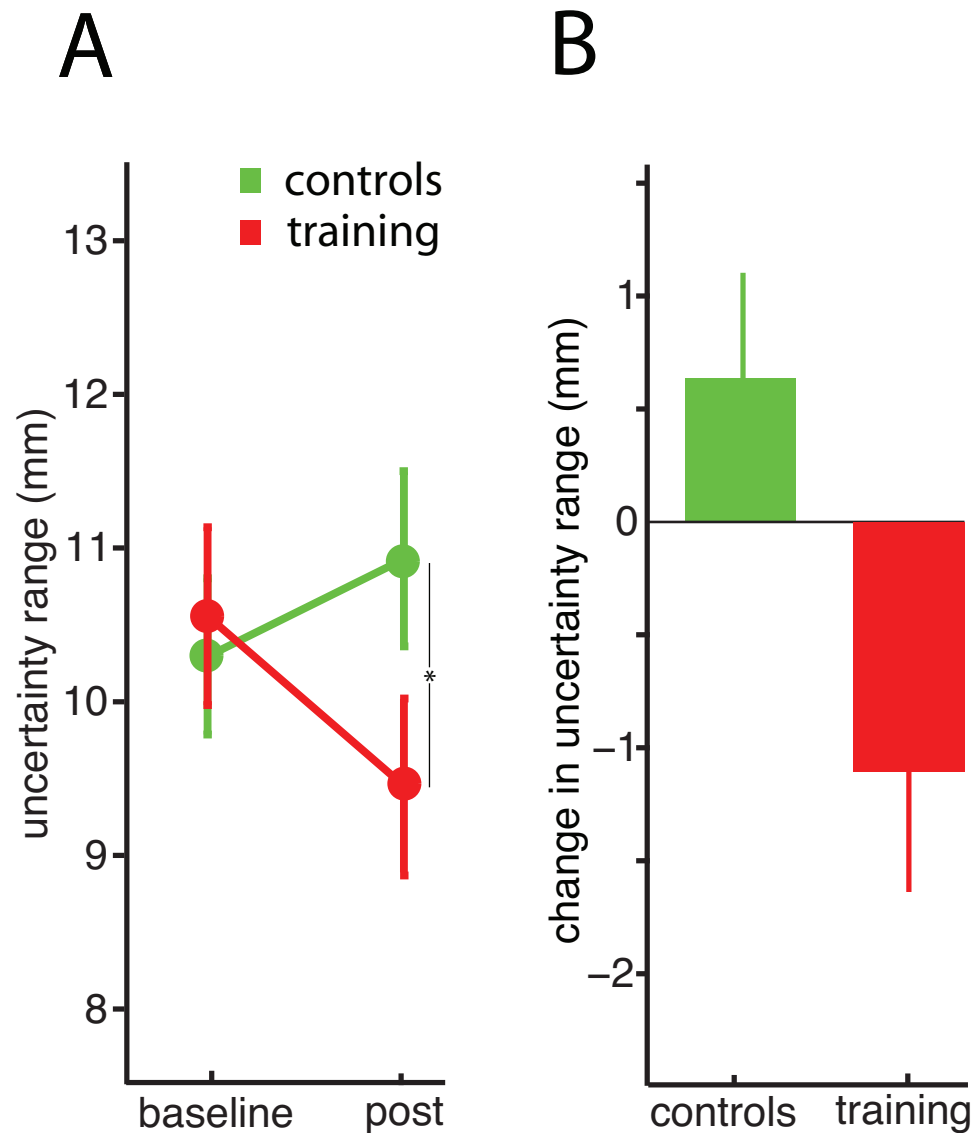
Figure 3.6: Proprioceptive acuity is improved following motor learning. A: mean $\pm$ SE) uncertainty range measured at baseline and following motor learning for subjects who performed movements at the perceptual test location and for control subjects who performed no motor learning. Uncertainty range is inversely related to proprioceptive acuity. B: change in uncertainty range between baseline and retest. The motor learning group (training, red) demonstrates an improvement in proprioceptive acuity relative to control subjects. Statistically significant post hoc Tukey comparisons are noted: *P< 0.05.

measured uncertainty range. Averaged together, the two matched groups had a mean ($\pm$ SE) baseline uncertainty range of $11.45 = 0.47$ mm that decreased to 10.14 ± 0.49 mm following learning, representing an 11% improvement in acuity. In contrast, subjects who performed unmatched learning demonstrated no change in acuity (baseline, 11.056 ± 0.48 mm; following learning, 11.051 ± 0.45 mm). A split-plot analysis of variance was performed with two between-subjects factors (proprioception test: right vs. center, and learning: matched vs. unmatched) and one within-subjects factor (time: baseline vs. post). A significant interaction effect of learning location and time was found ($F(7,91) = 3.974$; $p < 0.05$). Post hoc tests showed a significant difference between perceptual acuity at baseline vs. following learning ($p < 0.05$) for subjects who performed matched learning. Subjects who performed unmatched learning showed no such change ($p > 0.9$). For the subject groups who underwent matched learning, no difference was found in the acuity improvement when subjects who performed movements in the $100cm^2$ patch were compared with those who moved along a left-right transverse line. Our results suggest that proprioceptive acuity is not improved broadly across the workspace but is only modified in the region in which motor learning occurred.

3.3.4 Control Tests

Sensory signals. It should be noted that motor learning also provides subjects with a specific set of sensory signals related to the movement trajectories experienced over the course of learning. The possibility exists that the pattern of changes in proprioceptive acuity observed may be due to this sensory experience alone and do not specifically depend on motor learning per se. To assess this possibility, we performed a control
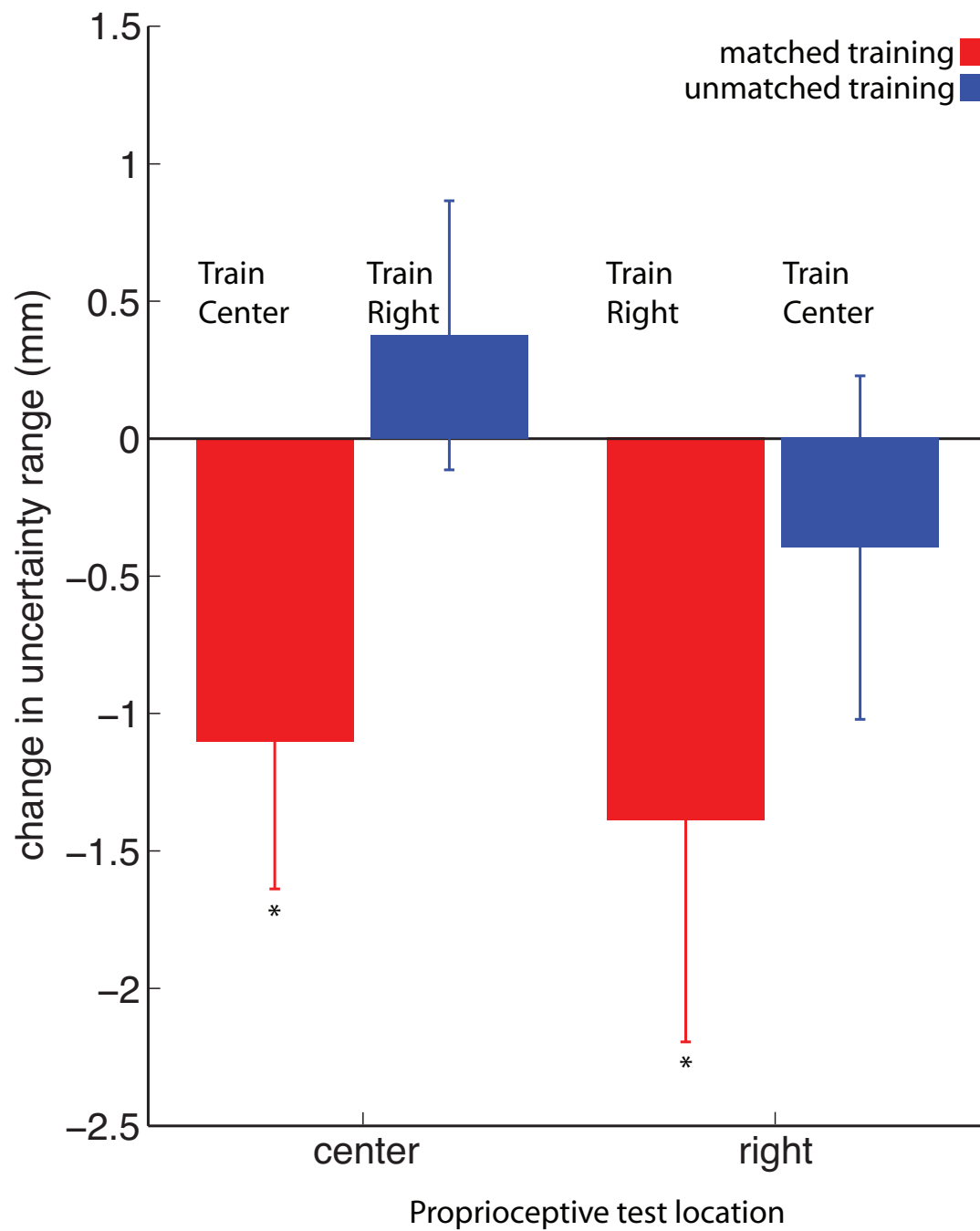
Figure 3.7: Mean ± SE) change in uncertainty range is given as a function of motor learning location (center vs. right) and the location of proprioceptive tests (center vs. right). A decrease in uncertainty range (and thus an improvement in proprioceptive acuity) was observed only in the workspace locations at which motor learning was completed (matched training, red): *P< 0.05. No change in uncertainty range occurred in workspace locations distant to the location of motor learning (unmatched training, blue).

study in which subjects did not actively move their limb but nevertheless experienced the same movement kinematics as those who underwent active movement. Subjects (n = 18) grasped the handle of the robotic linkage, which was programmed to move their passive limb through the same trajectories recorded from a previous subject in experiment 1. Figure 3.8, solid bar, shows changes in proprioceptive acuity for subjects in the passive control. These subjects did not show any change in acuity (p = 0.57, paired 1-tailed t-test). One potential concern with this control test is that subjects may not have dedicated the same amount of attention to the task as subjects who performed active movement (Hospod et al. 2007). To control for this possibility, we tested an additional group (n = 18; Fig. 3.8, shaded bar) who were asked to attend to the passive movements of their limb. These subjects were instructed to pay attention to the direction of the passive movements and to count the number of times their limb was moved in a leftward direction. This task proved to be at least difficult enough so that no subjects performed at ceiling; thus it is likely that this task was providing significant attentional demands on the subject. As before, no reliable changes in proprioceptive acuity were observed for this group (p = 0.56), suggesting that passive sensory experience in the absence of active motor learning does not result in changes to proprioceptive acuity. Subjects were instructed to remain passive throughout proprioceptive tests and to grasp the handle in a consistent fashion throughout the study. Despite these instructions, it is possible that subjects changed the way they grasped the robot handle, for example, by applying differential amounts of force for different testing positions or for proprioceptive testing at baseline vs. following learning. Differences such as these could conceivably influence their responses during proprioceptive testing (Allen and Proske, 2006; Ribot-Ciscar et al.,

1991; Walsh et al., 2006, 2009). To assess this possibility, we examined the measured force applied to the handle before and after proprioceptive tests. We measured force for at all test locations (0 ± 0.7, 1.3, and 3.0 cm) during baseline and compared those with measurements following motor learning. We found no statistically reliable difference in either the direction or the magnitude of this force ($p > 0.3$ in all cases). These results suggest that grasping behavior did not change as a result of learning and thus presumably did not affect estimates of proprioceptive acuity.

Learning. The possibility exists that motor learning during the movement task may not be necessary for the observed changes in sensory acuity. Perhaps any spatially matched arm movements are sufficient for sensory acuity improvements, even those resulting in no changes to movement accuracy. To assess this possibility we ran an additional control study. Subjects (n = 25) performed reaching movements and perceptual testing in the central workspace location. Movements were made to the same visual targets as in the main experiment, but we modified the task to minimize the opportunity for learning. The cursor representing hand position was not displayed, preventing subjects from learning about movement errors incurred throughout the motor task. We also changed the display of visual targets such that instead of remaining on the screen until the subject reached the target, each target was displayed for a duration equal to the mean presentation time for experimental subjects and then extinguished. Thus target presentation was independent of subject behavior, but subjects in the control were exposed to a similar set of visual stimuli as subjects in the main study. Control subjects were instructed to move to the targets as quickly and as accurately as possible. Thus subjects in the control group produced the same kind of movements (similar in speed and amplitude) as subjects in the main experiment but
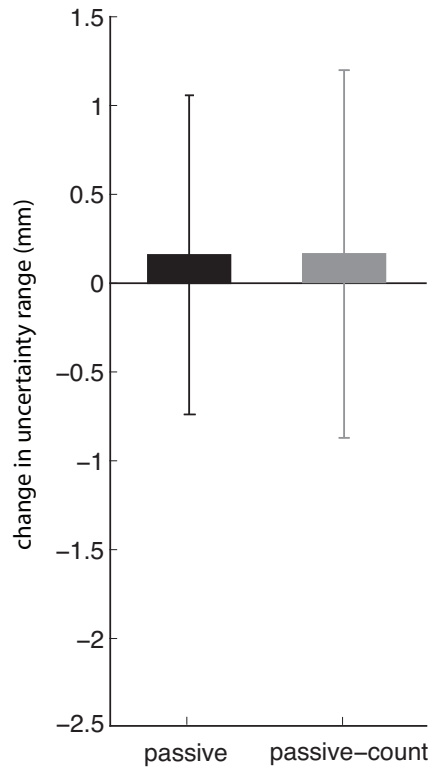
Figure 3.8: Mean ± SE) change in uncertainty range for subjects in the passive controls. Subjects did not perform active motor learning but experienced the same kinematic trajectories as subjects who did (passive, solid). The robot was programmed to move each subject's passive arm through the same kinematic trajectories as a subject chosen from the main study, who performed active motor learning. Passive-count (shaded) gives mean change in uncertainty range for subjects who were specifically asked to attend to the passive movements by counting the number of times the robot moved their hand in a leftward direction.

did not receive feedback that would be required to improve their performance over time. We examined movement performance for control subjects to verify that a range of kinematic features was similar to that for the experimental group and to test for any sign of learning. Figure 3.9A shows mean peak tangential velocity across the motor learning session for control subjects and for subjects in the main experiment who performed motor learning in the center workspace location, matched to the central perceptual test location. It can be seen that movement speeds for the control group were in the same range as those for subjects in the main experiment. Statistical tests showed that mean peak tangential velocity did not reliably differ between controls and subjects in the main experiment for any of the blocks, including the final training block (means: experimental, 0.215 ± 0.008 m/s; control, 0.228 ± 0.012 m/s; t-tests, $p > 0.05$ in all cases). Some have reported proprioceptive drift over time in the absence of any visual feedback (Brown et al. 2003a, 2003b). To test for the possibility that movements of control subjects drifted over the course of the movement task, we measured mean x and y position for each of the four training blocks. No reliable differences were observed ($p > 0.05$ in all cases). We also measured total distance traveled and found that the average movement distance did not differ between groups in any of the blocks (block 4 mean distance per movement: experimental, 10.5 ± 0.32 cm; control, 9.95 ± 0.61 cm; t-tests, $p > 0.05$ for all pairwise tests on the 4 blocks). Thus movement kinematics were similar for experimental and control groups. Movement accuracy for control subjects was measured several different ways across the motor task, and in each case, no statistically reliable differences were found. Figure 3.9B shows movement accuracy (absolute PD) along the normalized movement length. A two-factor within-subjects analysis of variance was performed to test for

any differences in PD. Neither factor (blocks 1 and 4) nor percent distance (10:90) was significant ($p > 0.4$ in both cases). In addition, none of the nine pairwise comparisons along the trajectory, made between the first and last training block, were statistically reliable (paired t-tests, $p > 0.4$ in all cases). We also measured for each movement 1) the smallest distance achieved between the subject's hand and target and 2) the distance between the hand and target at the end of each movement trial. Neither of these measures were significantly different when the first motor block was compared with the fourth and final block ($p > 0.05$ in both cases). To summarize, control subjects performed movements with qualitatively similar kinematics over the course of their motor training, but in contrast to subjects in the main experiment, controls did not improve movement accuracy. Figure 3.9C shows sensory acuity before and after the movement task for controls (black) and for subjects in the main experiment (red). In contrast to subjects in the main experiment, who showed a reliable improvement in proprioceptive acuity (a decrease in uncertainty range), the uncertainty range for control subjects following the motor task was not statistically different from baseline. These results support the idea that improvements in proprioceptive acuity seen in the main experiment are dependent on motor learning.

