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Briasha Jones

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Does hand dominance matter in non-standard visuomotor transformations?

by

Briasha Jones

Undergraduate honors thesis under the direction of

Dr. Marc Dalecki

Department of Kinesiology

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& Agricultural and Mechanical College
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ABSTRACT

Previous non-standard visuomotor transformation studies using variations of standard mapping and eye-hand decoupling tasks focused on dominant hand use. The present study expanded this work by including the non-dominant hand. Twenty-four right-hand dominant adults (M=21 yrs.; 12 females) slid their index finger along a vertical or horizontal touchscreen to move a cursor that was always displayed in the vertical plane. In four different action-perception conditions, the finger and cursor moved either in the same plane and for movement trajectory related variables but not for endpoint related measures. Across conditions, the initial direction error was larger when performing with the non-dominant hand ($p<0.001$), suggesting spatial movement planning deficits in the non-preferred hand. Furthermore, a significant hands x conditions interaction for path length ($p<0.05$) revealed longer movement trajectories for the non-dominant hand when movements were performed in the same plane but opposite to the cursor direction, but similar performance for dominant hand movements in the horizontal plane and opposite cursor direction. Our findings suggest for the non-dominant hand an overall eye-hand coordination deficit for spatial planning, and an inversely related deficit to the eye-hand decoupling level for trajectory execution.

Key words: Eye-hand coordination; Hand asymmetries; Eye-hand decoupling; Cognitive-motor integration

1. Introduction

The use of touchscreens has become increasingly popular in the past two decades due to technical advances resulting in a growing number of studies that investigated the nature of hand movements along touchscreens during cognitively demanding visuomotor tasks. These studies included variations of standard and non-standard mapping task conditions, based on different levels of eye-hand decoupling (Dalecki, Gorbet, & Sergio, 2019; Gorbet & Sergio, 2006, 2009; Gorbet & Sergio, 2016). During typical “standard” visuomotor mapping tasks, the spatial mapping of eye and hand movements align. A common example is to look and to reach out for an apple on the table and grasp it. Visually guided movements can also be performed while eye and hand movements are spatially decoupled. These tasks have been described as “non-standard” visuomotor mappings (Gorbet & Sergio, 2016; Wise, di Pellegrino, & Boussaoud, 1996).

These ‘non-standard’ tasks can be divided into an implicit and explicit component of non-standard mapping (Gorbet & Sergio, 2019). Implicit components include a rather “natural” spatial decoupling, e.g., when the plane with the visual target information differs from the plane in which the hand moves. A common example is moving a computer mouse in a horizontal plane to control a cursor viewed on the vertical screen. Explicit components are different and require a cognitive rule to be implemented before the correct motor action can be executed (Gorbet & Sergio, 2009), e.g., steering when parking a car backwards and looking through the back rear. It induces a feedback reversal between vision and motor action and requires additional cognitive resources since the intuitively aligned movement direction of eye and hand needs to be decoupled (Gorbet & Sergio, 2016). These non-standard mapping tasks require cognitive-motor integration, and have therefore also been called ‘cognitive-motor integration tasks (Dalecki, Albines, Macpherson, & Sergio, 2016).

Various cognitive-motor integration studies in healthy human individuals have been conducted to enhance the understanding of behavioral outcomes and neural activation patterns during these standard and non-standard visuomotor mapping tasks. When the plane and/or direction of the eye and hand movements were decoupled, the preparation and execution of hand movements became generally slower (reduced peak velocity) and/or less efficient (larger path length and endpoint error). Thus increasing the level of decoupling led to a decline in performance when compared to standard mapping conditions (Dalecki, Gorbet, & Sergio, 2019; Gorbet & Sergio, 2009). Importantly, all of the above-mentioned cognitive-motor integration studies in healthy populations focused on the dominant hand; i.e., the behavioral patterns of visually guided pointing during these standard and non-standard mapping tasks remain unknown for the non-dominant hand. Knowledge about non-dominant hand performance may contribute to enhancements in sensitivity of the use of cognitive-motor integration-tasks as an assessment tool, since these tasks have been used also in studies with neurological populations (Hawkins & Sergio, 2014; Salek, Anderson, & Sergio, 2011; Tippett, Sergio, & Black, 2012).

