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Using touch or imagined touch to compensate for loss of proprioception: A case study

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Proprioception is the sense of the position of one's own body. Here, we present a case study of an individual with proprioceptive loss in one limb consequent to stroke. The patient indicated that merely touching his impaired arm with his unimpaired arm temporarily restored his proprioception. We examined this claim and the effects of imagined touch by the unimpaired arm. Assessments were made using three-dimensional tracking of reaching trajectories towards targets in conditions of light and darkness. Both actual and imagined touching significantly reduced movement error and jerk, specifically for targets located in regions that both hands would be able to reach.

Keywords: Proprioception; Stroke; Imagery; Motor control; Vision; Bilateral.

Upper extremity hemiparesis is a common impairment resulting from stroke, affecting about 80% of stroke survivors (Sommerfeild, Eek, Svensson, Holmqvist, & von Arbin, 2004). Less common is proprioceptive loss – the inability to sense, in the absence of visual input, the location of the limb in space. The case of Ian Waterman demonstrates there may be an ability overcome loss of proprioception through visual guidance (Azar, 1998). Here, we present a case study of a 76-year-old male who suffered intracerebral hemorrhage to the right thalamus resulting in such a sensory deficit; damage to the thalamus has been shown to lead to proprioceptive loss in earlier reports (e.g., Sacco, Bello, Traub, & Brust, 1987). The patient articulated an ability to resolve his movement impairment by actually touching his affected limb with his unaffected limb. We examined this claim in addition to the idea that imagined touch by the unaffected limb would also ameliorate the impairment. We used a three-dimensional movement tracking device to assess reaching trajectories of his affected limb in light- and dark-room conditions, while the limb was touched or imagined to be touched by his unaffected limb.

Use of an unaffected limb to improve movements by an impaired limb has been demonstrated in a few previous studies. Modulation of grip force was found to be improved for an upper limb hemiparetic when the affected limb was lightly touched by the unaffected limb (Aruin, 2005). The increased regulatory response through the additional sensory input was similar to that found in a low-friction skateboard condition, suggesting improvement through light touch may be due to carryover of motor control via intact movement tracking of the unaffected limb. In a follow-up study, grip force was found to be reduced no matter where the affected limb was touched (e.g., finger, wrist) revealing a generalized point-of-contact effect on the impaired arm (Iyengar, Santos, & Aruin, 2007). Similar effects on the modulation of grip force in multiple sclerosis patients have been reported (Iyengar, Santos, Ko, & Aruin, 2009). Moreover, attenuation of tactile extinction has been reported to result from touch of an unaffected

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hand (Coslett & Lie, 2004). Finally, several groups of researchers have reported the benefits of light touch on the reduction of postural sway in typical populations (e.g., Jeka & Lackner, 1994; Rogers, Wardman, Lord, & Fitzpatrick, 2001; Vuillerme & Nougier, 2003). Significant relationships between balance and behavioral results including gait and reaching in stroke survivors have been found (Nichols, 1997). Thus, while there is an implied relationship between light touch and reaching, studies directly examining the relationship between the two have not been reported.

Bringing the second limb to participate in a task by touching the first limb changes the nature of the task to a bimanual movement situation. Although synergistic bimanual movements are sometimes easier to perform (Neilson & Neilson, 2005), the use of bilateral movements does not always work well as a strategy post-stroke rehabilitation (e.g., Chang, Tung, Wu, & Su, 2006). Chang and colleagues suggest that benefits from bilateral movement situations may be specific to patients with mild impairment. In general, improvements seen via touch from an unaffected limb may be based on a restoration of three-dimensional orientation of the affected limb in space, rather than an alteration of the task to involve two limbs (Morris et al., 2008). That is, the inclusion of touch from the second limb drives some attention to the three-dimensional coordinates associated with the unaffected limb providing an aid for the mind and brain to use as it control movements by the affected limb.

Movements with the contralesional, hemiparetic arm are slower than those performed by the unaffected limb. Such movements are also typically more variable and segmented and less accurate (Archambault, Pigeon, Feldman, & Levin, 1999; Cirstea & Levin, 2000; Cirstea, Pitito, & Levin, 2003). Although some of these pathological features are a result of the cortical damage itself, some result from patients' attempts to compensate for the decreased control of the paretic limb. For example, stroke patients may adopt a unique movement strategy to overcome motor impairments. The utility of these abnormal movement synergies has been debated; some argue that such patterns are beneficial and necessary to restore functionality, while others argue that they are dysfunctional and barriers to rehabilitation because the movements are unnatural or largely inefficient in terms of biomechanics (Cirstea & Levin, 2000).

