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Research article

Inter-limb transfer of kinematic adaptation in individuals with motor difficulties

Jin Bo[a,b,c,*], Chimei M. Lee[a,d]

[a] Department of Psychology, Eastern Michigan University, Ypsilanti, MI 48197, United States
[b] School of Physical Education, Central China Normal University, Wu Han, P. R. China
[c] Center for Human Growth and Development, University of Michigan, Ann Arbor, MI 48109, United States
[d] Division of Clinical Behavioral Neuroscience, Department of Pediatrics, University of Minnesota, Minneapolis, MN 55455, United States

HIGHLIGHTS

- Individuals with normal motor ability showed a positive inter-limb transfer on motor planning when feedback was regular.
- When feedback was enhanced, inter-limb transfer was found on temporal control but not on spatial control or motor planning.
- A clear internal model, instead of motor abilities, is critical for inter-limb transfer on kinematic adaptation.

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ABSTRACT

A previous study suggested that adults with greater motor difficulties demonstrated less adaptation under a regular error feedback schedule (gain = 1:1) but reached a similar level of adaptation compared to controls when feedback was enhanced (gain = 1:2). In light of these findings, the present study examined inter-limb transfer after adults adapted to visuomotor distortions with their dominant hand on either regular or enhanced feedback schedules. Results revealed that successful transfer related to the magnitude of adaptation with their dominant hand regardless of the individuals' motor abilities on the regular feedback schedule. When the feedback was enhanced, the transfer was not related to either the adaptation of the dominant hand or individuals' motor abilities. We argue that a stable internal model is essential for inter-limb transfer in kinematic adaptation.

1. Introduction

The ability to acquire motor skills is extremely important for daily activity across the life span. A number of studies on children with Developmental Coordination Disorder (DCD) revealed poor adaptation to distortions in a range of visuomotor tasks [1–3]. Although learning deficits persist throughout adulthood among this population [4–6], our understanding of motor learning in adults with motor difficulties remains limited.

Inter-limb transfer refers to the phenomenon that learning or adapting to a new task with one hand influences the subsequent performance of the opposite, untrained hand [7,8]. This has been demonstrated in a number of visuomotor adaptation tasks, such as force perturbation [9,10] and visual feedback rotation [11]. Some studies suggest that inter-limb transfer is asymmetric and unidirectional from the dominant to the non-dominant hand [9,12], whereas others indicate that inter-limb transfer can be symmetric and bidirectional [7,13]. It has been argued that each arm may have different controllers or internal models. Each controller or internal model has access to the other such that selected information can be transferred to reduce redundant and competing solutions [14].

It has been proposed that successful inter-limb transfer requires the perception of movement errors, including visual, haptic, and proprioceptive information [15–17]. Nevertheless, how error feedback influences inter-limb transfer is still unknown. Malfait and Ostry [17] reported that substantial transfer occurred in a suddenly introduced novel condition but was not found in a gradually introduced condition [17], highlighting the importance of perceived motor errors. In contrast, recent studies on dynamic adaptation suggest that the magnitude of feedback does not necessarily influence the amount of transfer [18–20]. Poh et al. [21] were interested in the effects of implicit and explicit perception of errors. Unlike

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[*] Corresponding author at: 301M, MJ Science Building, Department o Psychology, Eastern Michigan University, Ypsilanti, MI 48197, United States.
E-mail address: jbo@emich.edu (J. Bo).

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the findings of Malfait and Ostry [17], they stated that conscious error perception is not required for inter-limb transfer, and explicit strategies could enhance participants' transfer. As a result of these inconsistent findings, more studies are needed to clarify how these factors influence inter-limb transfer.

A recent study demonstrated that enlarged visual feedback of movement errors could enhance the adaptation for individuals with motor difficulties [22]. Participants performed a visuomotor task to adapt to a 30° visual distortion under two conditions, where the real hand movement error was either directly presented on a computer screen (i.e., regular schedule: gain = 1:1) or doubled on the screen (i.e., enhanced schedule: gain = 1:2). Results showed that individuals with greater motor difficulties showed less adaptation than those with normal motor abilities on the regular feedback schedule. However, when visual feedback of the movement error was enhanced, participants demonstrated a similar level of adaptation regardless of their motor abilities.

Since the enhanced visual feedback increases adaptation among adults with motor difficulties, it is possible that it could also facilitate inter-limb transfer. The goal of this study was to examine inter-limb transfer after the dominant hand was exposed to a visuomotor rotation task. Participants performed two adaptation schedules where the visual feedback of movement error was either regular (gain = 1:1) or enhanced (gain = 1:2) using their dominant hand. After each adaptation schedule, participants were asked to make the same movement using their non-dominant hand. Based on our recent findings [22], two hypotheses were tested: (1) individuals with greater motor difficulties would show less inter-limb transfer when they displayed weaker adaptation on the regular schedule (measured by *after-effects*); and (2) individuals with greater motor difficulties would show similar levels of inter-limb transfer when they had compatible adaptation on the enhanced schedule (measured by *transfer-effects*).