Not surprisingly, hand asymmetries during visually guided reaching and pointing tasks have been studied extensively in the past century. It is now widely accepted that each hemisphere/limb system appears to be specialized in different aspects of dominant and non-dominant hand performance. One of the more widely accepted theories outlining these differences is called the ‘dynamic dominance theory’ (Sainburg, 2014; Wang & Sainburg, 2007). During aiming movements, the dominant arm shows advantages for coordinating intersegmental dynamics as required for specifying trajectory, speed, and direction, while the non-dominant arm shows advantages or similar performance compared with the dominant hand in controlling limb impedance, as required for accurate final position control (Bagesteiro & Sainburg, 2002). Whereas, final position accuracy improved to the same extent for both arms, initial movement direction improved only for the dominant arm (Duff & Sainburg, 2007). Most of the former studies were performed in the horizontal plane; however, the lateralization of movements, in particular regarding initial direction and trajectory, persisted also when movements were performed in the vertical sagittal plane (Tomlinson & Sainburg, 2012). In addition, dominant arm movements have been shown to be straighter with more temporal consistency; thus implying that the dominant arm performs with greater efficiency than the non-dominant arm (Heuer & Hegele, 2007). Other studies showed larger hand differences with a higher movement speed, while the hands showed less differences or the difference showed even an advantage of the non-preferred hand when the task requirements dictated more complexity and slower performance (Carson, Goodman, Chua, & Elliott, 1993; Goble & Brown, 2007; Roy & Elliott, 1989).

Based on the knowledge from the aforementioned studies, non-dominant hand performance may be even less affected than dominant hand performance due to an increase of demands when performing a more challenging non-standard mapping ‘cognitive-motor integration’ task as compared to a standard mapping task. However, no previous study has examined visually guided pointing along a touchscreen with the dominant and non-dominant hand during standard and non-standard mapping eye-hand decoupling tasks in the vertical and horizontal plane. Therefore, the main aim of the present study was to examine visually guided pointing with the dominant and non-dominant hand during a standard mapping task with vision and action in alignment, and three variations of non-standard mapping tasks with vision and action being unaligned. Based on previous research on cognitive-motor integration and research linked to the dynamic dominance theory and hand asymmetries, we hypothesized that across task variations, dominant hand performance is superior to non-dominant hand performance with respect to trajectory path formation, while movement accuracy characteristics remain rather similar between both hands. We also predict that hand asymmetries will be altered by the level of decoupling between vision and action. Furthermore, which is possibly counterintuitive, we predict that hand asymmetries decrease with an increasing level of eye-hand decoupling. Our predictions are based i) on studies that showed larger hand differences with higher movement speed and fewer differences (or even an advantage) of the non-preferred hand during slower and more complex tasks, and ii) on previous cognitive-motor integration studies that showed that movements become slower and more complex with an increasing level of eye-hand decoupling.

2. Material and Methods

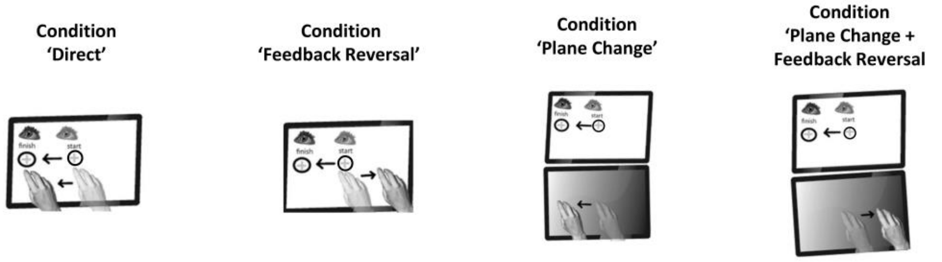
2.1 Participants

Twenty-four right-handed young adults (mean 21.38 ± SD 2.93 yrs., range 18 to 33 years, 12 females, 12 males) participated in this study. Handedness was determined with a 12-item version of the Edinburgh inventory (Oldfield 1971) and all participants reported to be healthy without a history of a neurologic disease. The study protocol was approved by the Human Participants Institutional Review Board of Louisiana State University, and participants gave informed consent prior to participation.