3.4 Discussion

We investigated the effects of motor learning on human proprioception and found that proprioceptive acuity is improved following motor learning. Improvements to proprioceptive acuity occurred only for limb configurations matching those experienced during motor learning and depended specifically on active motor learning. No
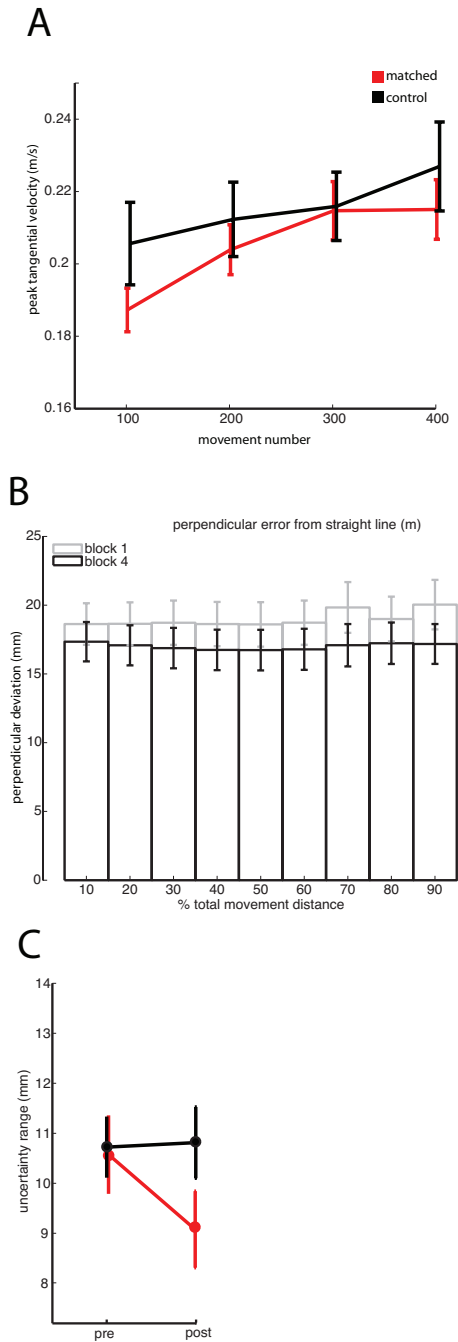
Figure 3.9: A: mean $\pm$ SE) peak tangential velocity of move- ments made during the motor task for the matched experimental group (red) and the control group (black). B: PD from a straight trajectory throughout normalized movement distance for blocks 1 and 4. No pairwise comparisons at any point in movement distance were significant ($p > 0.4$ for all comparisons, paired t-tests). C: uncertainty range at baseline (pre) and following the motor task (post) for the matched experimental group (red) and the control group (black).

improvement in proprioceptive acuity was observed for subjects who did not undergo active motor learning but who experienced the same movement kinematics as those who did. In addition, no improvement in acuity was observed for subjects who performed similar movements but who did not improve motor performance over time. In the present study, proprioceptive acuity was improved by $\sim 11\%$ following motor learning, representing a sizable proportional improvement from baseline levels of acuity. Although this effect size is modest in absolute terms, it is on the same order of magnitude as the improvement in movement accuracy. Our findings are consistent with the idea that motor learning is a process of sensorimotor adaptation consisting not only of changes to motor signals but also modulation to sensory systems (Ostry et al., 2010). The present findings represent the first report of a spatially localized tuning of proprioceptive acuity following recent motor learning. In a recent study (Ostry et al., 2010), it was observed that the directional bias of perceived hand position changed with motor adaptation to a viscous force-field, and the perceptual bias varied with the direction of the experienced load. This is in contrast to the improved acuity of sensed hand position in the current study, observed when subjects learned to move accurately to targets in the absence of a novel, external load. Together, these data suggest that the nature of perceptual change is coupled to the particular type of motor adaptation. Future studies may clarify the degree to which motor learning and perceptual change are causally linked. The changes in proprioceptive acuity observed in the present study occurred after only 10 min of motor training and were measured during 8 min of perceptual testing. These effects therefore represent a relatively rapid adaptation of the sensorimotor system. Future studies may determine how long the observed proprioceptive changes persist over time and whether they remain coupled

with the retention of motor learning (e.g., Ostry et al. (2010)). It should be noted that although perceptual changes were found following active movement but not passive movement, this may not necessarily imply that passive movements are less salient. Indeed, a recent study found that the direction of passive hand movements is more accurately perceived than that of self-generated movement (Scheidt et al., 2010). To investigate sensory changes due to motor learning, we developed a novel paradigm that avoided active movement during the perceptual response and avoided the sort of interhemispheric and intermodal coordinate transformations involved in other methods of assessing proprioceptive function (Adamo and Martin, 2009; Desmurget et al., 2000; Goble and Brown, 2008, 2007; Leibowitz et al., 2008; Sittig et al., 1985; van Beers et al., 1998; Wann and Ibrahim, 1992). This technique does require subjects to remember the reference position of their limb while their hand is brought to the test location, so it should be noted that there is a memory component involved in their response. However, the impact of this is likely minimal, because the duration between the presentation of the reference position and the subject's response is short, between 800 and 1,500 ms. The specific neurophysiological basis for the modulation of proprioceptive acuity we observed has not been determined, although there are a number of possibilities, including peripheral modulation of sensory afferents and cortical changes in sensory-motor processing. For example, it is known that changes in spindle afferent signals are mediated by alpha- gamma coactivation during active movement (Ribot-Ciscar et al., 2009). However, it is not clear how this mechanism could explain the change in proprioceptive acuity we observed, since the perceptual test does not involve active movement. Studies using the microneurographic technique to measure spindle afferent signals in vivo have found modulations of spindle

afferent signals when subjects attended to and classified passive rotations of their ankle joint (Hospod et al., 2007). The authors have shown in a subsequent study (Ribot-Ciscar et al., 2009) that attention to different aspects of the passive joint rotations, to either position changes or changes in movement velocity, produced different kinds of modulation of spindle afferent firing. Isometric muscle contraction also has been shown to increase spindle sensitivity immediately following motor activity (Ribot-Ciscar et al., 1991; Walsh et al., 2006, 2009). Together, these studies support the idea that the central nervous system modulates the sensitivity of the primary proprioceptive sensors. Studies of brain areas related to proprioception do not suggest clear putative neural mechanisms underlying the acuity changes we observed. Studies of adult cortical plasticity in animal models of the somatosensory system have assessed changes to intracortical depression and excitation in barrel cortex in rats following whisker removal and resulting sensory deprivation (Finnerty et al., 1999; Fox and Wong, 2005). S1 hand representations in monkeys have demonstrated changes to the size of neural representations in S1 following peripheral nerve stimulation (Recanzone et al., 1990) or surgical syndactyly (Blake, 2005; Clark et al., 1988; Jenkins et al., 1990). Similar adaptive changes have been shown to occur in primary motor cortex (Kleim et al., 1998; Nudo et al., 1996). These findings, however, depend on fundamentally different timescales to elicit behavioral changes, involving days or weeks of sensorimotor learning. In contrast, the effects reported in the present study are the result of ~ 10 min of motor learning and therefore represent highly dynamic changes to perceived limb position. Use-dependent changes to cortical excitability have been found to occur over short timescales in primary motor cortex and presumably reflect increased excitability of cortical areas related to the recently practiced

movement (Classen et al., 1998; Pascual-Leone et al., 1995). Our findings therefore may reflect a sensory component of short-term sensorimotor plasticity during which parallel changes to motor and sensory areas occur throughout motor learning (Ostry et al., 2010). Interestingly, our analysis of kinematic accuracy found that subjects not only moved with greater precision as their hand approached the target but also were more variable at the beginning of movement. We hypothesize that this results from increased movement speed as a result of motor learning. Figure 3.10 shows peak tangential velocities for the kinematic data sets shown in Fig. 5. Tangential velocity increased across the movement trajectory as a whole, but subjects only increased movement accuracy as their hand neared the target. These data might be interpreted within a motor control theory that postulates active reduction of motor variability strictly in task- relevant domains while admitting motor variability increases within task-irrelevant areas (Domkin et al., 2005; Scholz et al., 2003; Scholz and Schöner, 1999; Todorov and Jordan, 2002; Valero-Cuevas et al., 2009; Verrel, 2010).

We attempted to determine whether motor learning itself is required for the perceptual acuity effect by conducting a control experiment in which subjects were not provided with visual feedback of any kind. We showed that although these subjects produced movements that were kinematically similar to those produced by subjects in the main experiment, the control subjects did not show motor improvement over training. Importantly, control subjects also did not show changes in proprioceptive acuity, suggesting that motor learning is a necessary condition for this effect. It should be noted that on the basis of this control study alone, one cannot exclude the possibility that visually guided movements, by providing an opportunity to calibrate vision and proprioception, may also result in proprioceptive change. Although
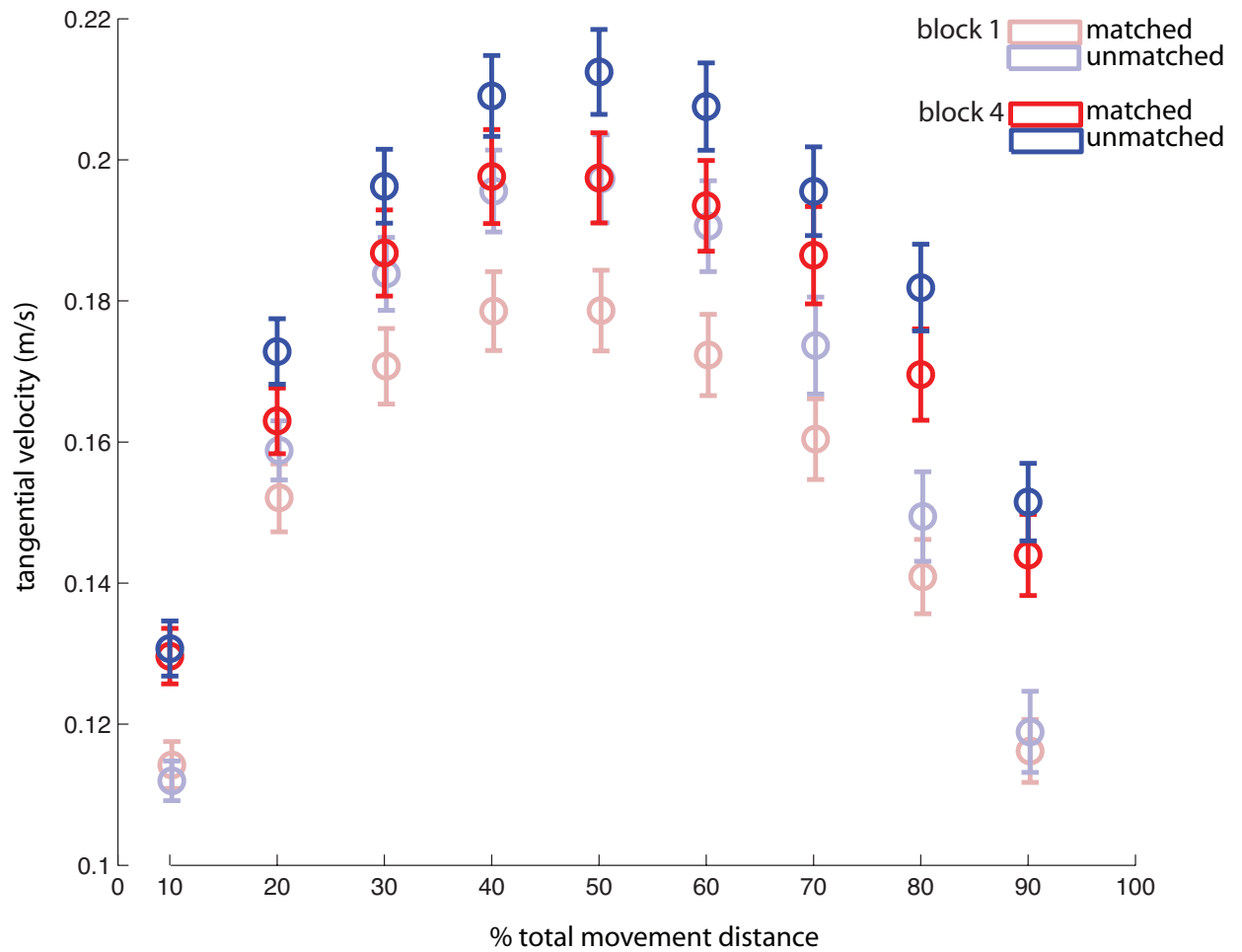
Figure 3.10: Mean ± SE) tangential velocity throughout the movement is shown for matched (red) and unmatched subjects (blue). Block 1 data are denoted by shaded lines; block 4 data are denoted by solid lines.

strictly speaking we cannot rule out this possibility, the fact that the perceptual test in the present study occurs in the absence of any vision mitigates its likelihood. The findings reported in the present study are important because they demonstrate that proprioception is not simply used by the motor system as a static map of the position of our limbs. Rather, the sense of body position is modulated over the course of motor learning. Motor commands not only generate movement but also may result in modulation of the sensitivity of our proprioceptive sense. This relationship may reflect one way in which the sensorimotor system optimally recruits sensory areas for use in motor tasks. More generally, our findings support the idea that motor learning modifies not only motor areas of the brain but also affects somatosensory systems (Ostry et al., 2010). This new way of thinking about motor learning could lead to novel approaches to rehabilitation that specifically exploit the link between sensory change and motor learning.

3.5   Acknowledgments

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Chapter 4

Retention of proprioceptive acuity improvement from motor learning

4.1   introduction

Several recent studies in motor control have begun to examine the relationship between proprioception and motor learning. Recent studies have shown that motor learning of reaching movements is accompanied by systematic and reliable changes to proprioception of the hand (Ostry et al., 2010; Vahdat et al., 2011; Wong et al., 2011). These results support the notion that motor learning and sensory behaviour are linked. It is therefore interesting to investigate the persistence of sensory changes that occur with motor learning.

The persistence of motor learning over time has frequently been studied within the context of finger movements (Robertson et al., 2005). Subjects were asked to perform a set of key-pressing movements in sequence. Within the long set of number sequences a short 5-digit sequence was inserted pseudorandomly at greater frequency than statistically likely, thereby providing subjects with unconscious training on a particular sequence of finger movements. After a period of sleep, subjects showed better retention of these practiced finger sequences as demonstrated by both fewer errors and faster movement speed. Thus in some movement tasks, sleep has been shown to augment performance.

Similar improvements after 24 hours have been observed for arm movements (Brashers-Krug et al., 1996), suggesting that 24 hours might in fact result in offline motor improvement. However, while Donchin et al. (2002) observed maintenance of motor learning over 24 h, no additional improvement was observed. Thus, evidence is mixed regarding the persistence of motor learning of arm movements.

Here we wish to measure the durability of sensory acuity changes following motor learning practice, as observed in (Wong et al., 2011). We performed psychophysical

measurements of the sense of hand position before and after a session of motor learning. We then had subjects return to the lab 1, 4 and 24 hours after motor learning. Interestingly, we observed that improved proprioceptive acuity was detected immediately following learning, and subsequently re-appeared 24 hours later.

4.2 Methods

4.2.1 Subjects

21 subjects (11 females; ages 18-20 years) were randomly assigned to one of two groups. All subjects reported no history of visual, neurological, or musculoskeletal disorder. Written informed consent was obtained from each subject before participation. The University of Western Ontario Research Ethics Board approved all procedures.

4.2.2 Apparatus

Subjects performed reaching movements and tests of proprioceptive acuity while grasping the handle of a robotic manipulandum (InMotion Technologies) in the right hand (Figure 6.1). A six-axis force transducer (ATI Industrial Automation, Apec, NC; resolution: 0.05 N), located inside the handle, measured forces at the hand. All subjects were seated at a desk and interacted with the experimental robot in the horizontal plane at shoulder height (see Fig. 3.1). A custom air sled, placed beneath the subject's right elbow, supported the arm against gravity and minimized friction between the arm and the desk. During motor learning, visual information was displayed via a mirror and LCD monitor display system (Kistemaker et al., 2010). The
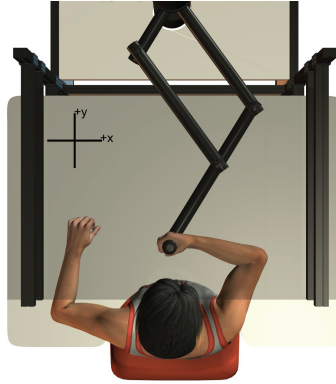
Figure 4.1: Subjects sat in a chair and performed shoulder-height reaching movements and proprioceptive tests with their right arm. A mirror was placed at chin height which occluded vision of the real arm, and onto which a visual cursor was presented that represented hand position during movement tasks. A custom-built airsled supported the upper arm at all times.

horizontal mirror was placed just below chin height and occluded the subject's view of his or her arm. Visual feedback of hand position was provided on the mirror in real time using the LCD display. Proprioception tests took place in the dark, and subjects were asked to close their eyes.

4.2.3   Experimental Protocol

At the start of each experiment we measured baseline proprioceptive acuity. This perceptual test was followed by motor learning (explained below), during which reaching movements were made to visual targets (except for control subjects, as noted). Finally, subjects performed a proprioception test immediately following learning. For control subjects, the learning phase was replaced with a control task (reading quietly) of the same duration. Following either motor learning or quiet reading, we had subjects return to the lab at durations of 1, 4, and 24 h following the motor learning

phase.