2. Methods

2.1. Participants

Twenty-seven adults (10 males, 17 females; aged 18–34; the same group of individuals in Lee and Bo [22]) were recruited from the Ypsilanti-Detroit metropolitan area. All participants had intelligence quotients higher than 80 based on the *Shipley Institute of Living Scale* [23]. Five of the 27 participants were left-handed based on the *Edinburgh Handedness Inventory* [24] (left-handedness ranges from −73.33 to −46.67; right-handedness ranges from 46.67 to 100). The Adult Developmental Coordination Disorders/Dyspraxia Checklist (ADC) [25] was used to evaluate participants' motor abilities. Four participants had a total score higher than 90, indicating the presence of DCD; two had scores between 80 and 90, suggesting high risk of DCD; five had scores between 70 and 80, indicating the presence of motor difficulties; and the other sixteen participants had scores lower than 70, suggesting normal motor functioning.

2.2. Procedures

After obtaining informed consent, participants were seated in front of a computer monitor with one hand holding a joystick. Visual feedback of the joystick movements was provided to the participants in real-time on the monitor. The digitized data of the participants' movements in x/y coordinates were collected at a sampling rate of 60 Hz. A customized computer program written in PRESENTATION (www.neurobs.com) was used to present the visual stimuli for adaptation.

Participants performed two adaptation schedules in the counterbalanced order on two separate dates (at least 10 days apart). On each of the schedules, participants were asked to move a cursor as fast and as straight as possible from the home position to a target. The home position was displayed at the center of the screen, and the target appeared randomly in one of eight locations around the home position (Fig. 1B). The home position was visible throughout the duration of the testing. The target appeared as soon as the cursor stayed in the home position motionless for one second and disappeared as soon as the cursor entered the target.

Both schedules consisted of seven phases in order (Fig. 1A): (1) Non-dominant hand baseline: 24 trials (8 trials × 3 blocks) with normal feedback of the hand movements; (2) Dominant hand baseline: 24 trials (8 × 3 blocks) with normal feedback; (3) 1st exposure phase: 32 trials (8 × 4 blocks) with the visual feedback of the dominant hand movement rotated 30° counterclockwise; (4) 2nd exposure phase: 48 trials (8 × 6 blocks) with the visual feedback of the dominant hand movement rotated 30° counterclockwise on the *regular error feedback schedule* (gain = 1:1, Fig. 1C), or with the enhanced visual feedback which doubled the discrepancy between the dominant hand movement and ideal movement on the *enhanced error feedback schedule* (gain = 1:2, Fig. 1D); (5) 3rd exposure phase: 32 trials (8 × 4 blocks) with the visual feedback of the hand movement rotated 30° in the same way as the 1st exposure phase; (6) Post-exposure phase for dominant hand: 8 trials (8 × 1 block) with normal visual feedback of the dominant hand movements to test *after-effects* (i.e., participants made movements in opposite directions compared to their movements during the exposure phases); and (7) Post-exposure phase for non-dominant hand: 8 trials (8 × 1 block) with normal feedback to test *transfer-effect* (i.e., whether the non-dominant hand showed similar *after-effects* as the dominant hand). The manipulation of visual feedback in the 2nd exposure phase was the main focus of the current study. The 1st and 3rd exposure phases were included to minimize the possibility of novel mapping with a magnified scale of visual rotation and to avoid the frustration associated with making large errors when participants were suddenly moved from baseline to the doubled error phase. Throughout the exposure phases, six catch trials (i.e., back to no rotation) were inserted after every 16-exposure trials to track adaptation progress [26].

2.3. Data analysis

The velocity time series were subjected to a dual-pass 8th-order Butterworth filter with a cutoff frequency of 10 Hz. Customized MATLAB scripts searched the velocity time series and marked the starting points for each movement when the velocity exceeded 20% of the peak velocity. In cases when the algorithm failed to mark the right points, the experimenter manually made the adjustment.

Three dependent variables were calculated: (a) directional error (DE, a measure of motor planning) was defined as the directional deviation of the actual movement direction when participants reached the peak of their tangential velocity profile from the ideal movement direction; (b) movement time (MT, a measure of temporal control) was defined as the time taken to move from the home position to the target position; and (c) root mean square error (RMSE, a measure of spatial control) was defined as the average point-to-point spatial deviation of the actual movement trajectory from the ideal vector between home and target positions [27].

To measure overall adaptation of the dominant hand, the *after-effect* was calculated based on the mean differences between the post-exposure block and the last block of baseline for the dominant hand. The *transfer-effect* was defined as the mean difference between the post-exposure block and the last block of baseline for the non-dominant hand. Paired *t*-tests between the post-exposure block and the baseline were used to evaluate overall adaptation