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Control of discrete bimanual movements: How each hand benefits from the other

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HIGHLIGHTS

- When both hands move simultaneously, each hand benefits from the other.
- Right-handed participants moved both hands, one of which could not be seen.
- Both hands moved in the same direction, or in opposite directions.
- The (invisible) left benefits from the (visible) right hand's trajectory control.
- The (invisible) right benefits from the (visible) left hand's position control.

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ABSTRACT

Lateralized sensorimotor hand functions are often investigated separately or sequentially for each hand, e.g., in matching tasks, but rarely under more ecological circumstances where both hands move simultaneously. Using a novel bimanual paradigm in 21 young, healthy participants, this study addresses how postulated lateralized control processes of one hand influence control of the other hand across modalities. More specifically, in this paradigm one hand operates under visuomotor conditions, while the other hand receives no visual feedback and operates predominantly under kinesthetic control. Performance of the hand that does not receive visual feedback is compared between when moving alone (unimanual condition) and when moving together with the contralateral visually controlled hand (bimanual condition). Results suggest that during concurrent bimanual movements the 'invisible' hand benefits from specific control proficiencies of the 'visible' hand, indicating crossmodal and interhemispheric sharing of information that complements each hand's own strengths. These findings lend further support to a more differentiated view of functional lateralization of handedness.

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1. Introduction

The root of the word 'dexterity' reflects an old concept of handedness that has been used to describe an easily detectable characteristic of hand function: The right hand (Lat. dexter = right) is, on a population level, usually considered as more proficient and skilled, and the left hand is considered as its poorer performing analog. This concept of handedness posited a general left hemisphere specialization ('dominance') for motor output and arm/hand skills [1], resulting in faster, stronger, more accurate and consistent performance of the dominant arm [2–6]. At the same time, studies recognizing a nondominant hand advantage for some tasks [7] laid the groundwork for a more differentiated picture that would evolve over the years, and pointed at specialized roles for each hand, related to different functional specializations of each brain hemisphere.

One notion that emerged (and went against the general left hemisphere/right hand dominance for motor output) was that the type of sensory feedback might contribute to performance asymmetries, as suggested by studies in unilateral stroke patients [8]. More recent studies have shown that processing of proprioceptive information seems to be lateralized. For example, dynamic [9], or static position matching tasks [10,11] found the nondominant left limb to be more accurate than the right limb; this was interpreted as left limb/right hemisphere advantage in detecting and processing proprioceptive information. Other experiments, using visuomotor paradigms, also showed that end position accuracy in planar arm movements was higher for the left hand/right hemisphere system

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under different load conditions than for the (dominant) right hand [12].

The matching tasks frequently used are often sequential in nature – first one hand establishes the reference position, then the other, or the same, hand tries to match this position. This approach either implicitly, or explicitly [13], introduces a memory component that is hard to quantify. The purpose of this study was to determine whether and how kinesthetic control of one hand would be affected by the concurrent movement of the contralateral, visually guided, hand. During simultaneous bimanual activation, the left hemisphere has been shown to be overall dominant, but with the right hemisphere being proficient in spatial functions [14]. Based on the notion of specialized and complementary control mechanisms for each arm [15], I hypothesized asymmetric influence of the visually guided hand on the hand that did not receive visual feedback, depending on the control processes governing either visual hand. More specifically, the visually guided dominant hand should influence trajectory control of the nondominant hand not receiving vision, and the visually guided nondominant should influence the dominant hand not receiving vision with respect to endpoint accuracy.

2. Materials and methods

2.1. Participants

Twenty-one adults (11 females) with a mean age of 21.1 ± 1.0 years participated in the experiment. All were right-handed, as determined by their preferred hand use for everyday activities, and had normal or corrected vision. The Institutional Review Board at Michigan State University had approved all experimental procedures.

2.2. Apparatus and procedure

A participant was seated in front of a table with two joysticks (Thrustmaster® T16.000M) positioned next to each other, with a 19″ LCD widescreen monitor positioned horizontally above the joysticks. The set-up was aligned such that the cursor position displayed on the computer screen by each joystick was directly above the actual joystick position. The computer screen prevented vision of the hands during task performance. Presentation® software (Neurobehavioral Systems) was used for stimulus presentation and data acquisition; the (*x, y*) position time series was sampled at 75 Hz.