4.2.4 Movement task

The motor learning task used in this experiment was nearly identical to that in Wong et al. (2011). Briefly, subjects moved their hand to 5-mm (diameter; circular) targets presented pseudorandomly, within a 10 × 10-cm workspace centred either on the location of proprioceptive testing or in a location 25 cm to the right (Fig. 3.1). A cursor (small filled circle, diameter 4 mm) was displayed in real time to represent the position of the hand. Motor learning consisted of 5 blocks of 100 movements (500 movements total). Subject instructions were told to "move your hand to the target as quickly and accurately as possible." Once the hand was within 2 mm of the target's centre, the current target was extinguished and the next target appeared. Movement time was recorded for each trial, beginning when the target appeared and ending when the hand arrived within 2 mm of the target's centre. Subjects were provided with their total movement time after each block and were encouraged to improve this time over the course of learning. This training required approximately 10 minutes to complete.

4.2.5 Proprioceptive measurement

The proprioception measurement procedure has been reported previously (Wong et al., 2011). This test was performed in the absence of vision with subjects' eyes closed and an opaque mirror resting at shoulder height to block vision of the hand and robot. The subject's unseen right hand was moved by the robot along a left-right axis, 18 cm in front of the body. Subjects made two-alternative forced-choice judg-

ments about whether they perceived their right hand to be left or right of a previous reference location. The reference location was in the center of the 10×10-cm movement area. Each perceptual judgment was composed of three phases: a 2-s hold phase during which the hand was held stationary at the reference position, a randomized passive movement that brought the hand indirectly to the test location, and the subject's response ("left" or "right"). During the passive movement phase, the subject's hand was moved along a line, first from the reference location to a peripheral location positioned at least 6 cm away from the reference, and then back to the test location (near the reference). To reduce the possibility that subjects might use cues related to passive movement speed or direction to aid their judgments of arm position, the passive movement between each reference and judgment position was randomized in terms of duration (between 1,000 and 1,600 ms, square distribution), total distance travelled (14 ± 2 cm, SD normal distribution), and direction (left/ right). The passive movements were designed to be smooth, using a bell-shaped velocity profile. After the subject's response, the limb was again moved passively with random distance, speed, and direction to a peripheral location, before the hand was returned to the reference location to start the next trial. This passive movement prevented the subject from receiving any trial-to-trial feedback about the accuracy of their responses and hence minimized the possibility of adaptation over the course of perceptual testing.

We used the method of constant stimuli to present subjects with proprioceptive judgment locations. Subjects were tested at 7 different distances (0 ± 0.7, 1.3, and 3.0 cm) from the reference location for a total of 74 judgments, requiring approximately 8 min to complete. The test locations more distant from the reference location were tested fewer times because subjects performed at 100% accuracy on these posi-
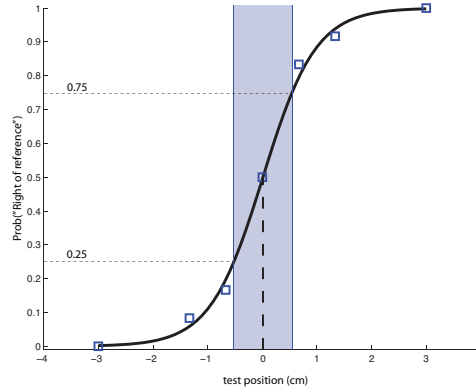
Figure 4.2: Open squares denote the probability with which a subject reported a given hand position to be right of the reference location, as a function of the actual hand location. Subjects' responses were fit to a binomial model using a cumulative normal distribution function. The shaded region represents the uncertainty range of the fit, and the vertical dashed line denotes the perceptual bias.

tions. Each judgment location was approached via leftward and rightward distractor movements an equal number of times.

A logistic function was fit to the set of binary response data across test locations. Proprioceptive acuity was quantified as the distance spanning the 25th and 75th percentiles of the logistic function (Fig. 3.2). This measure, sometimes called uncertainty range (Henriques and Soechting, 2003), is inversely related to sensitivity, and thus smaller values represent greater perceptual acuity. Statistical analysis of changes in proprioception and of kinematic measures were assessed using analysis of variance and Tukey post hoc tests.

4.3 Results

4.3.1 Motor Learning

We first assessed the subjects' ability to improve performance on reaching movements. We measured the subjects' total time taken to intercept all 100 targets, and saw this time decrease across learning for all subjects in the experimental group (Figure 4.3). A repeated measures analysis of variance with one within-subjects factor (time: block 1, 2, 3, 4 and 5) was performed to determine reliable differences in movement time, and found a significant effect of block on time required to intercept targets ($p < 0.001$). Tukey tests measuring pairwise differences between blocks found significant differences between block one and all subsequent blocks, and also a significant difference between the second and fifth block ($p < 0.05$ in all cases). These data support the notion that subjects were able to improve performance of accurate reaching movements over the course of learning.

4.3.2 Proprioceptive Acuity

To determine whether motor learning results in changes to proprioceptive acuity and thereby replicate the findings of Wong et al. (2011), we estimated uncertainty range at baseline and again immediately following motor learning (n = 11). To control for the possibility that observed changes in proprioceptive acuity might be due to the passage of time and not motor learning per se, we tested a second group of subjects (n = 10) who did not perform the motor learning task but read quietly for a matched duration of time. Figure 4.4 A shows measured uncertainty range for both groups of subjects. The uncertainty range (mean ± SE) for the control subjects who did
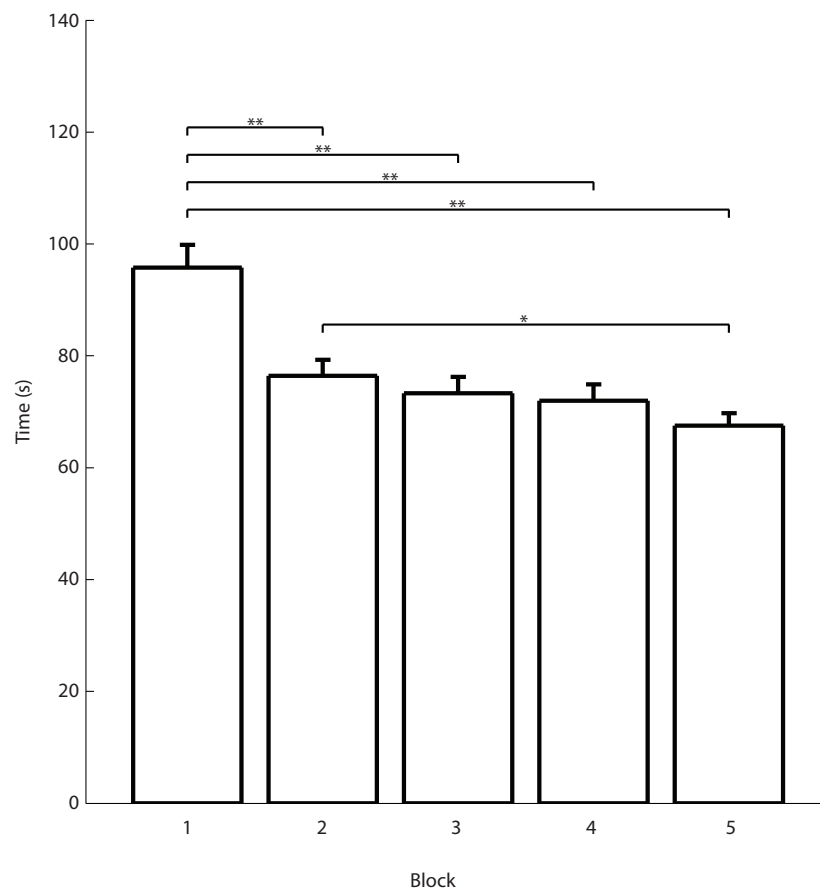
Figure 4.3: Mean $\pm$ SE total time to intercept 100 targets for subjects in the experimental group. Block is listed on the x-axis, time is listed on the y-axis (smaller indicates shorter total time).

not undergo learning was 12.8 ± 1.51 mm at baseline and 11.24 ± 1.69 mm on postlearning retesting (Fig. 4.4, control data shown in blue). In contrast, subjects who performed the motor learning task demonstrated uncertainty ranges at baseline of 14.14 ± 1.49 mm that decreased to 8.92 ± 1.2 mm following learning, representing a substantial increase in acuity approximately 36% of baseline (Fig. 4.4, data shown in red).

4.3.3 Retention of proprioceptive acuity changes

We also measured proprioceptive acuity at the 1, 4, and 24 hour intervals post-motor learning. Figure 4.4 shows that tests of proprioceptive acuity that continued to be performed on testing day did not show relative improvements to baseline. However, 24 h later, proprioceptive acuity again seemed to improve relative to baseline, with uncertainty range measured at 9.52 ±1.02 mm. A mixed analysis of variance was tested for the effects of group and time, and found a significant effect of time ($p < 0.005$), and no significant interaction effect or group effect ($p > 0.05$ in both cases). Tukey post-hoc comparisons showed significant differences between control and experimental groups at baseline ($p < 0.05$). Within the experimental group, subjects showed reliable differences at both immediate post-learning, and also at 24 h following learning ($p < 0.05$ in both cases). At no point did the control group show decreases in uncertainty range relative to baseline ($p > 0.05$ in all cases).

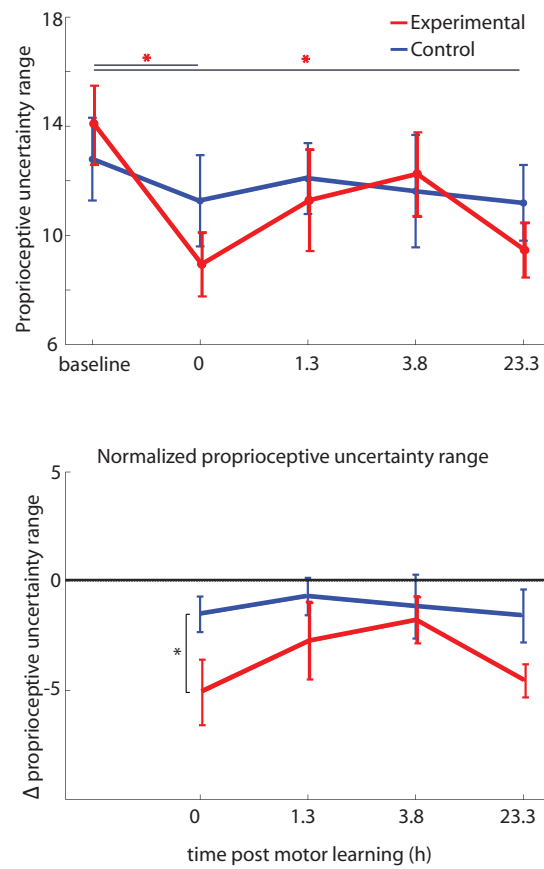Figure 4.4: Mean ± SE uncertainty range for subjects in the control (blue) and experimental (red) groups. Time of proprioceptive measurement is shown on the x-axis, uncertainty range (smaller indicates better acuity) is plotted on the y-axis.

4.4 Discussion

In this study we measured proprioceptive acuity changes after motor learning. Improvements to proprioceptive acuity of the hand were measured immediately following motor learning, but were however not observed during the remaining tests 1 and 4 h post-learning. Interestingly retention of perceptual acuity changes was observed 24 h post motor learning. These results are consistent with the idea that changes to proprioceptive sensitivity may be surprisingly long-lasting, such that relatively short amounts of motor learning - approximately 15 minutes - can result in perceptual changes.

The fact that perceptual changes were observed at a time interval 24 h post-learning is similar to previous studies demonstrating retention of adaptation for reaching movements (Brashers-Krug et al., 1996). However, failure to observe perceptual changes 1 and 4 h post-learning deviates from established motor-learning retention findings.

Studies of motor learning regarding the retention of learned movements have been observed to result in mutual competition when more than one novel adaptation is learned (with the same effector; see Krakauer 2009). Learning two opposite-direction, velocity-dependent force-fields in sequence results in catastrophic interference (Cothros et al., 2006; Caithness et al., 2004); adaptation for these novel forces results in complete forgetting of any previous learning of the opposite force-field. Since our results show that perceptual changes are durable of a magnitude similar to motor learning tasks, it may be that such interference also contains a sensory component.

Sensory improvements, measured post learning, disappear on remaining day 1 tests but return the following day. The fact that proprioceptive acuity changes were

not apparent at 1 and 4 h but were again measurable 24 h later is interesting, but the mechanisms underlying such acuity changes are not clear.

Since sensory changes have been observed to occur in concert with motor adaptations to the movement task (Ostry et al., 2010; Vahdat et al., 2011; Wong et al., 2011) it is relevant to consider previous investigations of the persistence of motor learning. Research has indicated that the ability to recall motor commands seem to depend on sensory cues to mediate recall, and such cues previously deemed to be important include contextual parameters such as joint configuration (Malfait et al., 2002), visual signals (Osu et al., 2004; Wada et al., 2003), and not the point of application of load (Davidson et al., 2005) or particular haptic cues (Cothros et al., 2008). In the current study, all of these task parameters were constant throughout sensory retesting. Reward schemes have also been shown to significantly improve short (6 h) and even long-term (30 day) retention of motor tasks when compared to null or negative reinforcement (Abe et al., 2011). Again however, In the current experiment the control and experimental groups were provided with the same incentives. These contextual cues therefore do not seem to be the likely source of the observed results for perceptual acuity.

In another study investigating the process of motor performance retained over time, is has been observed that motor performance may further improve even in the absence of additional motor learning – a process termed offline motor learning. Such observations have been observed in a somewhat different motor learning task in which subjects are asked to perform a sequential finger tapping task (Debas et al., 2010; Robertson et al., 2004, 2005). In these experiments, improvement in motor performance occurs 12 h post training, and has been shown to be independent of circadian

factors - initial training time, whether morning or evening, has no effect on the offline improvement. Interestingly, a duration of normal sleep has been shown to be necessary for offline learning benefits to occur specifically for motor tasks in which subjects are aware of the trained movements. Perhaps surprisingly, offline learning occurs regardless of sleep if subjects are kept unaware of the specific trained movements; this blocking of awareness can be accomplished by (for example) including the trained movements within a larger set of other movements at only slightly higher frequency than normal. In Debas et al. (2010) it was also observed that motor-learning tasks did not benefit from a sleep-consolidation phase more than a matched awake period of time. It might be that similar sleep-dependent mechanisms underlie the observed proprioceptive acuity affect. However, the results of the current study are different from those collected in previous offline learning studies because in this case no improvement relative to previous *peak* performance was observed; rather subjects merely reacquired sensory acuity improvements that were demonstrated immediately post-learning. Future studies may further explore the nature of retained improvements to proprioceptive acuity.

4.5 Acknowledgments

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Chapter 5

Can proprioceptive training improve motor learning?

5.1 Abstract

Recent work has investigated the link between motor learning and sensory function in arm movement control. A number of findings are consistent with the idea that reducing motor error through learning is associated with systematic changes to proprioception (Haith A 2008; Ostry et al. 2010; Vahdat et al. 2011). Here, we investigated a possible role for proprioception in learning: we tested if motor learning could be improved by providing subjects with proprioception of a desired hand trajectory. Subjects were instructed to reproduce both the time-varying position and velocity of novel, complex hand trajectories. Subjects underwent 3 days of training with 90 movement trials per day. Active movement trials were interleaved with demonstration trials. For control subjects, these interleaved demonstration trials consisted of visual demonstration alone. A second group of subjects received visual and proprioceptive demonstration simultaneously; this group was presented with the same visual stimulus but in addition, their passive limb was moved through the target trajectory by a robot using servo control. Subjects who experienced the additional passive proprioceptive demonstration of the desired trajectory showed greater improvements during training movements than control subjects who only received visual information. This benefit of proprioceptive training was seen in both movement speed and position error. Interestingly, additional control subjects who received proprioceptive guidance while actively moving their arm during demonstration trials did not show the same improvement in positional accuracy. These findings support the idea that proprioceptive training can augment motor learning, and that this benefit is greatest when the subject passively experiences the goal movement.

Keywords: human motor learning, proprioception, arm movements, reaching, sen-

sorimotor plasticity

5.2   Introduction

A number of recent studies have tested the degree to which motor learning directly influences sensory perception. Visual perception of object motion changes after motor adaptation to a novel force-field (Brown et al., 2007). Increased visual sensitivity can also develop near the functional end of learned tools (Brown et al. 2011). The perception of movement curvature and movement symmetry can be changed through the provision of altered visual feedback (Cressman and Henriques, 2009; Malfait et al., 2008).

There is also evidence that proprioception is affected by recent motor learning. The sense of hand position changes following visuomotor adaptation (Cressman and Henriques, 2009; Haith et al., 2008). A similar sensory change has been observed after adaptation to novel forces. Performing reaching movements in the presence of a directional force-field results in systematic changes to the perception of one's hand position (Ostry et al., 2010). Specifically, the sensed hand position becomes biased in the direction of the experienced load. This change in perceptual bias is not observed when subjects merely experience the same trajectories passively, and therefore seems to occur directly as part of a sensorimotor learning process.

Distinct from perceptual bias, the sense of hand position can also be tuned to greater precision. Learning to generate accurate movements also results in improvements in sensory acuity (Wong et al. 2011), and the improved sense of limb position is spatially localized to the area of training. It thus might be hypothesized that the

learning process includes both sensory and motor changes that together mediate new behavior (Vahdat et al., 2011).