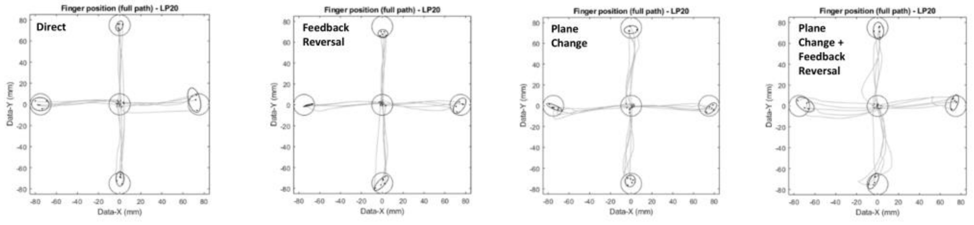
2.2 Procedures

Study participants sat on a chair at a desk in front of a Dell Inspiron 5000 15.6-inch touchscreen laptop (resolution 1920 x 1080 pixel, 60Hz, i.e., delays are maximal 16.6 ms between movements and visual presentation) which presented the experimental task. Participants performed four different visuomotor transformation tasks, once with the non-dominant hand and once with the dominant hand, with hand use and the order of the conditions randomized across participants. In the first task (condition ‘Direct’), the spatial location of the viewed target and the required movement (sliding the index finger along the vertical touchscreen to move a crosshair cursor from screen center to a peripheral target) were in alignment (cf., **Fig. 1a**). In the second task (condition ‘Feedback Reversal’), targets were viewed on the vertical laptop touchscreen and the participants slid their index finger into the opposite direction to displace the cursor (i.e., a feedback reversal). That is, to move the cursor to the left, they had to slide their finger to the right, etc. (cf., **Fig. 1b**). In the third task (condition ‘Plane Change’), targets were viewed on the vertical laptop touchscreen, but participants slid their index finger now along a horizontal touchscreen (Keytec OPTIR 15.6-inch, resolution 1920 x 1080 pixel; i.e., similar than the vertical touchscreen) (cf., **Fig. 1c**). In the fourth task (condition ‘Plane Change + Feedback Reversal’), targets were again viewed on the vertical laptop touchscreen, but participants slid their index finger along the horizontal touchscreen and in the opposite direction to displace the cursor (again a feedback reversal). (cf., **Fig. 1d**).

1a) Experiment Conditions



1b) Dominant hand raw data of the four experimental conditions, participant LP



1c) Non-Dominant hand raw data of the four experimental conditions, participant LP

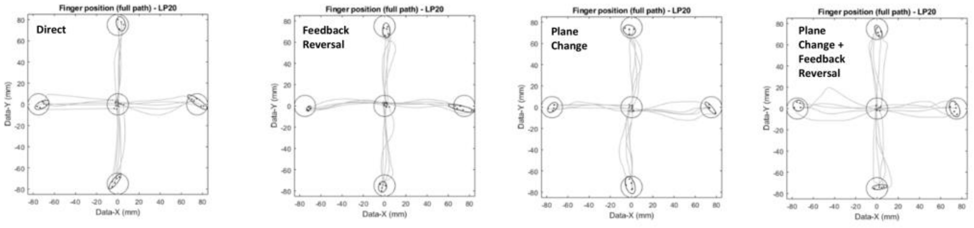


Fig. 1: a) shows the four experiment task conditions requiring different levels of eye-hand decoupling. Light grey eye and hand symbols denote the starting position (i.e., around the home target in the screen center). Darker grey eye and hand symbols denote the instructed eye and hand movement direction. Circles denote the central home (start) and peripheral (reach) target. Peripheral targets were presented randomly in one of four locations (left, up, right, down). The crosshair denotes the cursor feedback given to participants, and the black arrows represent the

movement direction for eye- and hand movement. In task condition ‘Direct’, finger and cursor moved in the vertical plane and the same direction. In task condition ‘Feedback Reversal’, finger moved in the vertical plane, but cursor and finger movement direction were opposite. In task condition ‘Plane Change’, finger moved in the horizontal plane, but the cursor and targets were displayed in the vertical plane. In task condition ‘Plane Change + Feedback Reversal’, it was similar than in condition ‘Plane Change’ but the cursor movement direction was opposite to the finger movement. **Fig. 1 b)** and **c)** present typical full hand path data of one participant for the **b)** dominant hand and **c)** non-dominant hand in the four experimental task conditions. Grey dots in the center circle (home target) represent the start position of the movement. The light grey solid lines represent the full trajectory path of the movement trials, and the ellipses in the peripheral circles (goal targets) denotes the 95% C.I. for the final endpoint of the finger movements (dark grey dots). Note the poorer hand path trajectory with increasing complexity level across both hands, but a poorer performance with the non-dominant hand compared with the dominant hand for the trajectory path rather for the conditions ‘Direct’, ‘Feedback Reversal’, and ‘Plane Change’ but not for condition ‘Plane Change + Feedback Reversal’.

The diameter of the peripheral targets presented on the vertical touch screen was 20 mm and red colored. These targets could appear to the left, right, above or below a central target (diameter also 20mm). The distance between the centers of the peripheral and central target (i.e. the screen center) was 75 mm. The task was displayed on a 170 x 170 mm black background with the remaining background on the screen colored grey to maintain a constant visual border. Participants performed 20 trials per condition, per hand (i.e., 5 trials to each peripheral target), thus, a total of 160 trials per participant (20 trials x 4 conditions x 2 hands). The order of the conditions was randomized across participants and the order of hand use (dominant, non-dominant) was counterbalanced across participants and sex. To facilitate task comprehension, each participant performed two practice trials in each direction in all task conditions, and for both hands.