Several studies have shown that stroke patients tend to use excessive grip force to lift objects and often use two hands for tasks previously requiring one hand only (Quaney, Perera, Maletsky, Luchies, & Nudo, 2005). Aruin (2005) measured the amount of grip force in three different arm support conditions: no support, arm supported by a skateboard, and arm lightly touched by but not supported by the unaffected arm. When the arm was supported by the skateboard or lightly touched, lower grip force levels were used. These results indicate that extra sensory information could be used to modulate grip force even when it was not associated with increased stability. Better grip force modulation in support or touch conditions was seen in both hemiparetic and normal participants, demonstrating that additional sensory input can help individuals with and without motor impairments to plan more efficient movements. Individuals with sensory deficits such as proprioceptive loss would presumably show even greater improvements in this context, as the additional sensory input would correct for some of their impairment. The touch of the unaffected limb could provide the location cues no longer received from the affected limb.

Here we present the case of PR (initials are anonymous identifiers) stroke survivor who experiences both hemiparesis and proprioceptive loss. In the course of conversation, PR described and demonstrated an intriguing compensatory strategy. Not only does PR use sensory input from his unaffected arm to aid in reaching with his affected arm, he also claims to be able to overcome some of his motor deficits by merely imagining touching the affected arm. Such a strategy is intriguing in light of previous findings demonstrating overlapping networks for motor imagery and motor planning. Both modalities of motor action are tied to activity in the supplementary motor area, premotor cortex, and the cerebellum (Decety et al., 1994; Gerardin et al., 2000; Jeannerod, 2001; Roland, Skinhøj, Lassen, & Larsen, 1980; Stephan et al., 1995). Thus, imagination of an action, at the neural level, is a lot like execution of action. In fact, this functional relationship is the basis of the use of mental practice to facilitate motor performance. Positive effects of mental practice or motor imagery on motor performance has been demonstrated in athletic performance in typical populations as well as a means for facilitating functional recovery in stroke survivors (Fontani et al., 2007; McEwen, Huijbregts, Ryan, & Polatajko, 2009; Stevens & Stoykov, 2003).

The current study was therefore undertaken to quantify PR's reaching ability in a variety of conditions and to test the effectiveness of his actual and imagery-based touch compensatory strategies for overcoming his proprioceptive loss. Detailed results for the two experiments follow the presentation of methods, similar for both experiments except for the target locations used.

METHODS

Participants

The primary participant was PR, a 76-year-old male who suffered a hemi-thalamic stroke 3.5 years prior to the study. As a result of this event PR has significant loss of proprioception in his left arm. When PR is able to see his left arm he is able to reach effectively for targets. If deprived of visual cues, however, PR's reaching behavior becomes much more erratic. Although the level of sensory deficit was not measured for upper and lower limb specifically, the sensory loss was apparent in both portions of his limb, as evident in overall limb errors in simple matching position tests conducted in the lab. For example, under eyes closed conditions, the patient's unaffected limb was placed in a distinct position by the experimenter (e.g., extended to the side, directed by upper limb, or, movement of the lower limb only to be horizontal with the floor) and the patient was asked to match that same location with his affected limb. In his affected left limb, PR was able to achieve wrist extension of 56°, flexion of 63°, supination of 59°, and pronation of 75°. To assess overall motor control and function, two standard clinical assessments were performed: the Fugl–Meyer Evaluation of Physical Performance and the Wolf Motor Function Test. PR had a Fugl–Meyer upper extremity score of 40 (normal functioning or max score is 66), placing his motor function on the cusp between moderate and mild impairment. The results of the Wolf Motor Function test are summarized in Table 1. PR's total time for all tasks in the Wolf was 445.5 s. He exceeded the maximum time allowed for three of the tasks. No apraxic or cognitive deficits were present in PR, as reported in his medical records and as displayed during personal interaction. He maintained strong verbal and written skills, even typing a lengthy paper about his deficits since his stroke. Given his functional assessments, PR may be considered a patient with moderate-to-mild impairment and a good candidate for intervention using bilateral tasks (Chang et al., 2006).