Here we examined the relationship between proprioception and motor learning to determine the role of specific proprioceptive experience. The present experiments test the hypothesis that passive proprioception of desired movements can improve motor learning. Subjects were provided with the task of reproducing a specific hand trajectory, either a circle at constant velocity, or a handwritten word (see Figures 5.1 and 5.7). Throughout the training period subjects were regularly provided with a visual demonstration of the desired movement. Experimental subjects were additionally provided with proprioceptive information of the desired trajectory - the hand was moved by a robot precisely through the desired time-varying positions in concert with visual presentation of the hand's desired location. Subjects who experienced this additional proprioceptive information were better able to learn the desired movement.

5.3   Materials and Methods

Subjects Seventy (70) subjects between 17 and 38 years of age (38 females; mean age = 22.51 years) were randomly assigned to one of four groups. All subjects reported no history of visual, neurological or musculoskeletal disorder. 12 subjects were assigned to each of the passive (PASS) and control (CTRL) groups (of both circle and cursive writing tasks; see Results). 11 subjects were assigned to each of the additional reverse (REV) and active (ACT) groups. REV subjects controlled for the possibility that proprioceptive information about any movement (and not proprioceptive information about the desired movement itself) might result in learning benefits

(see Proprioceptive Specificity). ACT subjects tested whether proprioceptive information during active movement results in even further benefits to motor learning (see Active Proprioceptive Guidance). Finally, 12 subjects were assigned to each of two additional movement groups, writing-passive (wPASS) and writing-control (wCTRL), which were used to test if proprioceptive training benefits more complex movements. Written informed consent was obtained from each subject prior to participation. The University of Western Ontario Research Ethics Board approved all procedures.

Apparatus. Subjects performed reaching movements while grasping the handle of a robotic manipulandum (InMotion Technologies, Inc.) in the right hand. A six-axis force transducer (ATI Industrial Automation, Apec, NC; resolution: 0.05 N), located inside the handle, measured forces applied by the hand. All subjects were seated at a desk and interacted with the experimental robot in the horizontal plane at shoulder height (see Figure 5.1). A custom air-sled, placed beneath the subject's right elbow, supported the arm against gravity and minimized friction between the arm and the desk. During motor learning, visual information was displayed via a mirror and LCD monitor display system (Wong et al. 2011). The horizontal mirror was placed just below chin height and occluded the subject's view of their arm. Visual feedback of hand position was provided on the mirror in real time using the LCD display.

Experimental Protocol. The experiment occurred over three consecutive days, taking about 25 minutes per day. At the beginning of the experiment and following a brief 10-movement introduction to the experimental apparatus and task goal, a set of 20 baseline movement trials were recorded. Following this baseline, subjects began proprioceptive training, during which active movement trials were interleaved with demonstration trials. We manipulated the information provided during demonstra-
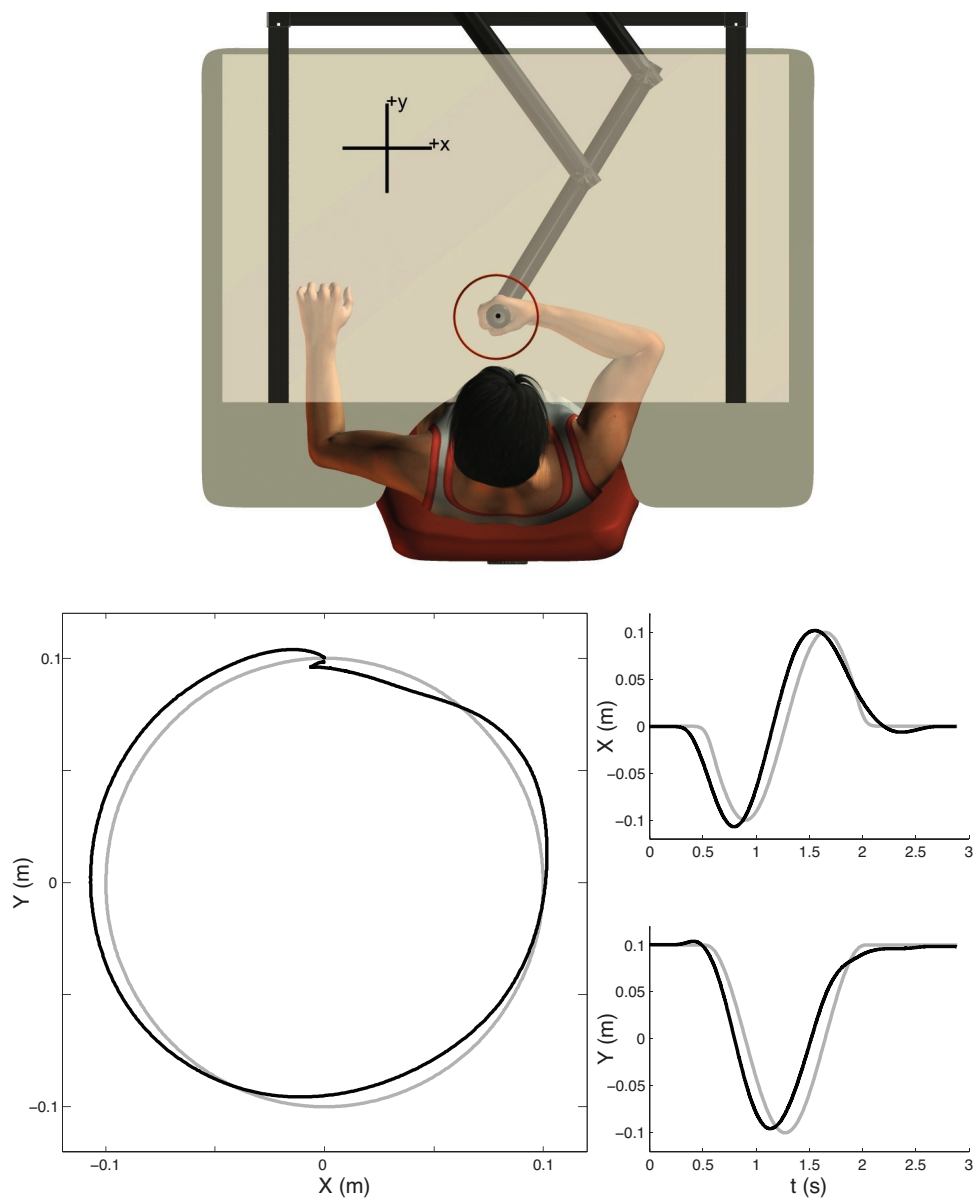
Figure 5.1: Experimental Apparatus and learning task. A: Subjects performed arm movements while grasping a robotic manipulandum and attempted to draw a perfect circle. B: Position trace of the Circle in space (x and y coordinates) and as functions of time. Example subject, final baseline movement, shown in black, relative to desired movement, in grey.

tion trials depending on subject group.

Movement Task. The complete set of 240 training movements (+ 80 demonstration trials) following baseline were divided into blocks of 30 movements. The goal movement was a perfect circle, radius 10 cm. This movement was chosen for several reasons. First, the movement is challenging: performance of the desired trajectory at sufficient speed does not result in asymptotic performance after very brief practice trials, and subjects continue to improve performance over more than 100 trials and across multiple days. A perfect circle is also complex to perform because it involves alternating patterns of joint torques and joint reversals. Second, the movement is naturalistic, featuring a constant tangential velocity (Gribble and Ostry, 1996; Lacquaniti et al., 1983). Finally, because subjects must learn a reaching movement of with constant radius, there is a clear means by which errors in the position of the hand can be analyzed independent from errors in movement velocity.

There were two kinds of trials in each block: training trials, and demonstration trials. Training trials were identical for all subject groups, and consisted of attempts to replicate the desired movement. Demonstration trials, and the sensory information contained about desired movement, were different depending on subject group.

In each block, subjects from all groups were first shown two visual demonstrations of the desired circle. The complete circle was shown as a red line, and a white cursor moved counter-clockwise around the circle at constant tangential velocity (between brief 0.2 s cosine ramps; average velocity of 36 cm/s; duration of 1.67 s). The subject's hand was held fixed at the starting location (at 12 o'clock) during these two visual demonstrations. In training trials, subjects were asked to replicate, as best as possible, the position and velocity of the demonstrated perfect circle. No visual

circle was displayed during training trials; only a cursor representing hand position was displayed. Training and demonstration trials were interleaved at a ratio of 2:1 throughout each movement block.

For experimental subjects (PASS, ACT, REV), the remaining demonstration trials featured the robotic manipulandum guiding their hand through the perfect circle in concert with the movement of the visual cursor (the robot was controlled using a PD controller, $2000N * m^{-1}$; $20Nsm^{-1}$). For all demonstration trials, visual information was the same across subject groups.

Post-baseline training on days 1, 2 and 3 consisted of 60, 90 and 90 training trials, respectively. Subjects were provided brief breaks every 30 movements to avoid fatigue.

Data Analysis. We used several independent measures to characterize changes to kinematics over the course of learning. Cross correlation index (CCI) was calculated for movements by computing the correlation between the desired and produced signals in both x and y, as functions of time. The mean of the two x-y correlations was used as one dependent measure of motor learning.

Positional error was calculated by measuring the absolute distance between the produced radial distance of the hand and the desired (10cm) radial distance, averaged over the entire circle.

Average velocity was measured for each trial to determine how well subjects approximated the desired (constant angular) velocity of the circle.

Statistical analysis of changes in kinematic measures were assessed using analysis of variance and Tukey post-hoc tests. Violations of sphericity were tested for and Greenhouse-Giesser corrections were employed to correct for any violations of

spirericity.

5.4 Results

We measured motor learning over the course of three days of training. Several kinematic variables were measured to characterize how subjects improved motor performance relative to baseline. We compared performance of subjects receiving visual demonstration of the desired movement (CTRL subjects) to subjects who were moved through the desired trajectory by the robot, together with visual presentation of the cursor movement (PASS subjects).

Cross correlation. To assess if proprioception of the desired movement improves motor learning, we measured subjects' ability to generate the desired positions [x,y] of the hand over time. As subjects achieve greater skill at generating the desired circle, the produced x and y position as a function of time should become more correlated with the desired x and y position signal, across the training period. Signal correlation is affected by both errors made in the position of the hand, as well as velocity matching error, and is thus in some sense a net measure of movement learning.

Figure 5.2a shows the cross correlation index (CCI) for both experimental (blue, PASS) and control (red, CTRL) subjects. This dependent variable is an error measure, with a score of 0 indicating no deviation between desired and actual position signals. Both subject groups clearly show learning over the three days of motor learning. Notably, large improvements are observable relative to baseline on day 1 for PASS subjects (blue) receiving passive proprioceptive training. At baseline, CTRL subjects demonstrated CCI of mean pm SD = 0.39 pm 0.18, and mean performance

for the remainder of day 1 was 0.34 pm 0.15. PASS subjects demonstrated similar performance at baseline (0.45 pm 0.22), but showed larger improvement immediately on day 1, reducing CCI to 0.21 pm 0.06. To test for reliable differences in CCI over the course of learning, an analysis of variance was performed with one within-subjects measure (4 levels: baseline, and each day of learning; Figure 5.2 b) and one between-subjects measure (groups: CTRL and PASS). A significant interaction was found ($p < 0.001$); Post-hoc tests showed that PASS subjects had smaller error on day 1 relative to baseline ($p < 0.01$), while CTRL subjects did not demonstrate this day 1 performance improvement relative to baseline ($p > 0.4$). On subsequent days 2 and 3, both subject groups showed improved performance ($p<0.01$). These data support the idea that passive proprioceptive demonstration trials improve the rate of motor learning.

Movement Velocity. We also sought to measure the ability of subjects to perform the desired average velocity. Figure5.3 shows average movement velocity across the training period. Clear increases in movement speed towards the desired speed (dashed line) are observed relative to baseline for PASS subjects upon presentation of the desired trajectory, while both subject groups asymptote to similar levels. Analysis of variance (one within-subjects factor, time [4 levels], one between-subjects factor, group) demonstrated an interaction between training time and group ($p < 0.05$); Post-hoc tests showed that average movement velocity was significantly higher for PASS subjects on day 1 ($p <0.05$); CTRL subjects did not increase movement speed on day 1 ($p > 0.05$). By training end, subjects had achieved an increase in movement velocity relative to baseline ($p < 0.05$ for both groups). These data also support the idea that passive proprioceptive demonstration trials improve the rate of motor
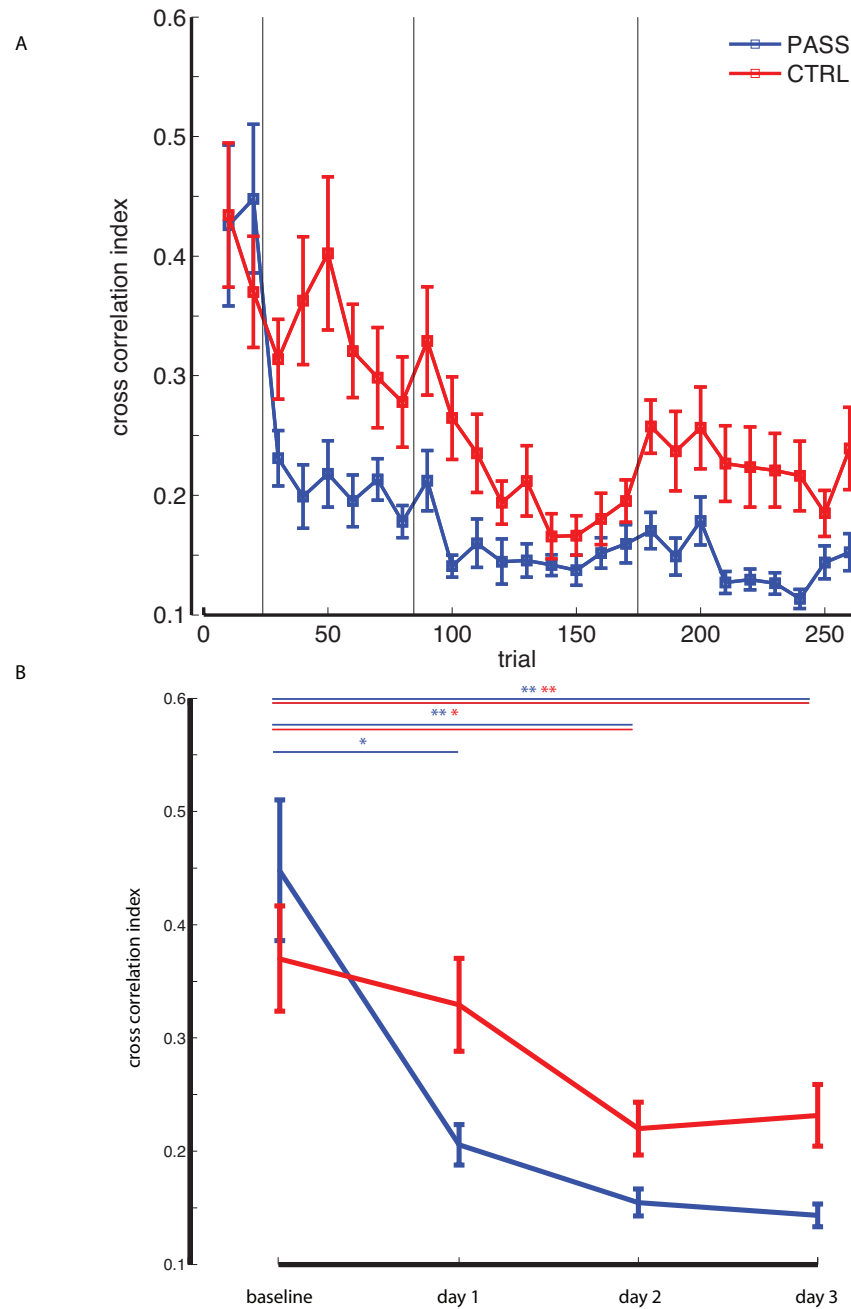
Figure 5.2: Motor learning: A. cross correlation index. Mean (pm SE) cross correlation index of performed movement to desired movement, averaged in bins of 10 movements. An index of 0 indicates no difference between the produced and desired movement trajectory. Blue represents data from passive subjects; control subjects are shown in red. B. Mean Cross correlation index averaged across training days. Statistical significance shown: * =0.05; ** = 0.01.

learning.

Positional Error. To determine if subjects were able to reduce the positional error of their movement, independent of any speed information, we measured the radial error - the deviation of the hand's position from the 10 cm radius - around the entire circle. We observed that subjects who received the passive training were also better at replicating the positions of the circle. Figure 5.4 shows the (absolute) positional error averaged across the entire movement trajectory, across the training period. Subjects in both groups reduce average radial error over the training period. Another analysis of variance with one within-subjects measure (time, 4 levels: baseline, Training day 1, 2, 3) and one between-subjects measure (group: Control, experimental) found a significant effect of training ($p < 0.02$). Post-hoc comparisons showed that the two groups do not differ reliably at baseline ($p > 0.4$). On days 2 and 3, PASS subjects performed better than baseline ($p < 0.01$) while CTRL subjects showed reduced positional error on day 3. Taken together, These results support the idea that the passive proprioceptive training specifically improves the motor system's ability to generate the desired positions of the hand. These results are consistent with the idea that the demonstration trials with proprioception of desired hand position improved the subject's ability to reduce movement error. These positional error reductions are particularly striking because PASS subjects have also shown great increases in movement velocity (as noted above).