A trial in the ‘Direct’ condition progressed from start to finish with: 1) a yellow colored center target was presented on the vertical touch screen. 2) Participants touched the touchscreen and moved the crosshair into the target with the index finger of their hand, and the color of the target changed to green. 3) After holding the center target for an inter-trial of 1000 ms (500-1500 ms), a red peripheral target appeared while simultaneously the center target disappeared, serving as the ‘go-signal’ for participants to slide their index finger along the touch screen to move the cursor to the target. 4) Once the peripheral target was reached and held for 250 ms, the peripheral target disappeared, and the trial ended. The next trial began again with the presentation of a yellow colored center target after an inter-trial interval of 1000 ms (500-1500 ms). The sequence was the same for the other three task conditions (Feedback Reversal, Plane Change, Plane Change + Feedback Reversal), but in the Plane Change and in the Plane Change + Feedback Reversal task conditions, participants moved their finger along the horizontal touchscreen to move the cross-haired cursor on the vertical screen.

Participants had full vision of their hand and fingers, however, participants were instructed to look at the vertical screen and to move the finger or crosshair (in the decoupled conditions) to the targets on the vertical screen and to move the finger/cursor as quickly and accurately as possible into the center of the peripheral target. Ambient distractions were kept to a minimum, and the room light was set on a low level during the experiment. The experimenter monitored participant's eye movements during the experiment and if incorrect eye movements were made, participants were reminded to always look towards the vertical screen and the presented targets but not to their hand during the horizontal task conditions. Incorrect trials were eliminated before final data analysis (< 2%).

2.3 Data Processing

Response time, finger position (x, y coordinates; 60 Hz sampling rate), and error data were recorded during each trial. Saved raw data were converted into a MATLAB readable format using a custom written C++ application. Individual movement paths derived from the cursor location were low-pass filtered with a Butterworth dual-pass filter set at 10Hz (Matlab, Mathworks Inc.). Trials were deemed errors if the finger/cursor left the center target prior to the required center hold time at the start of each trial (< 1,000 ms), reaction time was too short (< 150 ms) or too long (> 8,000 ms), or movement time was too long (> 10,000 ms). A trial was also eliminated from analysis when the initial movement exited the boundaries of the center target in the wrong direction. I.e., in the Feedback Reversal and Plane Change + Feedback Reversal condition, moving the finger towards as opposed to away from the visual target by more than 90^o from a straight line to the target. Less than 2% of the trials were eliminated from analysis due to errors.

Movement onset was set at the first occurrence of a sample passing the 10% of peak velocity threshold, which was determined using custom software. Movement offset was determined by the software as the sample point at which velocity fell below 10% of peak velocity and position data plateaued (i.e. when subjects stopped the cursor inside the peripheral target). Data scoring was verified visually to ensure that computed on- and offsets by the program were accurate. If start- and/or endpoint for a given trial was not automatically defined by the program, the analyzer provided the program an according frame around movement on- and offset (based on the velocity profile) along the time axis such that the program detected then the correct 10% thresholds. Processed data were saved and then loaded into a second custom written MATLAB analysis program to compute variables of interest similar to previous eye-hand decoupling studies (Arata, Phillips, Jones, Adkins, & Dalecki, 2019; Dalecki et al., 2016; Dalecki, Gorbet, Macpherson, & Sergio, 2019; Dalecki, Gorbet, & Sergio, 2019; Gorbet & Sergio, 2009).

2.4 Dependent Measures

The dependent variables of interest for each trial were reaction time, initial direction error, peak velocity, movement time, path length, and the absolute endpoint error. Reaction time (RT) was defined as the time in milliseconds between appearance of the peripheral target and disappearance of the central target (which functioned as the ‘go’-signal) and the movement onset (i.e. the participant began the movement execution by sliding the cursor towards the target, defined as 10% of peak velocity). The absolute initial direction error (IDE) was defined as the absolute angle in degrees between the vector between the start of the finger movement and the location of the finger at 100 ms and the vector between the start of the finger movement and the center of the peripheral target. Peak velocity (PV) was defined as the maximum velocity in mm/s during the movement. Movement time (MT) was defined as the time in milliseconds between movement onset and offset. Trajectory path length (PL) was defined as the cumulative trajectory length in mm of the path traveled between the defined start and end of the movement. The absolute error (AE), i.e. the endpoint accuracy, was defined as the distance in mm between the movement endpoint and the actual target position (defined by the x and y coordinates at the center of the peripheral target).

2.5 Statistical Analysis

Mean data across trials for each condition and hand of all dependent variables (RT, IDE, PV, MT, PL, AE) were entered into a mixed factors 2 x 2 x 2 ANOVA with Hand (Dominant, Non-dominant), Plane *of Finger Movement* (Vertical, Horizontal), and Cursor Feedback (Same, Reversed) as within subject factors. When a significant interaction between hand, plane, or feedback reversal was found, pair-wise comparisons were used to determine the origin of the effect. In addition, we did run a 2 x 2 x 2 ANCOVA with sex as a covariate to check whether outcome measures were affected by sex. All data was checked for normal distribution (Shapiro-Wilk’s test) and sphericity (Mauchly’s test) and were Greenhouse-Geisser corrected when sphericity was violated. A power analysis with G*Power (for a given Effect size f=.025, Alpha=.05, Power=.80, for Repeated measures within factors ANOVA) revealed a total sample size of 24 participants (Faul, Erdfelder, Lang, & Buchner, 2007). Statistical analyses were performed using SPSS statistical software (IBM Inc., version 25). Statistical significance levels were set to $\alpha < 0.05$.