TABLE 1
Wolf Motor Function Test Scores of PR

Task	*Time (s)*	*Functional ability score*
Forearm to Table (side)	3	2
Forearm to Box (side)	5	2
Extend Elbow (side)	2	3
Extend Elbow (weight)	2	3
Hand to Table (front)	3	3
Hand to Box (front)	2	3
Weight to Box	2	3
Reach and Retrieve	1.5	3
Lift Can	7	3
Lift Pencil	120	1
Lift Paper Clip	6	2
Stack Checkers	120	1
Flip Cards	15	2
Turn Key in Lock	120	1
Fold Towel	22	2
Lift Basket	15	1

An age-matched male with neither neurological disorders nor physical deficits served as a control participant.

Apparatus

A miniBird 500 motion tracking system (Ascension Technology Corporation, Milton, VT) was used to record each reach. A single sensor was affixed to the participant's index finger and a second sensor was attached to a glow-in-the-dark target. The tracking system continuously recorded the position of both sensors at 100 Hz with a resolution of ± 0.5 mm. In Experiment 1, a moveable target was placed in one of five locations on a target board in front of the participant (see Figure 1). The center target was 33 cm from the front edge of the table. The side targets were 20 cm to the left or right of center at distances of 18 and 48 cm from the front table edge. In Experiment 2, six targets were used, arranged in a semicircular array 11, 27, and 35 cm to the left and right of center; and 12, 26, and 37 cm from the front edge of the table. Target locations were not labeled and several non-target locations were also marked in order to prevent the participants from learning the locations prior to the beginning of trial blocks. Targets were marked using velcro tabs so that their location could be seen or felt by the experimenter placing the targets on the board.

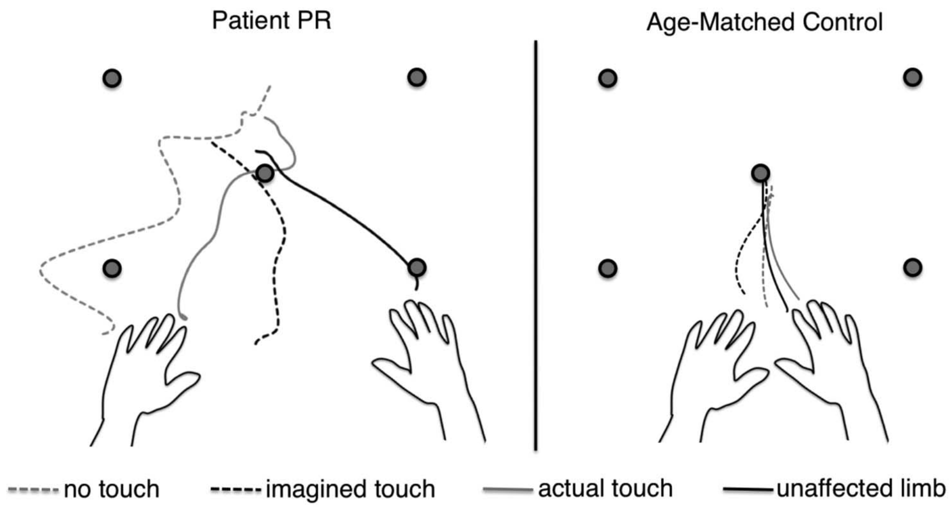

Figure 1. Five reaching targets were used in Experiment 1. Typical dark condition reaches are shown for Patient PR and the age-matched control. All reaches were aimed for the central target. For PR, an increase in reaching accuracy and smoothness was apparent for actual and imagined touch conditions.

Design

There were two trial conditions, *light* and *dark*. The *light* condition trials occurred in normal room lighting conditions. For *dark* conditions trials, all room lighting was eliminated except that emitted by the glowing target. Under these conditions, the participants could continuously see the target, but they could not gain any visual cues as to the location of their hands. Participants wore a black glove and sleeve to further minimize the possibility of receiving any visual information about the location of their arms. Both participants verbally confirmed that they could see the target clearly in both light and dark conditions.