Proprioceptive Specificity. We next investigated the degree to which this benefit of passive proprioceptive training was specifically due to the experienced movement trajectory. It might be noted that when subjects are passively moved through the desired trajectory, subjects are also given task-relevant information independent of
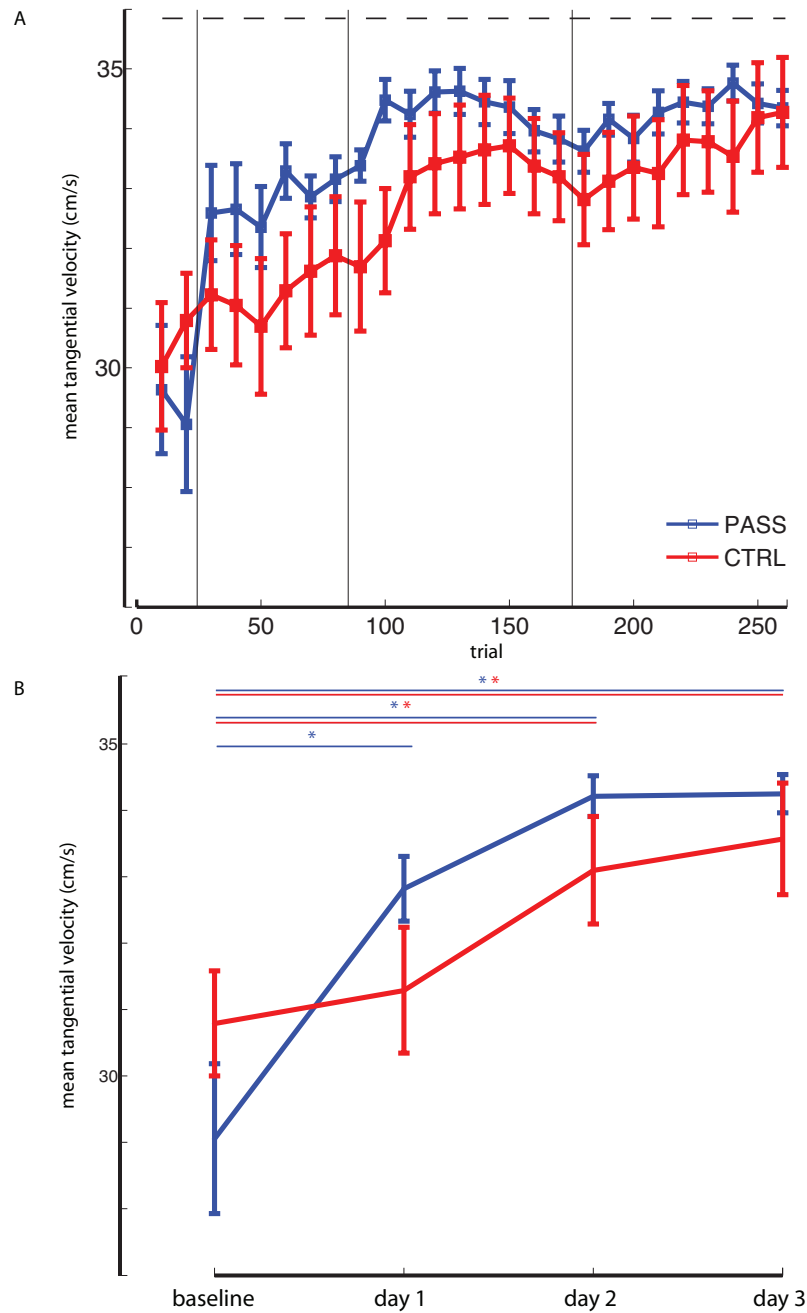
Figure 5.3: Mean tangential velocity: A: mean (pm SE) tangential velocity for subjects in the passive group (blue) and control group (red), averaged in 10 movement bins. Subjects learn to generate movements close to the average velocity profile (shown in dashed line); B: averaged across training days (*0.05, **0.01).

Figure 5.4: Positional Error: A. mean (*pm* SE) absolute radial error throughout learning for both subject groups (passive in blue, control in red), averaged over 10 movement bins. Subjects demonstrate reduction of this error over the course of learning; B averaged across training days (*0.05, ** 0.01).

the path itself. Timing information like overall movement duration is provided by a salient start and stop of the robotic manipulandum. In addition, it might be argued that passive demonstration movements also cause subjects to dedicate more attent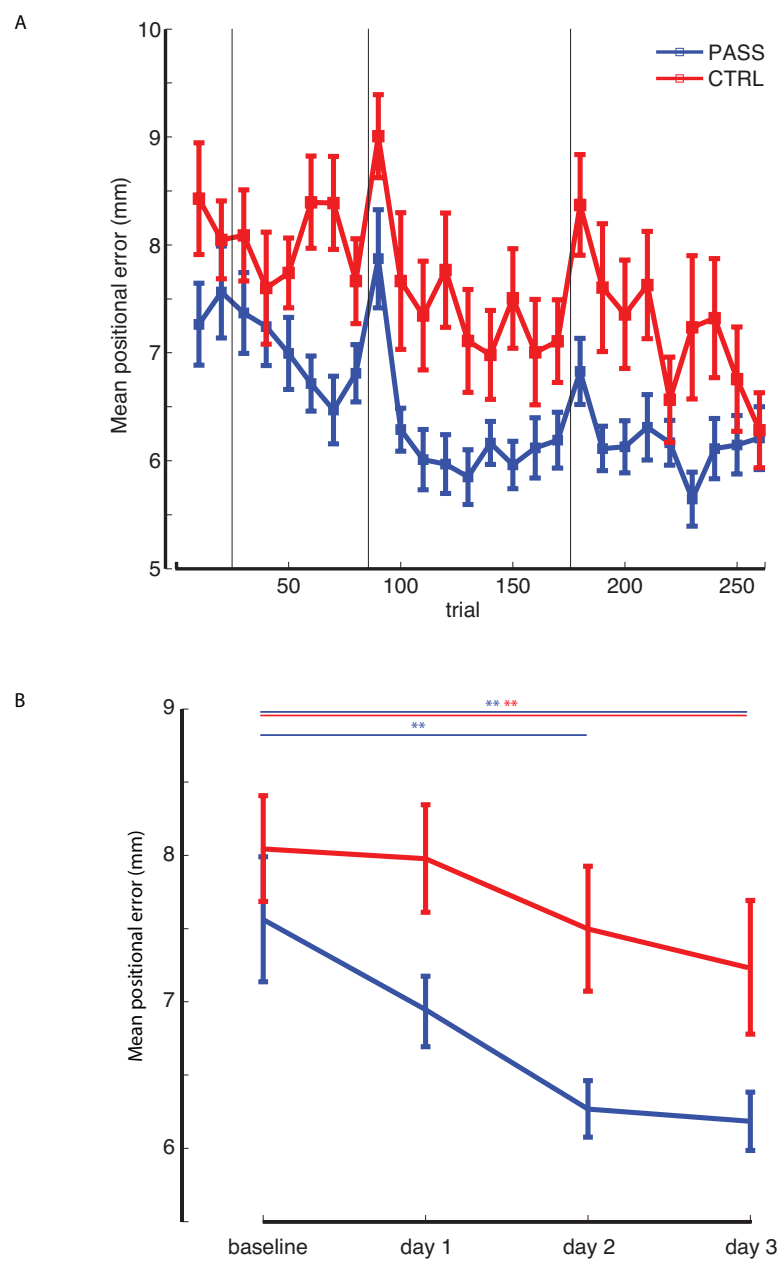ion to their hand during these demonstrations. Either or both of these aspects of proprioceptive demonstration might confound the role of proprioception itself in causing observed improvements for PASS subjects. To control for these factors, we provided a new group of subjects (n = 11, hereafter REV subjects) with the same experience of training and passive presentation trials, but in this case we manipulated the passive presentation trials such that the hand was moved through the opposite, clock-wise circle. As a result of this training, the magnitude of hand tangential velocity, and the range of joint angles experienced, were identical to those of passive subjects; movement duration is constant, and the task includes the same attentional demands on the subject as in the main experiment. Clearly however the sequence of hand positions is different. On the active movement trials subjects in this control were asked to reproduce the circular trajectory in the CCW direction, the same as subjects in the main experiment and opposite to the direction observed during their passive proprioceptive training.

Figure 5.5 (green) shows the changes to the CCI for these subjects. Subjects show similar improvements to cross correlation index (as subjects in the main experiment). CCI increased from 0.471 pm 0.19 to 0.324 pm 0.175 on day 1, and maintained the improvement over the following days. An analysis of variance was performed to assess differences between these additional groups of subjects (see statistics below: Active proprioceptive training). Post-hoc tests found that these subjects did not demonstrate the early day 1 improvement to CCI that PASS subjects demonstrated on day 1 (p

> 0.05). By days 2 and 3, REV subjects had significantly improved CCI relative to baseline ($p < 0.05$), similar to CTRL subjects.

Figure 5.6 shows mean positional error over the training phase. Unlike in the CCI, no improvements are seen over the entire learning phase. An analysis of variance (see statistics below: Active proprioceptive training) confirmed that these subjects did not demonstrate reliable improvements to their positional error, at any point during training.

Active proprioceptive training. It might be proposed that passive displacement of the arm is sub-optimal for providing valuable sensory information. In particular, it might be noted that the state of the arm, while relaxed, contains muscle states (length and associated time derivatives) significantly different than those required during active movement. It thus might be that some form of active motor learning - where the subject receives guidance through the desired trajectory while also generating active movement - would be more beneficial (see Marchal-Crespo and Reinkensmeyer 2009 for review). To test this hypothesis we provided an additional group of subjects (n=11; hereafter ACT subjects) with the same experimental protocol as the main experiment, with one change to instructions: instead of keeping their arm passive, subjects were asked to move actively with the robot during demonstrations of the desired circle. Thus, this experience might be described as augmented or robot assisted control. The PD controller's coefficients were kept the same as those used for PASS subjects.

Figure 5.5 (purple line) shows CCI error measured throughout learning. These subjects show similar improvements to those in the passive group of subjects. To test for reliable changes in performance from each day, a mixed analysis of variance was
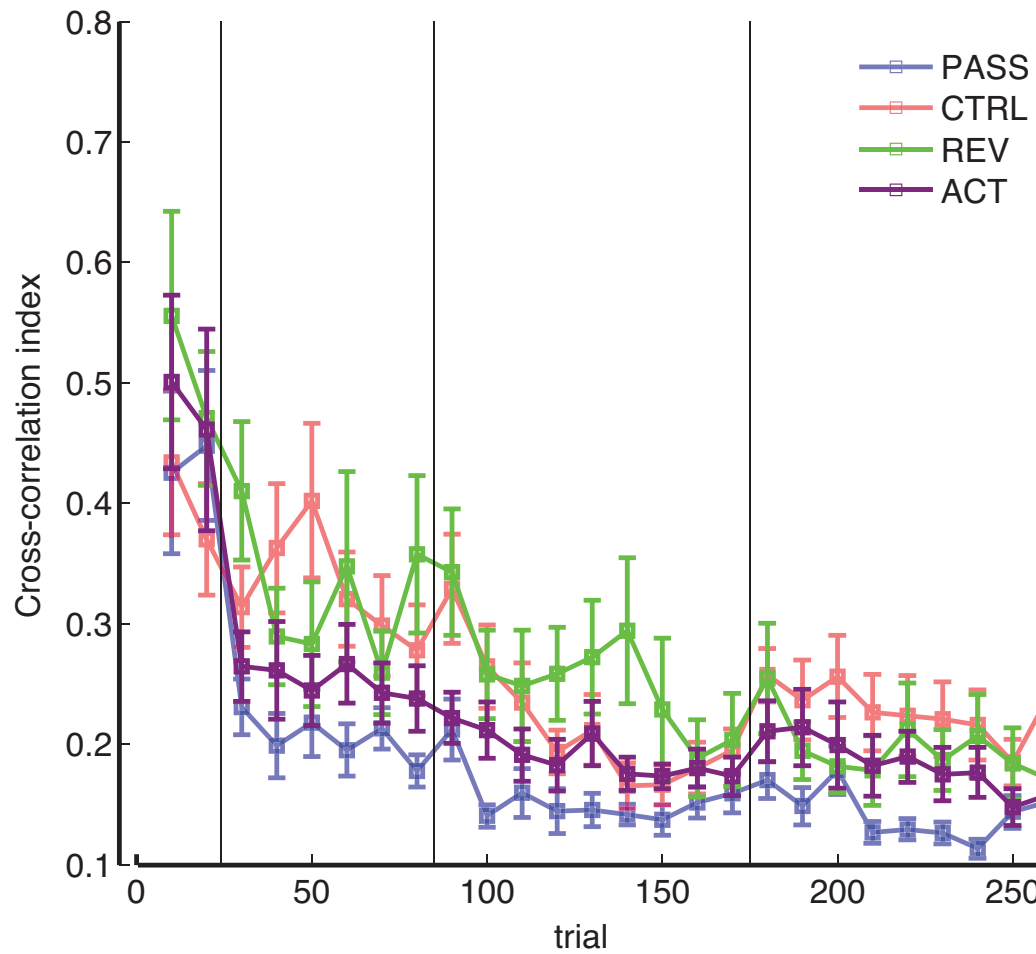
Figure 5.5: Data as shown in Figure 5.2(mean *pm* SE), with the addition of REV subjects (green) and ACT subjects (purple). Again, data were averaged over 10 movement bins.

performed with 1 between-subjects measure (4 levels: PASS, CTRL, REV and ACT groups) and 1 within-subjects measure (4 levels: baseline, and days 1:3). A main effect of training was found ($p < 0.001$). Post-hoc tests found that, similar to PASS subjects, these ACT subjects improved CCI on day 1 relative to baseline ($p < 0.05$) and maintained this performance throughout the learning period.

Figure 5.6 shows positional error over the course of learning. A mixed-design analysis of variance (with 1 within-factor: time, 4 levels; 1 between-factor: group, 4 levels) found a reliable factor of training time ($p < 0.01$). Post-hoc comparisons found no reliable reductions in positional error for ACT subjects, relative to baseline, for the training period. Together, these data suggest that actively moving the arm during proprioceptive demonstration trials helps to improve motor performance, but does not admit the same fine improvements to positional accuracy.

This inability of active movement during proprioceptive training to provide reduction in positional errors is surprising, and we sought to further understand the bases of this effect. One possible explanation for this result is that active demonstration trials may have been uninformative if active movement against the handle did not result in positional errors. If this is true, then we may expect that variations in force at the handle during demonstration trials may not be accompanied by positional error.

We examined mean force at the handle for all subjects, during all demonstration trials. It was observed that the variance of force during demonstration trials was indeed higher for ACT subjects than PASS subjects (SD $= 2.01 \, pm \, 0.95$ PASS vs 3.02 pm 1.58; $p < 0.05$). Because the manipulandum commanded tight control about the desired position, these varying forces at the handle did not result in reliable differences in positional deviation of the manipulandum during demonstration trials (means:
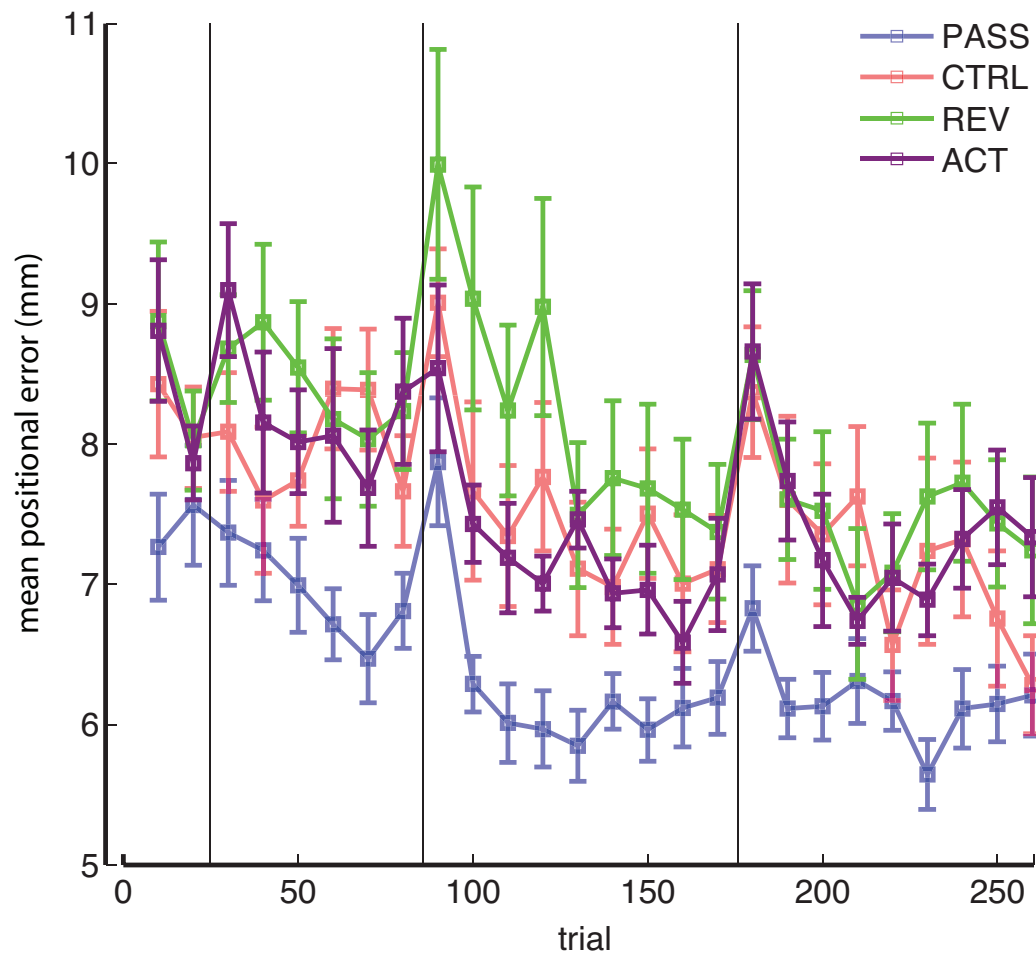
Figure 5.6: Positional error: data as shown in figure 2 (mean *pm* SE), with the addition of REV subjects (green) and ACT subjects (purple), data averaged over 10 movement bins.