3. Results

3.1 Dominant and non-dominant hand performance across Plane (of finger movement) and Cursor Feedback conditions

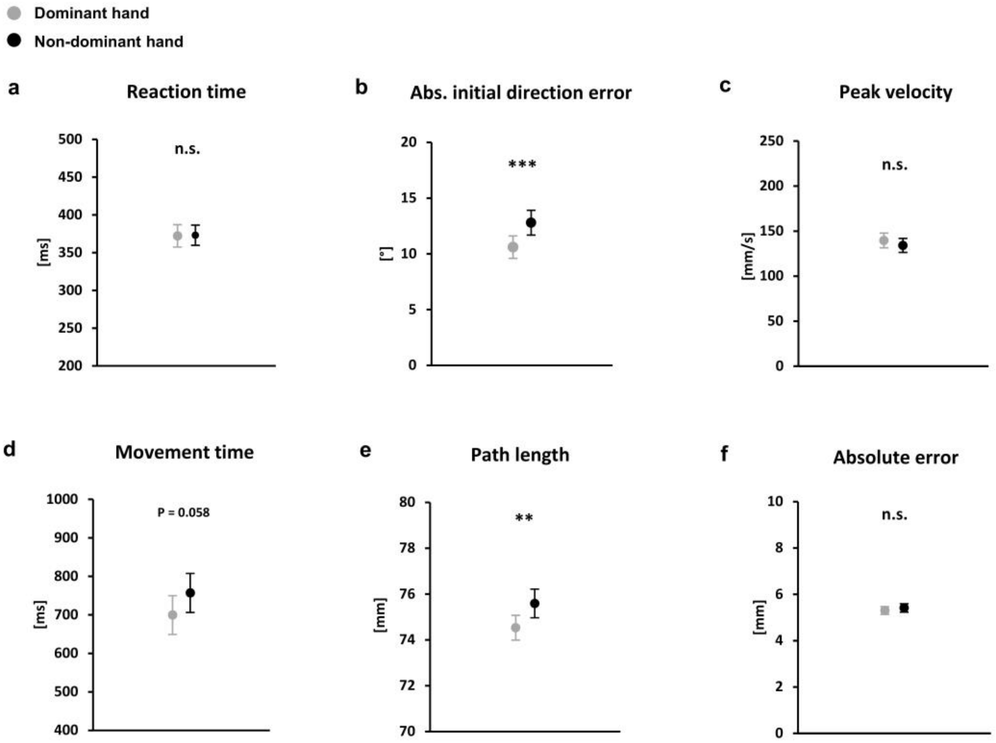


Fig. 2: Mean **a)** reaction time, **b)** initial direction error, **c)** peak velocity, **d)** movement time, **e)** path length, and **f)** absolute error of the dominant and non-dominant hand across all four task conditions. Note the performance difference between the non-dominant and dominant hand for Initial direction error and Path length but not for other variables. ** = p<0.01, *** = p<0.001, n.s. = nonsignificant. Error bars represent the standard error of the mean across participants and trials.

Table 1: Overview of significant or marginally significant results that included the factor Hand (Dominant, Non-dominant) for the mixed ANOVA. Abbreviations: MT = Movement time, PL = Path length, IDE = Initial direction error; H = Hand, P = Plane, CF = Cursor Feedback.

Variable	**Factor(s)**	**Effect values**
MT	Hand	F(1,22) = 4.011, p = 0.058, $\eta^2 = 0.154$
PL	Hand	F(1,22) = 10.735^{**} , $\eta^2 = 0.328$)
IDE	Hand	F(1,22) = 24.735^{***} , $n^2 = 0.529$
PL	H x P x CF	F(1,22) = 5.925^{*}, $n^2 = 0.212$