In both conditions, the participants completed three types of trials: *actual touch*, *imagined touch*, and *no touch trials.* In all trials, participants were instructed to reach out and touch the target with their finger tips. In the *actual touch* trials, PR lightly touched his hemiparetic left arm at a central location, just below the elbow, with the fingers of his unaffected hand while reaching for the target. The touch involved placement of the index, middle, and ring fingers on the medial dorsal portion of the lower limb, overlaying most significantly with the extensor digitorum. PR was specifically instructed to refrain from actively guiding the affected arm via push, pull, or other means with his unaffected arm. The touch remained in the same place on the arm during the entire touch trial block, and the touch remained static. For *imagined touch* trials, PR imagined performing the touch but did not actually do so while reaching for the targets. In the *no touch* condition, PR reached for the targets without the aid of either touch or imagined touch. The control participant was given similar instructions, substituting his non-dominant left arm in place of the hemiparetic limb. The three touch conditions were tested in both the light and the dark. For further comparison, PR also performed the *no touch* trial type with his unaffected (right) limb in both the light and dark conditions, and the control participant performed the same type of trial in both light and dark with his dominant (right) hand.

Overall, each participant completed 8 blocks of trials (2 lighting conditions × 4 trial types); three trial types involved the affected/non-dominant limb reaching and one trial types involves the unaffected/dominant limb reaching. Block order and order to target locations were randomized. Each block of trials in each condition included 10 trials (2 repetitions × 5 targets).

Procedure

At the beginning of each block of trials, the instructions were repeated to the participant. Once the participant indicated that he understood the instructions, he placed his reaching hand on the table in a neutral starting position at rest on the table at the body midline. The non-reaching hand rested in the lap. Both PR and the control participant were able to maintain the neutral, starting position for the duration of the trials. For the *dark* conditions, the lights were turned off after the instructions. At the beginning of each trial, the Minibird system was activated, the first experimenter gave a number indicating the trial location presented by the system at random, and a second experimenter put the lighted target in place. Once the target was in location, the second experimenter verbally indicated to the participant that the reach should begin. After the reach was completed, the participant returned his hand to the neutral start position, the Minibrid system was reset and the second experimenter moved to the target to the next location. Both PR and the control participant were asked to reach as quickly and accurately as possible. In addition, they were instructed not to correct inaccurate reaches after touching the target board. Both participants completed all reaches using only limb movement; no movement of the trunk was involved in the reaches.

Data analysis

The raw position data were smoothed with a third order Butterworth filter (cutoff frequency 50 Hz). Velocity, acceleration, and jerk (first, second, and third derivatives of position with respect to time) were then calculated based on these values. Movement onset was identified as the first time when the sensor moved more than 5 mm above the initial start height. As the participants began reaches for the targets, they consistently lifted their hand up from the table surface. At the end of the reach, they returned their hand to the table surface. We used this to demarcate when the reach began and ended. We identified movement onset as the first time when the sensor moved up more than 5 mm. We could identify the end of the movement as the first moment after the peak movement height that the hand dropped within 10 mm of its starting height. For each trial, we calculated movement latency, duration, and end-of-movement error. Average velocity and jerk during the reach movement were also calculated. Initial explorations of the data revealed clear similarities between the reaches directed at the two targets on the right and the two targets on the left. Data from these conditions were combined to result in three target conditions: left, center, and right.

EXPERIMENT 1: REACHING IN THE LIGHT AND DARK

When reaching for a target in the light condition, proprioception may enhance reaching but is not essential since the hand can be guided by visual information. In the dark, however, any reaching actions must be guided exclusively by proprioception. In this experiment, a glowing target was placed in various locations under both light and dark conditions and the participants were asked to reach out and touch it.

Results and discussion

PR's proprioceptive loss was apparent in the kinematics of the target touch task. In the dark conditions, when view of the hand was removed, PR's reaching errors were greatly increased (mean increase 50.4 mm for standard *no touch* reaches) (Table 2). Removal of hand view also increased the error for the unaffected limb but by a smaller amount (mean increase 22.3 mm). Similar tendencies were apparent for the smoothness of the movements. For the affected limb, darkness increased movement jerk by 1.4 cm/s^3, whereas for the unaffected limb the increase was only 0.01 cm/s^3. Reach latency, duration, and average velocity did not exhibit this trend, remaining relatively unaffected by the dark room condition. For the age-matched control participant, darkness produced significant reductions in reaching performance as well, but these changes were similar regardless of the hand used to reach for the target.