The experiment consisted of a unimanual and a bimanual part. Participants started with the right hand in unimanual mode, and performed eight trials during which they received online visual feedback of their movements via the cursor trace on the monitor. In this visuomotor condition, targets (diameter: 1 cm) were at either 25° or 155° angular location, and 8.0 cm away from the starting position (four trials/target). After this condition, participants performed 32 trials to four different targets, located at either 10°, 40°, 140°, or 170° (eight trials/target); in this kinesthetic-motor condition, visual feedback of the movements was extinguished as soon as the cursor left the home position; participants were instructed to move the right joystick swiftly and as straight as possible to where they estimated they would hit the target and then stop the movement until the target disappeared. After this, the left hand performed the same unimanual mode with the left joystick, moving to the targets in the left half of the display. This was followed by the first of two bimanual modes: both hands moved simultaneously and isodirectionally, first again with visual feedback for both hands (8 trials), then with visual feedback available only for one hand while the other moved in kinesthetic mode (one block of 32 trials); in one block the right hand remained visible, in the other it was the left hand. The second bimanual mode used anisodirectional movements (the hands moving in mirror mode); the order of the two bimanual conditions, and, within conditions, the order of which hand was 'visible' first, was counterbalanced. Studies using continuous movements have shown that mirror movements are more stable and easier to control than isodirectional movements [16]; having two modes would help to address the question whether a hypothesized influence of the visually guided on the kinesthetically guided hand modulated with coordination mode. The reason that each kinesthetic/visual condition was preceded by a short visual/visual part was to ensure that both hands could recalibrate to accurate movements between the kinesthetic/visual conditions; these trials were not included in the analysis. What was of interest were the 32 trials during which one hand moved under conditions of visual feedback, while the other hand moved without vision, and under conditions of predominantly kinesthetic feedback. Average movement times in bimanual mode were 995 ms, and movement paths were straight, showing that participants had followed the instructions properly.

In either mode or condition, participants had to stay at the endpoint for 500 ms; after this, the target disappeared (in the kinesthetic condition it did so irrespective whether participants hit it or not), and they returned to the home position. In the kinesthetic condition the cursor reappeared 1 cm outside the home position in order to assist in finding back to the starting position. The 2 blocks of unimanual, and 4 blocks of bimanual movements took about 45 min to complete. See Fig. 1 for stimulus display and experimental design.

2.3. Data analysis

The time series of each trial were dual pass filtered, using an 8th order Butterworth filter with a cutoff frequency of 10 Hz. Movement onset and offset were determined using an algorithm by Teasdale et al. [17]. To determine the influence of the contralateral visually guided hand on the hand that did not receive vision, the following metrics were computed for that hand: Root mean squared error (RMSE, in cm), defined as the average of the perpendicular distances (calculated at each sample of the trajectory) between the actual movement and a straight vector from movement start to endpoint, reflecting movement linearity and thus the quality of feedforward trajectory control in the absence of visual feedback; absolute end-point error (in cm), defined as the absolute distance between movement endpoint and the respective target location, and constant endpoint error in the *x*-dimension (i.e., lateral direction) and *y*-dimension (i.e., anterior/posterior; in cm) to capture movement over- or undershoot. The error coordinates were converted to movement trajectory space, so that error in the *x*-dimension became parallel error, i.e., along movement direction, and error in the *y*-dimension became error orthogonal to movement direction. It is important to note that in this experiment only the kinesthetically guided hands were of interest, and how they responded to different modes of coordination with the contralateral visually guided hand.

For statistical analysis, the 32 kinesthetic trials of each condition were averaged to represent kinesthetic performance under unimanual or bimanual conditions. Repeated measures ANOVAs were calculated for RMSE, absolute error, constant parallel and orthogonal error, with kinesthetically guided hand (left, right) and movement mode (unimanual, bimanual-iso[directional], bimanual-aniso[directional]) as within-subjects factor. For the ANOVAs, Huyn-Feldt adjusted *p*-values are reported; for post-hoc comparisons, Bonferroni-adjusted *p*-values are reported.

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