1.81 *pm* 0.5 mm PASS; 0.9 mm *pm* 0.53 ACT; p > 0.05). Thus active demonstration trials did not provide information about the relationship between muscle activation and motor error.

Other complex movements. We were also interested to see if other movements might similarly be improved by passive guidance through the desired trajectory. To do this we tested a new task: cursive writing of the short proper noun "liz". This movement requires an even longer trajectory (3.5 s) and features a complex velocity profile and higher peak velocities than the circular movement tested in the first experiment (Figure 5.7).

Figure 5.8 shows CCI for two new groups of subjects (wPASS in blue and wCTRL in RED). Clear immediate improvements are observable for wPASS subjects, in contrast to wCTRL subjects. A mixed analysis of variance found a main effect of training (p < 0.001) and a weak interaction (p=0.073). Post-hoc tests showed that wPASS subjects improved relative to baseline on day 1 (p <0.05); while again wCTRL subjects did not show signifiant improvement relative to baseline until day 3. These results support the notion that passive presentation of desired movement provides a benefit for learning.

5.5   Discussion

We measured the effect of proprioceptive training on motor learning and found that passive presentation of the desired trajectory results in faster motor learning. Subjects who experienced passive proprioceptive demonstration trials showed an improved learning rate - these subjects were immediately better at the task on day one - and
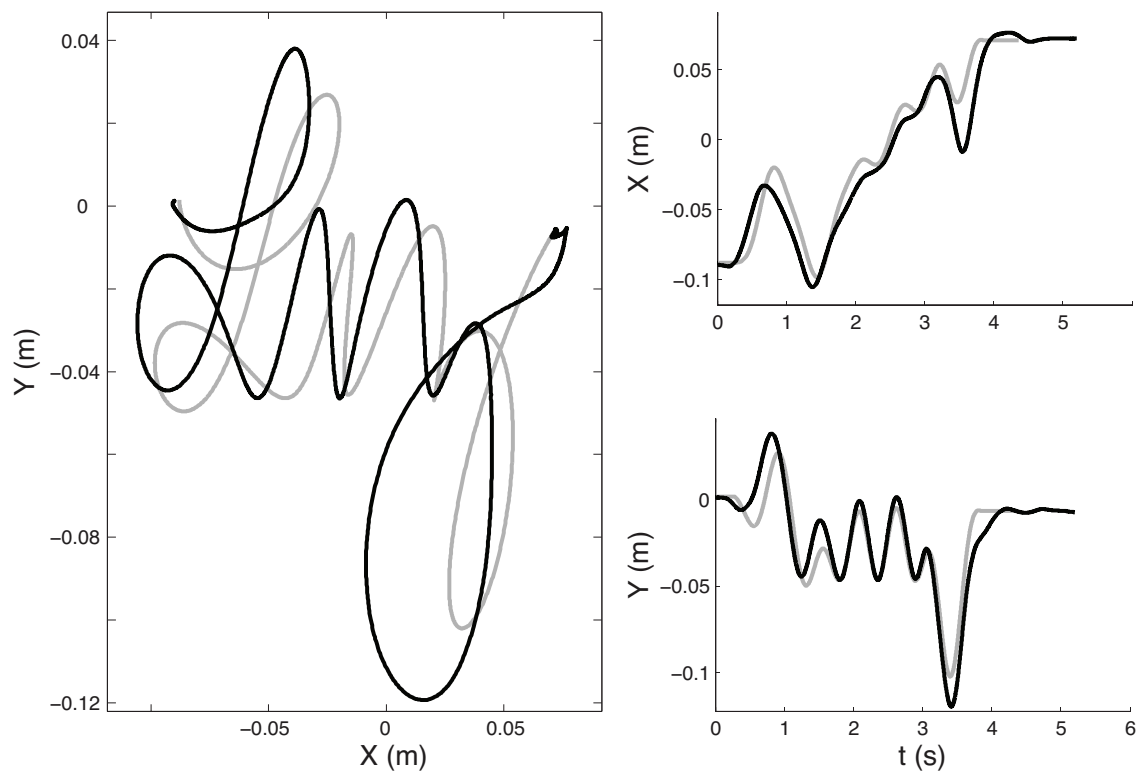
Figure 5.7: In this experiment subjects were required to copy the written proper noun Liz', shown from an overhead view (A), and x and y coordinates as functions of time (B and C). Desired (grey) and example (black) trial shown. One example subject, final baseline movement, is shown in black relative to desired movement, in grey.
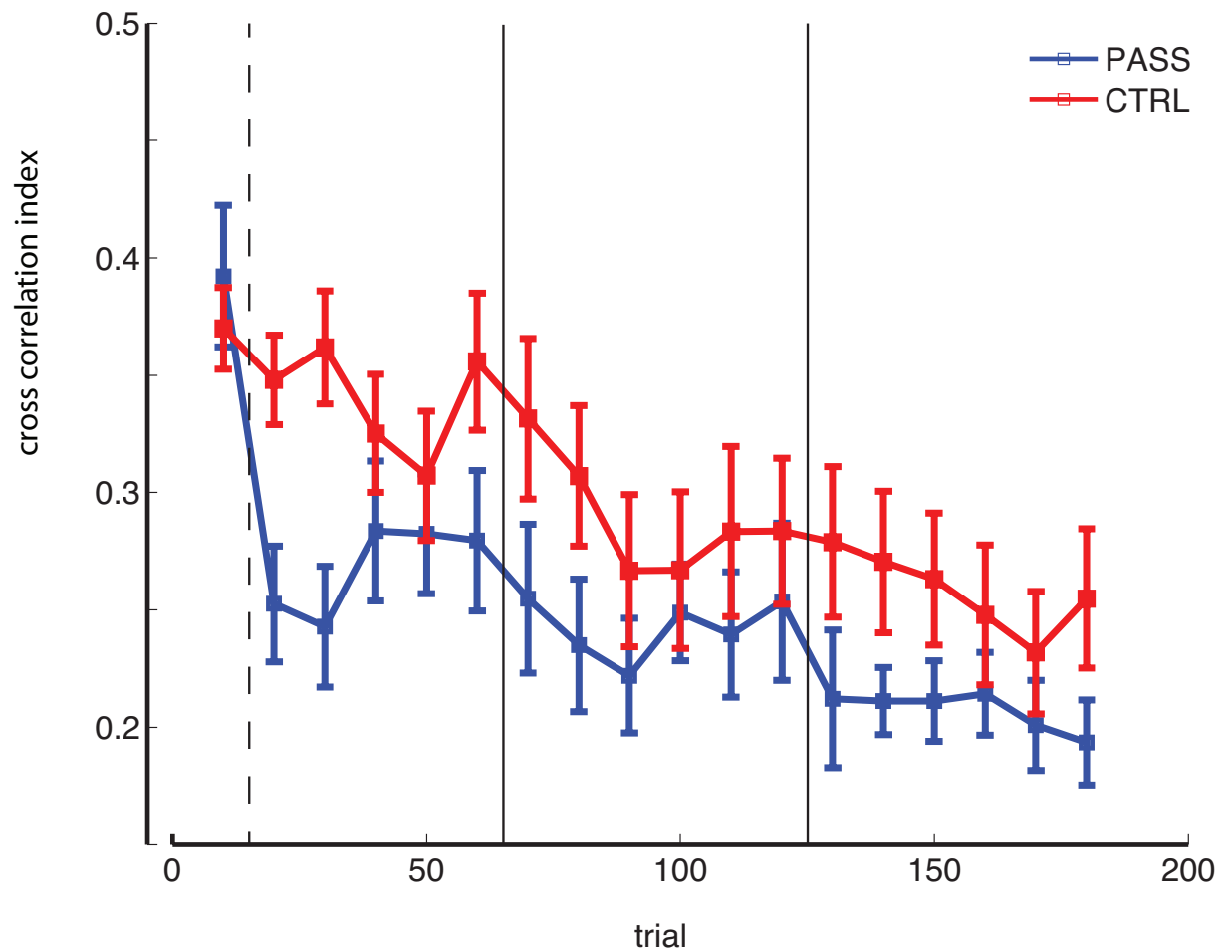
Figure 5.8: Cross correlation index of produced to desired hand position for subjects in the passive (blue) and control groups (red) on the cursive writing task, across the 3 training days.

maintained this improvement over the subsequent days. Control subjects did not show the same early improvements to CCI, velocity or position error. These data suggest that passive presentation of desired trajectories may be a useful method for augmenting motor learning. These improvements were not seen for control subjects who received passive demonstration of circles matched for speed but opposite in direction. Interestingly, we observed that proprioceptive presentation of desired movement in concert with active movement did not afford the same improvements to positional accuracy. This result suggests a specific role for purely passive proprioceptive demonstration in the improvement of positional accuracy during motor learning.

By providing new controls with a passive circle in the opposite direction, we attempted to determine whether the improvements to learning could be attributed to the movement trajectory itself. It might otherwise be argued that any arm motion would direct more attention to the arm. Similarly it might be argued that certain gross characteristics of movement - such as movement duration - are simply more salient during robot-guided proprioceptive demonstration trials. These reverse-circle control subjects received a matched range of joint motion, identical magnitude of hand velocity, and cognitive information about movement timing. Analysis of motor learning showed these subjects had delayed improvements to CCI similar to control subjects, and did not show the same improvements to purely positional accuracy. Since the learning benefits were not observed for these subjects, the results are consistent with the idea that the benefits to motor learning conferred by passive proprioceptive guidance can be attributed to the presentation of the trajectory itself.

The fact that speed and timing information was conferred from both passive and active demonstration trials better than for purely visual demonstration trials is con-

sistent with other experiments involving active haptic guidance (Feygin et al., 2002; Milot et al., 2010). Previous work involving active demonstration - movements with the aid of a robotic manipulandum - has also reported little or no benefits to positional accuracy (Robb and Pew, 1968; Armstrong, 1970; Bluteau et al., 2008; Feygin et al., 2002; Liu et al., 2006). While subjects in the current study performed 240 training movements, the length of training regime for motor learning has also varied significantly across previous experiments, ranging between 15 and 63 training movements, partly because the analysis of the effect of training type - haptic guidance and visual demonstration versus visual demonstration only - was performed within-subject. The current study also selected a task with considerably different kinematic parameters, with average velocity being more than 5 X that reported in the above studies. Given Fitts' law, this relatively high task difficulty may have provided greater likelihood for observing benefits to positional variability.

Previous studies have found that proprioception of remembered active movement is better than passive movement (Marteniuk, 1973), but only when the movement is self-defined and not externally determined (Stelmach et al., 1976). These results might speak to the current finding that positional error was reduced for PASS subjects and not ACT subjects. The previous literature might expect no benefit for active movement for movements are externally-defined, such as those in the current study.

Somatosensory afferent signals have been observed to be attenuated during movement (Brooke et al., 1997; Jones et al., 2001; Prochazka, 1989). Somatosensory evoked potentials have been shown to be gated during both active (Cohen and Starr, 1985, 1987) and passive (Staines et al., 1996) movement, and greater for movements (passive or active) with higher movement velocity (Rauch et al., 1985). It is therefore

interesting that despite these previous observations of down-regulated somatosensory signals, they clearly provide additional information to result in a motor learning benefit greater than the visual controls.

To determine the variability of subjects' application of force to the handle, we measured change in the force transducer signal across trials and observed active subjects having reliably greater variability. The recording of electromyographic signals during demonstration movements is another measure of arm activity, and would be a useful way of collecting such passive-subject data in the future explorations of proprioceptive training on motor learning. Additionally, while our data show that PASS subjects behaved differently than ACT subjects during demonstration trials, we cannot rule out the possibility that, against explicit provided instructions PASS subjects were not completely passive during demonstration trials and instead moving with the robot. If this is the case, it might be argued that PASS and ACT subjects are performing better than controls because they are receiving essentially extra practice. This does not however explain the benefits to positional error observed for passive subjects compared to ACT subjects.

In a recent study that examined movement adaptations within task-relevant vs irrelevant dimensions (Diedrichsen et al., 2010), it was observed that the motor system adjusts motor commands to replicate movement kinematics of previous trials, including subtle deviations caused by passive robotic guidance. The authors term such motor adaptations use-dependent, and discuss how such adaptations are restricted to task-irrelevant dimensions. It may be that a similar mechanism is at work in this study, although in the present study replication of the demonstrated circle is task-relevant given that it is the explicit goal for subjects.

The specific neurophysiological basis for the ability of passive movements to influence motor behaviour has not been determined. Recent studies have attempted to examine how afferents signalling muscle length are modulated depending on movement context. One recent study found that human spindle afferent signals may change based on movement context. Spindle reflexes from stabilizing ankle muscles show increased amplitude during quiet standing at an elevated ledge as compared to standing at ground height (Horslen et al., 2011). Since no changes in either H-reflex magnitude nor tonic muscle activation were observed, these data suggest that spindle sensitivity can be independently modulated in humans based on conditions of stress. These behavioral results support earlier findings of modulations to spindle afferent signals when subjects are required to actively attend passive joint rotation (Hospod et al., 2007). Taken together these results support the general notion that peripheral sensory signals may be modulated in a context specific manner. To our knowledge no studies have investigated the manner in which spindle behavior changes during the acquisition of a novel motor task.

The observed improvement in motor learning that results from passive proprioceptive demonstration is presumably based on changes in motor cortical regions. It may be that this results from direct cortico-cortico connections between proprioceptive and motor cortices, a network that has been shown to be altered during motor learning at short timescales (Vahdat et al., 2011). Other studies have reported rapid changes in motor cortical representations following motor practice (Classen et al., 1998; Pascual-Leone et al., 1995). As far as we know the present study is the first demonstration that passive proprioceptive training can result in reduced positional movement error during the learning of natural movements. Considerable research has been performed

on the benefits of haptic assistance in movement recovery in both clinical (for review see Marchal-Crespo and Reinkensmeyer, 2009; Lo et al., 2010) and healthy subpopulations (for review see Reinkensmeyer and Patton, 2009; Marchal-Crespo et al., 2010), where most often a robot is used to assist active movement. The current study may contribute to this growing body of research by detailing the specific benefits of passive sensory training for motor learning.

5.6   Acknowledgments

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Chapter 6

General Discussion

This thesis has presented a series of empirical studies aimed at exploring the relationship between sensory and motor systems during motor learning. In particular we have explored the manner of and extent to which proprioception can be modulated based on particular kinds of motor learning. We have also begun to explore a relatively untested area of proprioceptive training, specifically the ability of proprioceptive information about desired trajectories to affect the rate and magnitude of motor learning. Taken together, the results support the hypothesis that motor learning and proprioception are linked: sensory information about hand position is systematically modulated by motor learning, and proprioception of desired movement results in modulated motor learning.

In **Chapter Two** it was demonstrated that subjects who learned to adapt reaching movements in the presence of an external directional load also demonstrated changes to the perceived position of their hand. Perceptual change was linked specifically to active movement, since such perceptual changes were absent in control subjects who passively gripped the handle as the robot guided their hand through the movements made by experimental subjects. The persistence of this perceptual shift is durable for 24 hours, and occurs both for hand perception in dynamics and statics, and therefore not simply specific to reaching movements. This finding reports a new relationship between novel motor commands for environment dynamics and altered proprioception.

Chapter Three assessed proprioceptive changes in the context of a reaching accuracy task. It was shown that proprioceptive acuity is significantly improved after subjects have learned to generate reaching movements with greater precision. The spatial generalization of perceptual change was shown to be local in nature;

at locations 25 cm away from the motor training location, proprioception of the learned hand was unaffected. We also tested if passive sensory experience alone, in the absence of active movement, could be shown to cause perceptual changes. Here we observed no such change for passive subjects, suggesting that sensory experience is not sufficient to cause improvement in proprioceptive acuity. Finally, we tested whether *learning* itself was necessary for acuity improvements: subjects who performed active movements in the absence of learning also did not show improvements to perceptual acuity. Proprioceptive acuity therefore is tuned with motor learning in very specific ways that depend on a number of contextual aspects of motor learning.