We found that imagined or actual touch improved performance for the central and contralateral targets. We conducted a two-way ANOVA assessing the effects of position (central/contralateral vs. ispilateral) and trial type (no touch, imagined touch, or actual touch). This 2 × 3 design produced no significant main effects, but, as expected a significant interaction between the two factors, $F(2, 24) = 3.74$, $p = .038$. Such a result supports our assertion that imagined or actual touch influenced reaching accuracy differently for these two sets of target positions.

The primary goal of this experiment was to assess the patient's claim that touching his affected left limb with the fingers of the unaffected right limb improves his reaching accuracy or speed. Our data strongly support this assertion, but only for reaches made to targets in the center or on the right side of the display (Figure 2). For instance, reaching

TABLE 2
Experiment 1 movement characteristics – no touch trials

	Affected Left Limb		*Unaffected Right Limb*	
	Light on	*Light off*	*Light on*	*Light off*
		Patient PR		
Error (mm)	36.4 (6.0)	86.8 (11.1)	8.2 (1.5)	30.5 (6.2)
Jerk (cm/s^3)	0.9 (0.1)	2.3 (1.1)	0.2 (0.04)	0.2 (0.1)
Latency (s)	1.4 (0.1)	1.2 (0.1)	1.1 (0.1)	1.1 (0.1)
Duration (s)	1.5 (0.1)	1.5 (0.1)	0.9 (0.1)	1.3 (0.2)
Velocity (cm/s)	48.5 (3.0)	53.0 (2.9)	45.0 (3.1)	33.1 (3.3)
	Unaffected Left Limb		*Unaffected Right Limb*	
	Light on	*Light off*	*Light on*	*Light off*
		Age-matched control		
Error (mm)	8.5 (0.8)	21.5 (3.7)	9.4 (1.2)	35.3 (6.7)
Jerk (cm/s^3)	0.5 (0.04)	0.6 (0.1)	0.5 (0.1)	0.5 (0.05)
Latency (s)	0.8 (0.02)	0.9 (0.03)	0.8 (0.1)	0.8 (0.03)
Duration (s)	0.5 (0.04)	0.4 (0.04)	0.5 (0.04)	0.6 (0.1)
Velocity (cm/s)	72.4 (3.8)	83.1 (5.2)	73.5 (4.3)	61.9 (6.1)

error was high for *no touch* reaches made with the affected left limb, in the dark, to targets on the right side of the display (mean = 96.3 mm, $SEM = 16.9$). When the participant touched his left arm with his right hand during the reach, however, this error was strikingly reduced (mean = 51.5 mm, $SEM = 10.8$). A similar reduction was apparent if the participant just imagined touching the arm, but made the reach without actually performing the touch (mean = 50.6, $SEM = 16.3$). For reaches made to the left side of the display, however, touching or even imagining touching the affected limb increased reaching errors (Figure 2).

Movement jerk exhibited a similar trend. When the participant touched or imagined touching the affected arm, movement jerk decreased. As with movement error, however, this effect was apparent only on the right side of the display (*no touch* mean 8.5 cm/s^3, $SEM = 0.7$; *imagined touch* mean 7.0 cm/s^3, $SEM = 1.0$; *actual touch* mean 7.1 cm/s^3, $SEM = 0.8$).

All of these trends were also apparent for reaches made by PR in the light condition. The control participant did not exhibit these trends.

Both *actual touch* and *imagined touch* produced increases in reaching accuracy and smoothness for reaches directed to the center or right side of the display. Reaches made to the left, however, were hindered by touch or imagined touch. Patient PR suffered damage to his right motor cortex, an area primarily responsible for controlling the left arm.

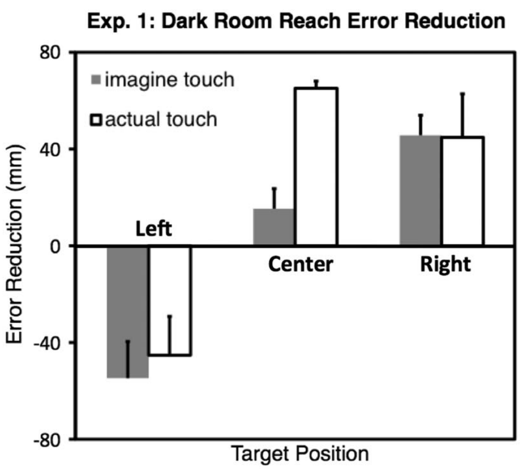

Figure 2. In Experiment 1, when PR touched the affected limb with the unaffected limb or imagined doing so, his dark room reaching errors were reduced for targets in the center and on the right side of the display. For targets on the left, the errors increased.

