

Bimanual coupling in amputees with phantom limbs

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People who experience phantom limbs following amputation sometimes report vivid movements in the phantom, both spontaneous and voluntary¹⁻³. Do these illusory movements reflect the operation of neural mechanisms that govern normal motor performance? By studying interference and coupling effects of the kind that arise during bimanual movements in normal subjects, we show that volitional movements of a phantom arm impose behavioral constraints comparable to those evident in real movement, even when the arm has been missing for over ten years. Thus, the neural mechanisms that generate this coupling continue to operate despite the prolonged absence of any proprioceptive or visual reinforcement. If the amputation was preceded by a peripheral nerve palsy, however, the phantom arm is reported as immobile ('learned paralysis'⁴). We did not observe coupling effects in patients with immobile phantoms.

Subject F.A.'s right arm was amputated just below the elbow following a boating accident in 1984. He has experienced vivid sensation of the missing limb since then. Very striking is his ability to move his phantom limb in a volitional manner. For example, when asked to reach for an object (real or imaginary) that is placed in front of him, he will describe precisely how his phantom fingers contact and grasp the object. Curiously, if the object is then pulled away by the experimenter, F.A. often experiences pain because the object is 'being wrenched away from the fingers.'

We investigated whether phantom limb movements reflect the operation of neural mechanisms that govern normal motor performance. We assessed phantom limb movement indirectly by applying a standard test used to examine coupling effects that arise when healthy subjects produce bimanual movements. In this test, subjects are asked to cyclically produce trajectories with both limbs. The direction of the movements is varied to be either the same (parallel) or different (orthogonal). Under normal movement conditions, the trajectories drawn by each hand are minimally affected in the parallel conditions in comparison to when either hand performs alone. In contrast, when the task requires movements in orthogonal directions, both trajectories deviate from their target paths⁵⁻⁷.

We capitalized on these known movement constraints to test whether spatial coupling would occur when one of the movements was produced by a subjectively movable phantom limb. F.A. pro-

duced bimanual movements by drawing on a digitizing tablet along a vertical axis with his intact limb while moving the index finger of his phantom limb in either a tapping (parallel) or twirling (orthogonal) motion, at a comfortable rate (Fig. 1). Standard deviation from the mean direction of lines computed across repeated cycles provides a precise measure of interference that cannot be predicted nor manipulated in any obvious way by subjects.

The performance of subject F.A. was indistinguishable from that of six control subjects who made actual movements with two intact limbs (Fig. 2). Significantly more spatial error occurred in the orthogonal condition compared to parallel or one-armed conditions for the phantom subject F.A. (using trial as a random factor, $F(2,14) = 11.31, p < .001$) and the control group ($F(2,10) = 18.42, p < .001$). These results indicate that spatial coupling persists in subject F.A., even without proprioceptive input from the missing arm. Notably, use of finger movement for the task of the other (phantom) limb ensures that we are not capturing aspects of coupling due to residual peripheral input from the remaining stump of the amputated limb, given that insertion of the metacarpo-phalangeal joint of the index finger would reside below the level of the amputation. The observed spatial coupling effects, therefore, are not due to biomechanical properties associated with movement of the phantom finger.

Do these effects depend on the subjective experience of movement? To explore this, we took advantage of a phenomenon that has been termed 'learned paralysis.' Some amputees who do not experience phantom movement have had a pre-

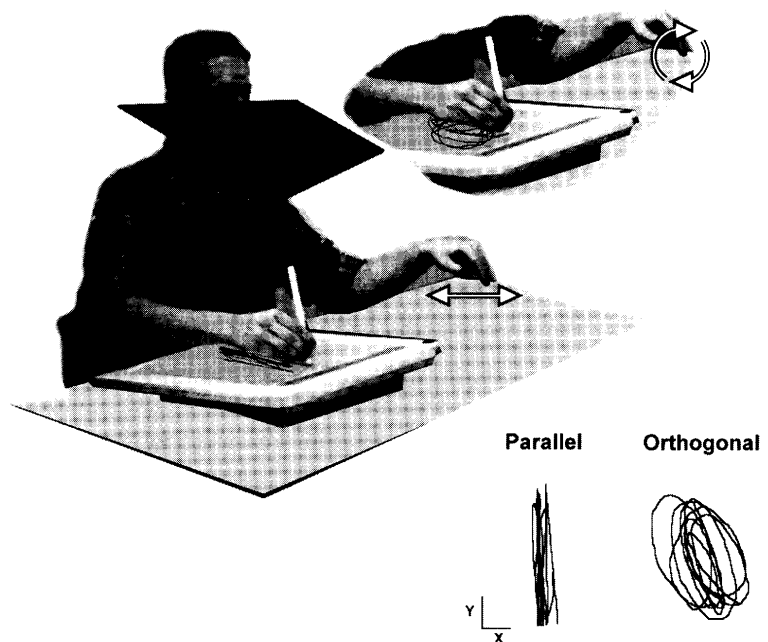


Fig. 1. Schematic diagram of the experimental setup depicting the two bimanual conditions: parallel (tapping) and orthogonal (twirling). The dominant limb always performed the drawing movement. x-y coordinates of the y-axis lines were recorded (at 78 Hz) using a digitizer tablet interfaced with a laboratory personal computer. Repeated cycles of movement were performed for eight ten-second trials per condition. Vision of the limbs was blocked by a shield appended to the wall behind. Raw data of one representative trial from each bimanual condition represent the form of interference observed in spatial coupling (inset). Informed consent was obtained from all subjects in accord with human ethics guidelines at the V.A. Hospital in Martinez and University of California and the University of Otago.