In **Chapter Four** we investigated the ability of changes to perceptual acuity to persist following motor learning. We observed that proprioceptive acuity changes persist even in the absence of additional motor training at a time interval 24 hours later, following one normal sleep cycle. These findings parallel previous results showing retention (and even improvement) of motor learning and support the notion that sensory changes are not ephemeral but rather persist to a degree similar to learned novel motor commands.

In **Chapter Five** we investigated if proprioceptive information about desired trajectories could improve motor learning. We found that by passively guiding the hand through the desired trajectory on demonstration trials interleaved with training trials, subjects showed an increased rate at which subjects learned arm movements, when compared to control subjects who only received visual information about the desired movement. This learning benefit was most salient in producing desired movement velocity, but decreases in overall position error were also observed. While previous work has shown some benefit to movement velocity, the observation of positional er-

ror reduction has not to our knowledge been observed. Finally, subjects who received active guidance during demonstration trials - trials in which the robot and subject together moved the handle - did not show decreases in positional movement error. These results suggest a unique role for passive proprioceptive information as a tool for augmenting motor learning.

The most important contribution of this set of studies is the further elucidation of the coupled nature of proprioception and motor learning. By identifying systematic sensory changes with motor learning, this work contributes to a relatively new line of research about the sensory aspects of learning novel motor commands.

6.1 Sensorimotor control

Our results show that motor learning results in changes to proprioception that manifest on a behavioural level. These results are consistent with the idea that sensory changes during motor learning are both specific and efficient. First, sensory changes were specific to the type of motor learning in the sense that motor learning for external and directional loads resulted in perceptual biases, while motor learning to acquire greater precision resulted in improved proprioceptive acuity.

Second, there is some evidence that such changes are efficient. Tuning proprioception of hand position occurred only following a motor learning task requiring accurate movement, and specifically for particular *locations* of the hand in the workspace. These data are consistent with the idea that sensory representations are highly movement dependent.

A natural question that follows concerns the direction of causality in this relation-

ship. Does motor learning cause perceptual change, or does perceptual change play a role in motor learning? At this point we can only observe that sensory and motor processes occur together. However it may be that both systems develop in concert and are in fact mutually dependent. It might be speculated that motor learning is in fact a sensorimotor process whereby motor learning results in perceptual changes, while these same perceptual changes mediate further changes to motor commands.

Recently, new data has shed light on the hypothesis that proprioception and motor learning are systematically linked. In Vahdat et al. (2011), both motor learning and perceptual change were measured for subjects who adapted to a directional force-field. A within-subjects analysis of both perceptual and motor changes showed that the ability of subjects to learn novel motor commands was correlated with the magnitude of perceptual shift. The authors measured the magnitude of hand deviation produced at the end of learning force-field A, and compared it with deviation made subsequently during the initial learning of a novel force-field B which applied forces exactly opposite to those of force-field A. It is therefore predicted that subjects who best learn force field A will be worst during the learning of field B, since the experience of two opposing force-fields has previously resulted in considerable interference (Caithness et al., 2004; Cothros et al., 2006, 2008). Indeed, the performance on field B was found to be linearly related to the magnitude of a given subject's perceptual shift. The technique used to identify this effect was to provide subjects with an additional final motor learning task in a novel interfering force-field. By measuring motor adaptation in an interference paradigm the authors measured differences between adapted behaviour and subsequent interference, and thus recorded deviations with greater dynamic range than those measured during a single adaptation paradigm. It therefore may be that

this experimental technique was more sensitive and necessary for the detection of within-subject correlation between motor learning and proprioceptive change.

6.2   Interpreting proprioceptive bias

What is the meaning of a perceptual bias in proprioception? Proprioceptive bias is most simply interpreted as the location at which the hand is most likely to be perceived. However, proprioceptive bias was determined in the context of psychophysical estimates that complicate such straightforward interpretation. In Chapter Two, proprioception was measured in two ways. In one method, proprioception was measured during active movement in which the left-right position of the hand was commanded to a desired position using a robotic manipulandum during active movement. Subjects were asked to answer the question "was your hand pushed to the right?" The second method was a static measure of proprioception, and required subjects to compare the non-moving position of their right hand with that of their left index finger. The left index finger was fixed 0.5 cm to the left of the (passively) moving right hand, and subjects were asked to report whether their hand was toward or away from their body.

It might be argued that if proprioception of hand position is altered from motor learning, then both *current* proprioception, but also the *reference* position (perceived straight movement), should be affected by motor learning. Given that we measure a difference between baseline and post-learning proprioception, under this interpretation is its clear that perceived and remembered positions would have to be affected differently. It is not clear why this would be true (why would a remembered posi-

tion be less affected by motor learning of the force-field?) which perhaps places the interpretation of bias into question.

In the case of psychophysical estimates using a static contralateral anatomical reference (such as the technique included in Chapter Two), there is no computed or remembered reference position. However the existence of interhemispheric transfer of motor learning (Malfait and Ostry, 2004) means that there is the possibility that perceptual changes also have transferred to the right arm. Since studies of inter-hemispheric transfer of learning have observed motor transfer to the untrained limb occurs in *the same direction* as the trained limb, we might hypothesize that any sensory transfer to the untrained arm will also occur in the same direction. It may then be concluded that if sensory transfer does occur, it would lead to an underreporting of bias shift. In fact, in an unpublished control study we attempted to assess the extent to which interhemispheric transfer occurred in our study. We measured reaching movements made with the untrained left arm (the arm that undergoes no motor learning of the force-field) both before and immediately following motor learning of the right arm. To quantify the magnitude of transfer to the left hand we compared the perpendicular deviation (PD) of the transfer movements made by the left arm to the final catch trial (single, randomly interleaved trials during learning where the force is turned off) made by the trained right arm at the end of the training period. We observed that the first transfer after-effect trial is roughly half the size of the end learning (though not statistically different from baseline; p > 0.05). Visually, no suggestion of motor transfer exists after the second transfer trial. Because the transfer trial PD is both modest in size, and is very transient, the degree of interlimb transfer appears to be small (and as noted above only reduce the magnitude of measured
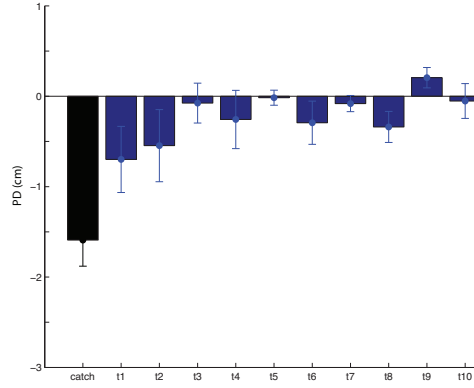
Figure 6.1: Evidence that some transfer of motor learning to the contralateral arm may exist.

perceptual changes).

Most generally, it might be argued that proprioceptive bias in fact does not reflect the comparison of two positions of the hand, but rather of applied force on, or even movement velocity of, the hand. Since hand velocity and force at the hand will necessarily occur during proprioceptive estimations, and moreover vary together in stimuli presentation, determining whether either of these parameters affects or determines psychophysical estimates of proprioception is challenging. In any case, the magnitude of the proprioceptive change is similar in judgment tasks used here in Chapters Two and Three, and also in previous work (Wilson et al., 2010; Fuentes and Bastian, 2010), which is consistent with the hypothesis that these quite different psychophysical tests, each with distinct potential issues, are estimating similar quantities.

6.3 What is the anatomical basis for motor learning and proprioceptive change?

The underlying anatomical basis for the observed proprioceptive changes has not been conclusively identified. Both peripheral and central mechanisms may play a role (and are not necessarily mutually-exclusive). Studies of the peripheral system show that afferent signals returning to the spinal cord can be altered based on attentional demands (Hospod et al., 2007) or a stressful movement context (Davis et al., 2011; Horslen et al., 2011). These experiments have not examined psychophysical acuity or bias, and as such do not directly address the anatomical nature of the current results. Davis et al. (2011) failed to find evidence of changes in cortical excitability in either somatosensory evoked potentials or tendon-tap evoked potentials during a posture maintenance task under a condition of increased stress (standing at the edge of a platform, suspended 3 m from the floor), evidence that contextual modulation of sensory signals need not be modulated via descending cortical signals. To explain the increased spindle afferent signals, both gamma-motor drive to muscle spindles in the leg (Prochazka et al., 1976) and also autonomic connections to muscle spindles, anatomically identified in cats (Barker and Saito, 1981), have been proposed. Interestingly, increased stretch-reflex amplitude in soleus muscle has been observed during mental arithmetic (Hjortskov et al., 2005), and has been similarly interpreted to be caused by autonomic components of segmental reflexes. Direct study of the psychophysics of proprioception under arousal-induced increases in spindle afferent signalling has not been performed, to our knowledge. Additionally, neither of these contexts specifically address perceptual change with motor learning.

Given the considerable evidence in monkey paradigms of modulations to the neural representations of tactile somatosensory cortex (Recanzone et al., 1992b,a; Xerri et al., 1999), at least under longer-term conditions requiring extensive sensorimotor training, it may be that our observed changes to human proprioception are mediated by similar mechanisms. Recently a study has replicated the main elements of Chapter Two and in addition investigated changes to functional connectivity in somatosensory areas (Vahdat et al., 2011). Resting-state fMRI scans were taken on each of two days, 1 h following arm movements (either in a null-field or during motor learning of a novel force-field as in Chapter Two) and psychophysical testing. Changes in perceptual function and motor learning were associated with changes in functional connectivity. First, Connections between Somatosensory Area II (SII) and frontal motor areas Premotor ventral area (PMv) and Supplementary Motor Area (SMA) were most strongly related to perceptual change. It has been previously observed that activity in PMv is correlated with activity in somatosensory cortex during voluntary movement without proprioceptive feedback (Christensen et al., 2007). SMA has been observed to be involved in perceptual learning (Romo et al., 2002; de Lafuente and Romo, 2006). Changes to connectivity were also observed to occur between anterior cerebellar cortex and clusters in the superior parietal lobule, and these connectivity changes were dependent equally on both motor and sensory change. These findings perhaps relate to recent studies showing a link between the cerebellum and posterior parietal cortex, where a role for this brain region in perceptual processing has been hypothesized (Strick et al., 2009).

6.4 Proprioception of desired trajectories improves motor learning: testing optimal control

Learning by visual observation of the actions of others (Mattar and Gribble, 2005) is perhaps behaviourally unsurprising. The idea has recently received anatomical basis by virtue of the discovery of the mirror neuron system (Gallese et al., 1996), a relatively new and powerful topic in neuroscience. The fact that some neurons in the primate brain are active both when doing and perceiving an action suggests a way for complex animals (including perhaps even the early studies of feline behaviour (John et al., 1968)) to rapidly acquire new movement, possibly expediting such a process occurring in isolation. The suggestive claim in Mattar and Gribble (2005) is that the mirror-neuron system's ability to learn about observed movement includes not only observed kinematics but also perhaps extends to include the relatively subtle perception of and subsequent adaptation for observed external environmental forces.

In contrast, the observed mechanism in Chapter Five of *proprioceptive* learning by observing is not supported by similar underlying neural circuitry, and seems hardly an ethological method by which motor learning is augmented; there is no natural mechanism (beyond the overzealous golfing instructor) by which animals may attempt to learn movements by being guided through desired trajectories. Thus, it might be pointed out that while proprioceptive learning by observation has theoretical benefits in a therapeutic context, it is very limited in its ability to inform us about the process of how motor learning occurs in the real system.

Here I propose that the ability of proprioceptive learning to cause improvements in performance may in fact address how the brain chooses motor commands for a

given task, and may be used to test a current influential hypothesis in motor control concerning the selection of motor commands.

Despite the fact that motor tasks are typically over-determined - meaning that there are often many ways of solving a given movement task - the brain seems not to choose randomly among this infinite set of solutions, but rather exhibits a stereotyped set of preferred movements. The principles that determine this preferred set are still largely unknown, and remain of interest in part because such solutions are very good: biological control continues (as of 2012) to outperform the work of engineers and roboticists. Perhaps as a result of the motor system's relative success, a current popular hypothesis proposes that the nervous system chooses these movements because they are optimal in some way. This hypothesis is quite prevalent (Todorov and Jordan, 2002; Nagengast et al., 2010; Ronsse et al., 2010; Scott, 2004; Diedrichsen et al., 2010b). These approaches have employed implementations of often mathematically complex algorithms for optimizing constrained multivariate cost (or *objective*) functions to achieve such solutions, and such studies (implicitly or explicitly) imply that the motor system is doing some computationally-equivalent calculation to arrive at motor commands. It is challenging to test this hypothesis directly, since it is always true that a movement can be considered optimal if a cost function is selectively chosen. Therefore, over the long term, the value of this hypothesis to motor control research is directly related to the cardinality of this set of cost functions. A theory of motor control proposing that the motor system picks a cost function to fit the task and subsequently finds the optimal solution to *any such* function is not a scientific hypothesis.

One use of proprioceptive learning by observing in motor control research might

therefore simply apply proprioceptive learning by observing to augment current motor performance. If it can be shown that the human motor system left on its own during learning (and therefore during its own hypothesized process of optimization) arrives at asymptotic behaviour that can still be further improved with an intervention of proprioceptive training, then these data would challenge the notion that such optimization occurs. Such results would also perhaps be consistent with a simpler hypothesis about how control signals are altered during motor learning.

It may therefore be that a significant principle used to select motor commands is simply to generate movements that achieve previously experienced afferent signals. This hypothesis has recently received some interest in the motor control literature and highlights the empirical fact that motor commands can be significantly affected by previous sensory experience. In a recent study, Diedrichsen et al. (2010a) provided subtle and gradual external perturbing forces at the hand that did not compromise task success (reaching movements to a wide target). After numerous such reaches, the robot was turned off: yet subjects made curved movements as previously performed. This conclusively shows that so-called *use-dependent* learning results in motor commands that reproduce sensory experiences, at least when such sensory experiences are task-irrelevant (i.e. in this case, they did not compromise reach success). Expanding this concept of use-dependent learning to motor-relevant dimensions in large task-spaces (such as athletic movements) may be a useful area of study, and our results in Chapter Five represent one step in this direction.

6.5   Further studies: proprioceptive bias

One interesting observed phenomenon in reaching movements has resulted in an apparent paradox noted previously in Chapter One. Brown (2003) investigated reaching movements made in a horizontal plane, in the absence of vision of the limb, but between two visible targets. Point-to-point reaches proceeded to drift from the initial aligned positions, unbeknownst to subject; after two minutes of reaching (75 trials), the new movements were in some cases 10 cm away from initial movements. Notably, movements were preserved in several respects: subjects maintained reach direction and reach magnitude, and therefore in Cartesian space movements were simply translated by several cm (offset leftward, toward the midline of the body, incidentally). The paradox results from the fact that the motor system must simultaneously both know and not know about reach errors. In one sense it is clear the motor system does *not know* about reaching errors since they continue to be made, uncorrected. In another sense, the motor system must *know* the arm is in a different location, to be generating such parallel reaches. This latter point is true from inverse dynamics: joint torques needed to generate these new reaches are necessarily different than those made initially. Indeed, in simulations using a torque-driven arm, if subjects had utilized the same motor command at the translated position, errors from between 10 and 30 degrees would have been resulted.

An interesting hypothesis that we would like to test is that movement commands are in fact constant throughout blind reaching movements. We might test this hypothesis in an interesting way by utilizing more realistic actuators - Hill-type muscle models - than the torque motors used in the analysis of the above study. In the former study inverse dynamics calculations were performed to calculate required joint

torques for observed kinematics. However in the real system joint torques are the result of muscle forces which follow activation dynamics and spring-like behaviour of muscle and tendon. In a number of previous studies it has been shown that realistic muscle properties result in substantially different behaviour than that observed using simpler models. A particular example for this difference occurs in ballistic jumping movements of the lower extremity, where a high degree of sensitivity to small changes in initial jump position has been observed if torque-motors are used. In contrast to this sensitivity is the relative robustness to initial positions observed for muscle-actuated systems (Soest et al., 1994). It has also been shown that such muscle properties in fact make it possible for simple motor commands to effectively move the arm between endpoints where simpler models fail (Gribble et al., 1998; Kistemaker et al., 2006). Therefore, a reconsideration of the above proprioceptive drift experiment would involve calculating muscle stimulation patterns to move between two targets, and utilize that command for a new movement starting at a position translated 10 cm away, thereby matching the final orientations found in the above study. If it can be shown that motor commands to more realistic muscles result in constant-magnitude, parallel movements, it would right away show something very interesting - the motor system need not recompute motor commands to result in parallel, constant-length movement.

Such a hypothetical demonstration would go part of the way to explaining the result: still unexplained is the fact that subjects continually change the endpoint of reaching movements throughout no-vision movements, such that movements drift considerably leftward over time. Interestingly, a recent study observed proprioceptive sensitivity that might help account for this observation. In Wilson et al. (2010) it

was observed that right-hand biases in proprioception were similar across-subjects - subjects were more likely to perceive their hand to be to the right. This misperception of hand position would in fact result in subjects shifting their reach endpoints left of previous visual targets. Taken together, the combination of constant motor commands and misperception of hand position might parsimoniously explain the paradoxical observations.