Our results suggest that the unimpaired left hemisphere motor cortex is able to partially compensate for this deficit when the reach is made into the region of space for which it is typically the primary action controller (i.e., in which the right arm would typically reach).

In order to more precisely characterize this effect, Experiment 2 was undertaken using a set of six reaching targets, arranged in a semicircle in front of the participant. If target position is key to the effect observed in this study, then we should see the effect

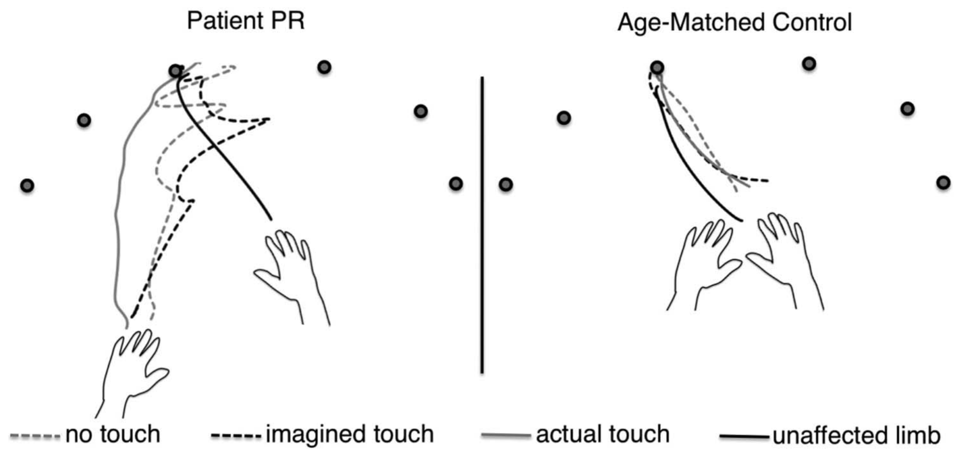

Figure 3. Six reaching targets were used in Experiment 2. Typical dark condition reaches are shown for Patient PR and the age-matched control. All reaches were aimed for the target located slightly to the left of center.

of touch and imagined touch change as the target shifts from left to right.

EXPERIMENT 2: GREATER VARIATION IN RELATIVE ORIENTATION

Approximately 2 months later, PR and the control participant were re-tested. The only difference in testing was the target array. Here, six targets presented in a semi-circular array were used (see Figure 3).

Results and discussion

Reductions in dark room reaching errors were only apparent for the two center targets used in this experiment (Figure 4). Average reaching error for *no touch* reaches made with the affected left limb, in the dark, to these central targets was 59.2 mm ($SEM = 9.8$); for *imagined touch* (mean = 26.0 $SEM = 11.8$) and *actual touch* conditions (mean = 38.9; $SEM = 5.3$), these errors were substantially reduced. Jerk was also reduced, from 9.7 cm/s^3 ($SEM = 2.2$) to 7.7 cm/s^3 ($SEM = 0.2$) for *imagined touch* and 7.1 cm/s^3 ($SEM = 0.5$) for *actual touch*. For the most extreme right and left targets, however, a clear increase in error and jerk was apparent. The ANOVA run in the first experiment did not reveal statistical significance in this experiment.

We initially found these results puzzling, since *imagined* or *actual touch* enhanced performance for targets on the right in Experiment 1. Considering the results of the two experiments together makes

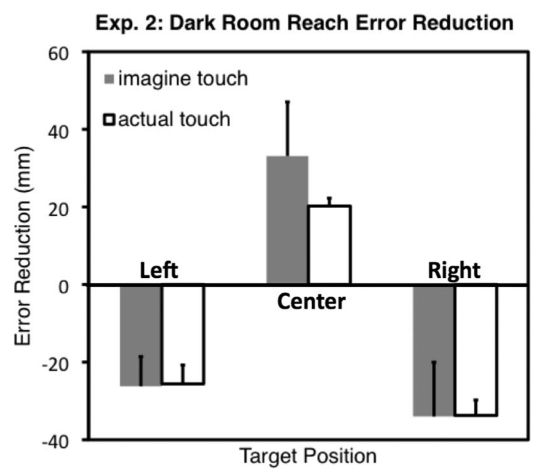

Figure 4. In Experiment 2, when PR touched the affected limb with the unaffected limb or imagined doing so, his dark room reaching errors were reduced for the two most central targets. For targets on the left and right, the errors increased.