* < 0.05, ** < 0.01, *** < 0.001

ANOVA revealed a significant main effect of Hand only for initial direction error (IDE) (F1, 22 = 23.791, p = 0.000; $\eta^2 = .508$). IDE was larger when using the non-dominant hand (12.8 ± SD 5.5 º) compared to the dominant hand (10.6 ± 4.9 º) (see **Fig. 2 b**). Notably, ANOVA revealed a significant three-way interaction of Hand x Plane x Cursor Feedback for PL (F1,22 = 6.182, p = 0.021; $\eta^2 = .212$). It showed a more pronounced path length deficit (i.e., non-dominant hand path was larger compared to the dominant hand) in condition Feedback Reversal than in condition Direct and Plane Change. Furthermore, condition Plane Change + Feedback Reversal did not show a hand difference (cf., **Fig. 3e**). Movement time (MT) showed only a trend for a main effect of hand (F1, 22 = 3.860, p = 0.062; $\eta^2 = .144$); the non-dominant hand tended to show longer MTs (756.9 ± SD 248.1 ms) than the dominant hand (699.6 ± SD 247.0 ms) (c.f., **Fig. 2 d**). RT, PV, and AE were not significantly affected by the factor hand (all $p \geq 0.144$) (c.f., **Fig. 2 a, c, f**).

Descriptive results are summarized in the **Supplementary File I**, and ANOVA outcomes in **Supplementary File II**. All significant effects in which hand used was a factor are summarized as well in **Tab. 1**.

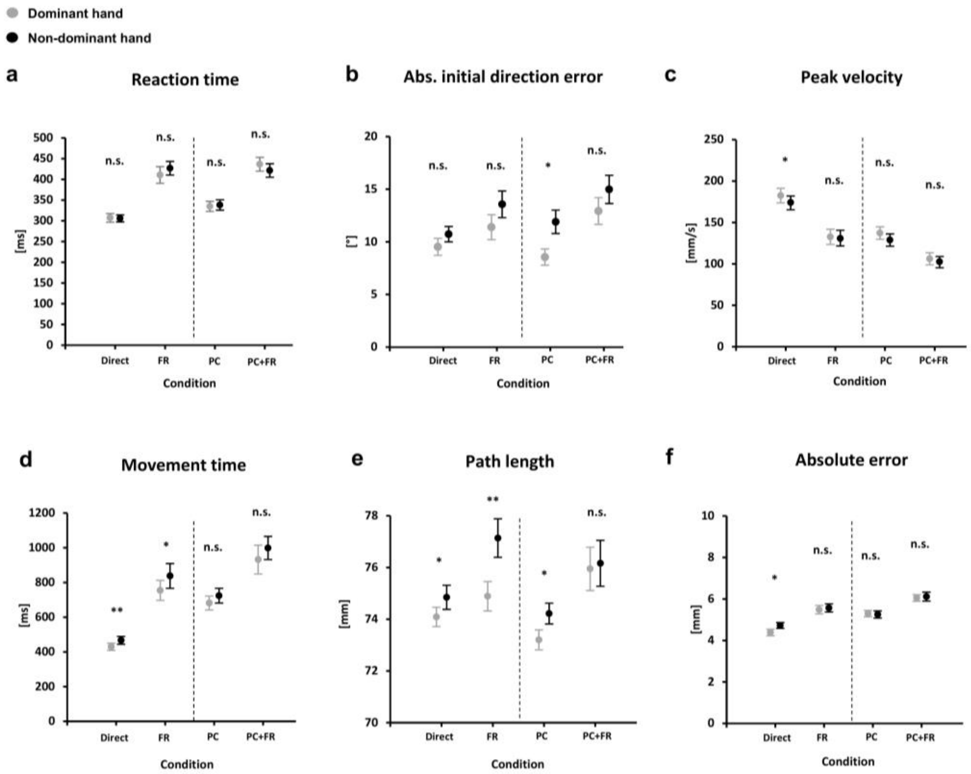


Fig. 3: Mean **a)** reaction time, **b)** initial direction error, **c)** peak velocity, **d)** movement time, **e)** path length, and **f)** absolute error of the dominant and non-dominant hand plotted for all four task conditions. Note the performance levels look different between both hands in particular for initial direction error **b)** and path length **e)**, and the number of significant differences between both hands decrease with increasing complexity of the conditions, i.e., from condition 'Direct' to condition 'Plane Change + Feedback Reversal'. * = $p<0.05$, ** = $p<0.01$, n.s. = nonsignificant. Error bars represent the standard error of the mean across participants and trials. Abbreviations: FR = Feedback Reversal, PC = Plane Change, PC + FR = Plane Change + Feedback Reversal