6.6 Further studies: testing a peripheral model for sensory prediction

Muscle spindles, sensory neurons mechanically situated in parallel with the muscle fibres, are thought to play a central role in signalling the state of a muscle fibre. Historically it has been proposed that these sensors encode muscle length and its velocity (Cooper, 1961). However, despite this hypothesized role, the nature of spindle afferent signal coding remains unclear: at rest, spindle signals are correlated with muscle length, velocity, acceleration and force (Vallbo, 1970); during movement, the function of spindle afferents may be modulated by efferent cortical signals (Kuffler et al., 1951; Hospod et al., 2007). Recent studies have proposed a new interpretation: spindles encode a prediction of muscle velocity, 100-160 ms into the future (Dimitriou and Edin, 2010). These results identify an important new direction of research in motor control: how does the brain learn the appropriate efferent signals to not only control movement, but also modulate the function of sensors such as spindles, to allow accurate prediction of upcoming movement?

The interpretation of how spindle afferents encode movement parameters critically

depends on the details of the musculoskeletal system accounted for in a given analysis. Surprisingly, a number of key aspects of the system have traditionally been excluded. For example, in Dimitriou and Edin (2010), spindle afferents were regressed onto muscle lengths that were not measured directly, but were inferred by an unrealistically simple model of muscle in which length is a static function of joint angle. Excluded entirely were muscle tendons, the tissue connecting both the work-performing muscle fibre and sensory spindle to the skeleton. Tendons behave as passive, nonlinear springs and eliminate the possibility of the assumed one-to-one relationship between joint angle and muscle length. Given the crucial role tendons play in the interpretation of motor control (Soest et al., 1994; Bobbert et al., 2006; Kistemaker et al., 2006), they may prove essential to understanding sensory function. Therefore, properly testing the idea that spindle afferents signal a prediction of future muscle state requires development of appropriate models incorporating this (and other) complexity.

In subsequent research, we would like to extend our currently-existing musculoskeletal modelling techniques in an attempt to directly test hypotheses, both traditional (Cooper, 1961) and novel (Dimitriou and Edin, 2010) about spindle encoding in the context of a realistic muscle model. The model would include a forearm, wrist, finger, and associated single and multi-joint muscle-tendon complexes. Simulations of finger movements reported in various empirical studies (Dimitriou and Edin, 2008a,b) would be carried out to provide a complete picture of muscle behaviour. By re-examining the relationship between joint angle, muscle fibre length and predicted spindle afferents, we would be able to directly test hypotheses about what features of movement may be encoded in spindle afferent signals. We would attempt to attribute proportions of the phase lag observed between joint angle and muscle length to com-

ponents that result from simple muscle dynamics, and consider the possibility that remaining phase advances of the position signal that do in fact result from predictive sensory behaviour.

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Chapter 7

Ethics approval

Research Participation System *Revised* F1LE

Study Information

Your study has been set up on the Research Participation system with the information listed. *(ADD TO*
If you need to make any corrections, please send them to Helen Harris as soon as possible. *# 071006)*

|	
Exp. ID:	071006
Password:	8KL6
Experimenter:	Wong
E-mail:	
Status:	G
Title:	Robot Experiment: Movement and Perception
Description:	In this experiment, participants are instructed to guide a cursor to targets while grasping a robot arm. Occasionally, the robot arm will move the arm, and subjects will be asked to report the location of their unseen hand. Completion of the experiment requires approximately 1 hour and 15 minutes and participants will each receive 1.5 research credits. PARTICIPANTS CANNOT HAVE PARTICIPATED IN EXPERIMENT #071007 "ROBOT EXPERIMENT: MAPPING PROPRIOCEPTION IN A WORKSPACE"
Credit Min:	1 **Credit Max:** 1.5
Gender:	Male and Female
Information:	PARTICIPANTS CANNOT HAVE PARTICIPATED IN EXPERIMENT #071007 "ROBOT EXPERIMENT: MAPPING PROPRIOCEPTION IN A WORKSPACE"
Alloted Hours:	80

You can also review this information on the web based RP System at:

http://psyclone2.ssc.uwo.ca/intropsy/index.html

1) Log into the Research Participation (RP) system by clicking on the "Researcher Login" button and using the Experiment ID# and password listed above.

2) You will have five options to choose from as you see below:

    i) View Experiment Information
       -This is the information that students see when they sign up for an experiment.
It includes most of the information that is listed above.

    ii) View Schedule
       - From this screen you can view all the appointments you have booked, you can cancel appointments for which no one has signed up, and you can assign students credit or penalty for attendance.

    iii) Add New Appointment Times

    iv) Book Appointment
       - Book another appointment if your study requires a follow-up appointment.

    v) Logoff
       - Closing your browser when you are finished will also log you off.

3) You should first check the "View Experiment Information" link to make sure the information is accurate. It should match the information on this sheet.
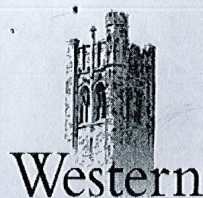
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Use of Human Subjects - Ethics Approval Notice

Review Number	08 10 12	Approval Date	08 10 09
Principal Investigator	Paul Gribble/Jeremy Wong	End Date	09 04 30
Protocol Title	Robot experiment: Movement and perception		
Sponsor	n/a		

This is to notify you that The University of Western Ontario Department of Psychology Research Ethics Board (PREB) has granted expedited ethics approval to the above named research study on the date noted above.

The PREB is a sub-REB of The University of Western Ontario's Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB) which is organized and operates according to the Tri-Council Policy Statement and the applicable laws and regulations of Ontario. (See Office of Research Ethics web site: http://www.uwo.ca/research/ethics/)

This approval shall remain valid until end date noted above assuming timely and acceptable responses to the University's periodic requests for surveillance and monitoring information.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the PREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of research assistant, telephone number etc). Subjects must receive a copy of the information/consent documentation.

Investigators must promptly also report to the PREB:
a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) all adverse and unexpected experiences or events that are both serious and unexpected;
c) new information that may adversely affect the safety of the subjects or the conduct of the study.

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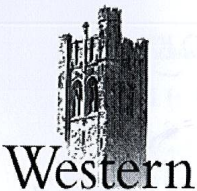
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Chair, Psychology Expedited Research Ethics Board (PREB)

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Principal Investigator	Paul Gribble/Jeremy Wong	End Date	11 04 30
Protocol Title	Robot experiment: Movement and perception		
Sponsor	n/a		

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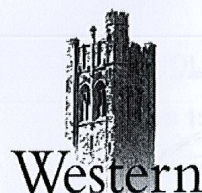
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Use of Human Subjects - Ethics Approval Notice

Review Number	10 09 25	**Approval Date**	10 09 30
Principal Investigator	Paul Gribble/Jeremy Wong	**Completion Date**	11 04 30
Protocol Title	Robot experiment: Movement and perception 2		
Sponsor	n/a		

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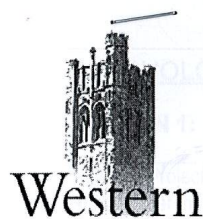
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Use of Human Subjects - Ethics Approval Notice

Review Number	11 10 03	**Approval Date**	11 10 07
Principal Investigator	Paul Gribble/Jeremy Wong	**End Date**	12 04 30
Protocol Title	Movement and perception		
Sponsor	n/a		

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Members of the PREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the PREB.

Clive Seligman Ph.D.

Chair, Psychology Expedited Research Ethics Board (PREB)

The other members of the 2011-2012 PREB are: Mike Atkinson (Introductory Psychology Coordinator), Rick Goffin, Riley Hinson Albert Katz (Department Chair), Steve Lupker, and TBA (Graduate Student Representative)

CC: UWO Office of Research Ethics

This is an official document. Please retain the original in your files

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Western

Use of Human Subjects - Ethics Approval Notice

Review Number	11 10 04	Approval Date	11 10 07
Principal Investigator	Paul Gribble/Jeremy Wong	End Date	12 04 30
Protocol Title	Movement and perception 2		
Sponsor	n/a		

This is to notify you that The University of Western Ontario Department of Psychology Research Ethics Board (PREB) has granted expedited ethics approval to the above named research study on the date noted above.

The PREB is a sub-REB of The University of Western Ontario's Research Ethics Board for Non-Medical Research Involving Human Subjects (NMREB) which is organized and operates according to the Tri-Council Policy Statement and the applicable laws and regulations of Ontario. (See Office of Research Ethics web site: http://www.uwo.ca/research/ethics/)

This approval shall remain valid until end date noted above assuming timely and acceptable responses to the University's periodic requests for surveillance and monitoring information.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the PREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of research assistant, telephone number etc). Subjects must receive a copy of the information/consent documentation.

Investigators must promptly also report to the PREB:
a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
b) all adverse and unexpected experiences or events that are both serious and unexpected;
c) new information that may adversely affect the safety of the subjects or the conduct of the study.

If these changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the newly revised information/consent documentation, and/or advertisement, must be submitted to the PREB for approval.

Members of the PREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the PREB.

Clive Seligman Ph.D.

Chair, Psychology Expedited Research Ethics Board (PREB)

The other members of the 2011-2012 PREB are: Mike Atkinson (Introductory Psychology Coordinator), Rick Goffin, Riley Hinson Albert Katz (Department Chair), Steve Lupker, and TBA (Graduate Student Representative)

Office of Research Ethics

The University of Western Ontario
Room 00045 Dental Sciences Building, London, ON, Canada N6A 5C1
Telephone: (519) 661-3036 Fax: (519) 850-2466 Email: ethics@uwo.ca
Website: www.uwo.ca/research/ethics

Use of Human Subjects - Ethics Approval Notice

Principal Investigator: Dr. P.L. Gribble	
Review Number: 13254E	**Review Level:** Expedited
Review Date: May 02, 2007	

Protocol Title: Cognitive and Sensory Basis of Motor Learning
Department and Institution: Psychology, University of Western Ontario
Sponsor: NSERC-NATURAL SCIENCES ENGINEERING RSRCH COU
Ethics Approval Date: May 10, 2007 **Expiry Date:** March 31, 2012
Documents Reviewed and Approved: UWO Protocol, Letter of Information, Consent and Debriefing Form. Advertisement/Announcement.

Documents Received for Information:

This is to notify you that The University of Western Ontario Research Ethics Board for Health Sciences Research Involving Human Subjects (HSREB) which is organized and operates according to the Tri-Council Policy Statement: Ethical Conduct of Research Involving Humans and the Health Canada/ICH Good Clinical Practice Practices: Consolidated Guidelines; and the applicable laws and regulations of Ontario has reviewed and granted approval to the above referenced study on the approval date noted above. The membership of this REB also complies with the membership requirements for REB's as defined in Division 5 of the Food and Drug Regulations.

The ethics approval for this study shall remain valid until the expiry date noted above assuming timely and acceptable responses to the HSREB's periodic requests for surveillance and monitoring information. If you require an updated approval notice prior to that time you must request it using the UWO Updated Approval Request Form.

During the course of the research, no deviations from, or changes to, the protocol or consent form may be initiated without prior written approval from the HSREB except when necessary to eliminate immediate hazards to the subject or when the change(s) involve only logistical or administrative aspects of the study (e.g. change of monitor, telephone number). Expedited review of minor change(s) in ongoing studies will be considered. Subjects must receive a copy of the signed information/consent documentation.

Investigators must promptly also report to the HSREB:
  a) changes increasing the risk to the participant(s) and/or affecting significantly the conduct of the study;
  b) all adverse and unexpected experiences or events that are both serious and unexpected;
  c) new information that may adversely affect the safety of the subjects or the conduct of the study.

If these changes/adverse events require a change to the information/consent documentation, and/or recruitment advertisement, the newly revised information/consent documentation, and/or advertisement, must be submitted to this office for approval.

Members of the HSREB who are named as investigators in research studies, or declare a conflict of interest, do not participate in discussion related to, nor vote on, such studies when they are presented to the HSREB.

Chair of HSREB: Dr. John W. McDonald
Deputy Chair: Susan Hoddinott

Ethics Officer to Contact for Further Information		
☐ Jennifer McEwen (jmcewen4@uwo.ca)	☒ Denise Grafton (dgrafton@uwo.ca)	☐ Ethics Officer (ethics@uwo.ca)

cc: ORE File

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Chapter 8

Vita

Name

Jeremy D. Wong

Post-secondary education and degrees

Western University, London ON 2005-2007 M.Sc.

Western University, London ON 2001-2005 B.M.Sc.

Honours and Awards

Frederick Banting and Charles Best CGS Doctoral Research award 2009-2012

Ontario Graduate Scholarship, 2009-2011 (declined)

Western Graduate Research Scholarship, 2005-2011

Western Honour Roll, 2002-3,2003-4

Publications

Wong JD, Wilson ET, Gribble PL (2011). Spatially selective enhancement of proprioceptive acuity following motor learning. Journal of Neurophysiology.

105(5): 2512-21

Kistemaker DA, Wong JD, Gribble PL (2010). The central nervous system does not minimize energy cost in arm movements. Journal of Neurophysiology. 104(6): 2985-94

Wilson ET, Wong J, Gribble PL (2010). Mapping proprioception across a 2D horizontal workspace. PLoS One. Jul 29; 5(7): e11851

Ostry DJ, Darainy M, Mattar AA, Wong J, Gribble PL (2010). Somatosensory plasticity and motor learning. Journal of Neuroscience. 14; 30(15):5384-93.

Cothros N, Wong J, Gribble PL (2009). Visual cues signaling object grasp reduce interference in motor learning. Journal of Neurophysiology. 102(4): 2112-20.

Wong J, Wilson ET, Malfait N, Gribble PL (2009). Limb stiffness is modulated with spatial accuracy requirements during movement in the absence of destabilizing forces. Journal of Neurophysiology 101(3): 1542-9.

Wong, J, Wilson ET, Malfait N, Gribble, PL (2009). The role of vision in limb stiffness control. Journal of Neurophysiology 101(1): 246-57.

Cothros N, Wong, JD, Gribble, PL (2007). Distinct Haptic Cues Do Not Re-

duce Interference When Learning to Reach in Multiple Force Fields. PLoSOne
3(4): e1990.

Cothros N, Wong, JD, Gribble, PL (2006). Are there Distinct Neural Represen-
tations of Object and Limb Dynamics? Experimental Brain Research 173(4):
689-97.

Presentations as a guest speaker

Wong JD, Kistemaker DA, Gribble PL (2011). Can proprioceptive training im-
prove motor learning of complex movements? Poster presented at the Society
for Neuroscience 41st annual meeting, 2011, Washington DC.

Kistemaker DA, Wong JD, Gribble PL (2011). Testing Predictions of Opti-
mal Control Models of Arm Movement. Poster presented at the 22nd Neural
Control of Movement conference, San Juan, Puerto Rico.

Kistemaker DA, Wong JD, Gribble PL (2010). The CNS does not minimize
energy cost in arm movements. Poster presented at the 21st Neural Control of
Movement conference, Naples, FL.

Kistemaker DA, Wong JD, Gribble PL (2010). The Central Nervous System
does not minimize energy cost in arm movements. Poster presented at the 40th
meeting of the Society for Neuroscience 2010, San Diego, CA.

Wong JD, Darainy M, Mattar AAG, Ostry DJ, Gribble PL (2009). Bias in

proprioception changes with dynamics learning. Poster presented at the Society for Neuroscience 39th annual meeting, Washington DC.

Kistemaker DA, Wong JD, Gribble PL (2009). Energy optimization in reaching Movements. Oral Presentation at the Proceedings of the XXIIth Congress of the International Society of Biomechanics, Cape Town, South Africa.

Wong JD, Wilson ET, Gribble PL (2008). Tuning proprioception with movement training. Poster presented at the Society for Neuroscience 38th annual meeting, Washington DC.

Wilson ET, Wong JD, Gribble PL (2008). Workspace-dependent differences in proprioception of the human arm. Poster presented at the annual meeting of the Society for Neuroscience, Washington, DC.

Wilson ET, Wong JD, Gribble PL (2008). Mapping proprioceptive sensitivity across a 2D workspace. Poster presented at the annual meeting of the Society for the Neural Control of Movement, Naples, FL.

Wong JD, Wilson ET, Gribble PL (2008). Movement effects on Proprioception. Poster presented at the Computational and Systems Neuroscience 5th annual meeting, Salt Lake City, UT.

Wong JD, Wilson ET, Malfait N, Gribble PL (2007). Visual and Proprio-

ceptive Determinants of Stiffness Control. Poster presented at the Society for Neuroscience 37th annual meeting, San Diego, CA.

Wong JD, Malfait N, Gribble PL (2007). The Role of Vision in Limb Impedance Control. Poster presented at the Society for the Neural Control of Movement 17th annual meeting, Sevilla, Spain.

Cothros N, Wong JD, Gribble PL (2006). Reaching Movements in Free Space Exhibit Small After-Effects but Do Not Disrupt Retention of Force Field Adaptation. Poster presented at the Society for the Neural Control of Movement 16th annual meeting, Key Biscayne, FL.

Cothros N, Wong JD, Gribble PL (2005). Distinct Neural Representations of Object and Limb Dynamics. Poster presented at the Society for Neuroscience 35th annual meeting, Washington, DC.

Wong JD, Gribble PL (2005). A connectionist model for attenuation of interference in motor learning. Poster presented at the UWO Physiology and Pharmacology Research Day, London, Ontario, Canada.