the results clear (Figure 5). The shaded targets in this display are those for which *imagined touch* enhanced reaching accuracy. A clear spatial effect is apparent, with enhancement in the center or slightly to the right of center. It may be that the ability of the uninjured motor cortex to compensate for the injured cortex is only effective for regions in which there is substantial overlap in the workspace of the two hands.

CONCLUSIONS

The two experiments we report here provide an assessment of the proprioceptive loss in patient PR. Reaching performance was most substantially

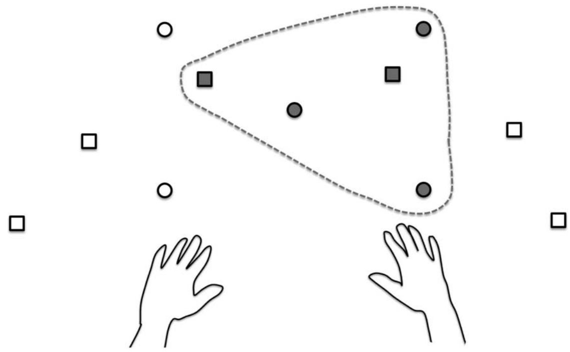

Figure 5. Targets from Experiments 1 and 2 are presented as circles and squares, respectively. Shaded figures are targets for which imagined touch reduced reaching error.

impaired with his left limb in darkened conditions in which he could see a target but not his own hand. His reaches to targets in the dark generally moved in the appropriate direction but the paths were erratic and the end-point placement was inaccurate. These impairments of the left limb are reduced not only when the patient touches it with the unimpaired right limb but also when the patient imagines engaging in such a touch action during a target-directed reach.

The attenuation of the proprioceptive deficits in conditions in which the patient imagined touching his limb was somewhat surprising and intriguing. Over the past two decades, a number of studies have reported on the overlapping features and neural circuitry for real and imagined action (e.g., Decety, 1996; Jeannerod, 2001). And, the two modalities of action are even constrained by the same rules of motor control, such as Fitts' Law (Stevens, 2005). Moreover, several studies have demonstrated significant gains in functional recovery in stroke survivors through the in the use of motor imagery as a rehabilitation technique (e.g., Stevens & Stoykov, 2003). But in the present study, the role of the imagery was tangential. The primary task involved physical movement of an affected or non-dominant limb. To our knowledge, this is the first demonstration of the use of an imagery task to attenuate a physical deficit online.

Of further interest is that the effect is mostly apparent, however, when the reaching target is located within the region of space where both limbs might easily reach, i.e., where the two hands might reasonably be expected to work together on some task with some bias towards the unaffected limb's side. PR demonstrated greatest reduction in trajectory error and jerk to targets in workspace that both limbs might access equally. The origin of the reduction in error remains in question. One possibility is that the reduction in movement error is synergistic in nature. That is, the affected limb may be moving best when it is in concert with the unaffected limb. In such a case, the compensation for proprioceptive loss is biomechanically, and not spatially, based. Another possibility is that the real and imagined touch by the unaffected limb is providing a carryover effect of spatial re-orientation. In such a case, motor control of the affected limb would be based on an estimation of location in space based on the proprioceptive cues from the unaffected limb and the explicit knowledge that it is touching the affected limb. In either case, the data presented here are intriguing in that they demonstrate modulatory effects on behavior from both real and imagined touch conditions. This result provides evidence of a shared functional role between real and imagined movement and presents another example of practical application of imagery in the rehabilitation context.

Based on the present work, rehabilitation techniques for individuals with upper extremity hemiparesis may find distinctive task effects based on the use of ongoing imagery tasks during motor movements using the impaired limb. Moreover, there may be value in attending to performance associated with unilateral and bilateral workspace parameters. For example, actual or imagined movement tasks may be found to be more successful when completed in workspace shared by both affected and unaffected limbs.

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