The following effects were found independently from the factor hand. A significant main effect of Plane for RT (F1, 22 = 8.863, p = 0.007; $\eta^2 = .278$), PV (F1, 22 = 70.284, p = 0.000; $\eta^2 = .753$), MT (F1, 22 = 54.243, p = 0.000; $\eta^2 = .702$), and AE (F1,22 = 40.081, p = 0.000; $\eta^2 = .635$) were shown, suggesting a performance decline when movements were performed in the horizontal plane (cf., **Fig. 3**). A significant main effect of Cursor Feedback was shown for all variables; i.e., RT (F1, 22 = 120.700, p = 0.000; $\eta^2 = .840$), IDE (F1,22 = 14.453, p = 0.001; $\eta^2 = .386$), PV (F1, 22 = 51.317, p = 0.000; $\eta^2 = .691$), MT (F1, 22 = 48.962, p = 0.000; $\eta^2 = .680$), PL (F1, 22 = 12.050, p = 0.002; $\eta^2 = .344$), and AE (F1, 22 = 38.354, p = 0.000; $\eta^2 = .625$), suggesting a performance decline with reversed cursor feedback for all variables (cf., **Fig. 3**). ANOVA revealed a significant interaction of Plane x Cursor Feedback for PV ($F_{1,22} = 5.400$, $p = 0.029$; $\eta^2 = .190$), showing that PV was higher in condition Direct (178.3 ± SD 33.5 mm/s) than in condition Feedback Reversal (131.8 ± SD 39.3 mm/s), Plane Change (133.1 ± SD 32.8 mm/s), and Plane Change + Feedback Reversal (104.4 ± SD 30.6 mm/s) (cf., **Fig 3c**). All other two-way and three-way interactions were non-significant (all $p>0.05$). Finally, the ANCOVA with sex as covariate did not reveal significant effects on hand, plane and feedback reversal for any of the measures (all $p>0.05$), i.e., all significant effects were independent from sex.

In summary, across the four different visuomotor conditions, the absolute initial direction error (IDE) was larger when the non-dominant was used compared with the dominant hand. Furthermore, the only significant interaction between hands and task conditions was found for path length (PL). Movement trajectory was less efficient for the non-dominant hand in the ‘Feedback Reversal‘ condition as compared to the ’Direct‘ and ’Plane Change‘ conditions, but as efficient as the dominant hand in the most the challenging ‘Plane Change + Feedback Reversal’ condition. Pairwise comparisons in each condition revealed an inverse relationship between the number of hand differences and level of decoupling between vision and action for dependent movement execution variables. In the standard mapping condition with vision and action aligned (‘Direct’), all movement execution variables (PV, MT, PL, AE) were deteriorated in the non-dominant hand (all $p<0.05$). However, with increasing level of complexity, fewer hand differences were detected. Non-dominant hand performance deteriorated only for two variables in the conditions which required one level of decoupling (‘Feedback Reversal’ and ‘Plane Change’), and notably, non-dominant hand performance was similar for all dependent measures to dominant hand performance in the most complex condition which required two levels of decoupling (‘Plane Change + Feedback Reversal’).

4. DISCUSSION

The present study examined visually guided pointing with the dominant and non-dominant hand during standard mapping and more challenging non-standard mapping tasks. Participants slid their index finger along a touchscreen in either the vertical or the horizontal plane to move a cursor from a center to peripheral targets, which were presented, always on the vertical display. Eye and hand movements were either aligned (i.e., on the same screen and eye and finger movements were made to the same direction) or unaligned (eye and hand movement direction dissociated, plane dissociated, or plane and movement direction disassociated). These different task conditions were used previously in cognitive-motor integration studies (cf., Introduction). Overall, independent of the level of decoupling, we found that trajectory-related measures such as spatial planning of unconstrained visually guided pointing movements deteriorated when using the non-dominant hand but that endpoint accuracy related measures were not affected. This finding supported our main hypothesis, which stated that we expect hand differences during these specific visually guided pointing tasks for movement trajectory-related but not for accuracy-related measures.

In the dynamic dominance hypothesis of motor lateralization, Sainburg and colleagues proposed that the dominant hand controls movement trajectory patterns more efficiently than the non-dominant hand, while the non-dominant hand controls more or equally efficient movement stability and endpoints (Sainburg, 2005; Sainburg, 2014; Wang & Sainburg, 2007). Our study results are in agreement with this hypothesis. Across the four visuomotor transformation conditions, it was shown that the initial direction error had larger deviations from the optimum when performing with the non-dominant hand compared to performance with the dominant hand; thus suggesting less efficient general movement control of the non dominant motor system (see **Fig. 2 b, e**). In contrast, movement endpoint accuracy was the same across conditions for both hands (see **Fig. 2 f**).