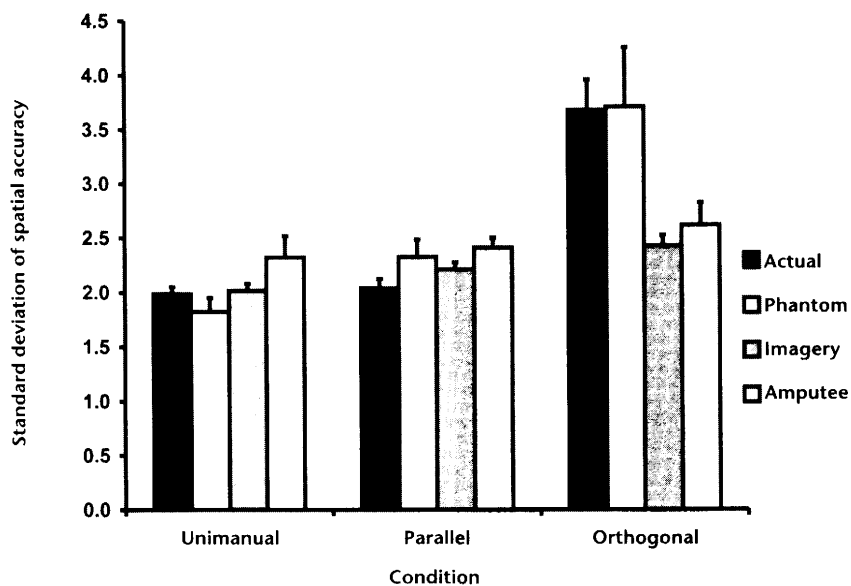


Fig. 2. Spatial interference for one-arm and two-arm conditions for all subjects. Spatial accuracy (zero is most accurate) and standard errors for drawing movements of one (intact) limb are shown for each of four groups: actual, six subjects with two intact limbs under actual movement conditions; phantom, a subject with vivid phantom limb movement; imagery, five subjects with two intact limbs under imagery control conditions; and amputee, three amputees without phantom movement. Directional header was computed as the straight-line vector connecting the first and last data points of each cycle of movement within a trial. Standard deviation from the mean value of this variable across repeated cycles captures the measure of spatial accuracy depicted here.

existing peripheral nerve injury causing paralysis for a few months prior to amputation. Learned paralysis might result from a continuously experienced mismatch, prior to surgery, between the expected consequences of issued motor commands and the resulting feedback. One such patient was D.S., whose left arm was amputated just below the shoulder in 1983 following a brachial plexus avulsion in 1982. He experiences vivid sensation of the fingers of his phantom limb, but no associated movement. Two additional amputees without the subjective experience of phantom movement were also tested by the same method. Subject N.G., an amputee of 24 years, lost his right arm just below the shoulder as a result of an industrial accident. He experiences a dull pain in the tip of his stump at all times but has no sensation of phantom limb movement. Subject P.S. lost his right arm as a result of a motorcycle accident seven years prior to testing, and reports vivid sensation of the limb without the experience of movement.

Amputees without experience of phantom movement showed no evidence of spatial coupling of the type that occurs with actual movements (Fig. 2; $F(2,8) = 2.71, p > .05$). Further, the original group of control subjects with two intact limbs were tested on an imagery task, in which they produced actual movement with one limb while vividly imaging movement of the other limb. As in the amputees with immovable phantoms, there was no evidence of spatial coupling of the type that occurs with actual movement ($F(2,4) = 2.48, p > .05$). These findings were not due to differences in timing variables (duration, variance in duration) across condition or group.

Our data demonstrate that similar spatial coupling occurs in normal bimanual movement and when an active limb movement is combined with a phantom limb movement. Control subjects under imagery conditions do not produce spatial coupling effects. Coupling, therefore, depends on the subjective experience of movement. Although there is significant overlap in the processes involved in imagery and action⁸, associated processes such as sending an efference copy of motor command signals to other brain regions may be specific to movement, even the subjectively experienced movement of phantom limbs. Learned paralysis may account for

the lack of subjective experience of phantom movement in some amputees. A mismatch between the expected sensory consequences supplied by efference copy and the resulting feedback before amputation may cause plasticity in the neural system that integrates these sources of information, thereby eliminating the subjective experience of movement, and corresponding spatial coupling effects, in those amputees who do not report moving phantoms.

Together, these findings have at least three important implications. First, spatial coupling cannot be attributed to biomechanical factors, but rather reflects spinal and/or supraspinal mechanisms. Second, the neural processes associated with the spatial properties of movement may remain intact for as long as ten years, even when their associated peripheral effects are absent. Third, residual spatial coupling is only manifest with the subjective experience of movement. We propose that learning-induced changes result from a mismatch between different sources of movement-related sensory information. Such changes seem to affect both the subjective experience of phantom movement and the coupling mechanisms between the two limbs.

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