Our second study aim was to investigate whether the level of decoupling between eye and hand movements alters the difference between dominant and non-dominant hand performance. We predicted the rather counterintuitive outcome that increasing the level of decoupling between vision and motor action decreases the performance differences between the hands (for details, see Introduction). The data of our present study did support this hypothesis. Along the four different eye-hand decoupling conditions and dependent variables used in the present and previous cognitive-motor integration studies (Arata et al., 2019; Dalecki, Gorbet, & Sergio, 2019; Gorbet & Sergio, 2009; Gorbet & Sergio, 2019), only path length showed a significant interaction between hands and the level of decoupling. The trajectory path deterioration effect was largest when the plane was not changed ('Direct' and 'Feedback Reversal'), while movement trajectories were similar between hands in the most challenging task condition ('Plane Change + Feedback Reversal') which required the participant to decouple at two levels (see **Fig. 3e**). In accordance with this finding, we found the most profound hand differences (i.e., for all movement execution but not for movement planning related variables) in the 'Direct' condition, fewer in the Feedback Reversal' and Plane Change' condition, and none in the 'Plane Change + Feedback Reversal' condition which requires participants to decouple two levels. Therefore, when performing these specific eye-hand decoupling tasks with increasing spatial complexity that requires committing of more cognitive resources (for un-aligning the movement direction of eyes and hand, i.e., cognitive-motor integration), performance of the non-dominant hand does not deteriorate more than for the dominant hand.

Hand effects were present for initial direction error but also for path length and almost for movement time. This pattern of findings is not surprising, since these variables are related to each other. If your spatial planning is off and you start your movement in the wrong direction, your path trajectory and required time for movement are expected to be longer as well. However, it seems that the human motor system can compensate (at least partially) the overall spatial planning deficit (i.e., larger initial direction error across conditions) of the non-dominant hand during the movement execution, since path length was affected for a few but not all conditions, and movement time was only marginally affected. The influence of the spatial planning error was also larger for the spatial (i.e., on path length) and smaller for the temporal (i.e., movement time) movement characteristics, which is not surprising as well.

Notably, the most complex task condition with two levels of eye-hand decoupling (‘Plane Change + Feedback Reversal’) was the most sensitive task condition for assessing subtle behavioral changes in cognitive-motor integration studies with neurological populations (Arata et al., 2019; Dalecki, Gorbet, Macpherson, et al., 2019; Hawkins & Sergio, 2014; Salek et al., 2011; Tippett et al., 2012). However, our present study suggests that dominant and non-dominant hand performance is similar in this task condition (see **Fig. 3**) possibly suggesting that assessments can be accomplished using either hand. In turn, one might argue that the use of the ‘Plane Change + Feedback Reversal’ task condition in combination with the use of the non-dominant hand would not provide additional sensitivity for assessing performance changes in neurological populations. Instead, based on the data of our current study, the ‘Feedback Reversal’ task condition might be the more promising one. In the few previous cognitive-motor integration studies with neurological populations that included also all of the four task conditions from the present study, the ‘Feedback Reversal’ condition was the second most sensitive condition for detecting deficits during the eye-hand coordination task (Brown, Dalecki, Hughes, Macpherson, & Sergio, 2015; de Boer, Echlin, Rogojin, Baltaretu, & Sergio, 2018; Hawkins & Sergio, 2014). Further cognitive-motor integration studies that include neurological populations, the current four task conditions, and the dominant and non-dominant hand should address our suggestion that the Feedback Reversal condition might be promising for a full assessment of neurological impact on cognitive-motor integration tasks. Findings derived from these future studies could have practical implications. An assessment tool that could be performed on just one touchscreen (vertical touchscreen only, testing the ‘Direct’ and ‘Feedback Reversal’ conditions), for example on a tablet or even on a larger cell phone, could be easier implemented in field tests than an assessment that requires two touch screens (vertical and horizontal).

The present study has limitations. It focused on specific movement outcomes deemed relevant considering previous eye-hand decoupling and cognitive-motor integration studies (Dalecki et al., 2016; Dalecki, Gorbet, & Sergio, 2019; Gorbet & Sergio, 2009; Gorbet & Sergio, 2019). Future work should implement in addition outcome variables that were not used in previous and present cognitive-motor integration studies but possibly are relevant considering findings of other hand asymmetry studies, i.e., such variables as movement jerk, time to peak velocity, etc. (Schaffer & Sainburg, 2017; Tomlinson & Sainburg, 2012). Future studies about cognitive-motor integration tasks and eye-hand decoupling could expand also the present work and scrutinize whether performance outcome differences between the hands relate to changes of arm kinematics and/or kinetics. Another limitation is that we did not record eye-movements. As in our previous eye-hand decoupling studies, the experimenter observed continuously whether participants followed the task instructions, and incorrect trials were eliminated before data analysis. Therefore, we believe that it is likely that the remaining trials used for data analysis were those where participants followed the relevant instructions important for eye-hand decoupling. A manuscript with a study that included eye-tracking during eye-hand decoupling tasks is currently in progress, albeit the study focused on the vertical plane and the dominant hand only (Yeomans, Phillips, Hondzinski, & Dalecki, 2019). Thus, further work is required to account for this issue in more depth.

Future studies could also investigate whether the same pattern of findings of hand differences during cognitive-motor integration tasks are also true in other age groups (such as youth and elderly persons) or in left-hand dominant participants, because in the current study all participants were right-hand dominant. Studies with the right dominant hand have shown that eye-hand decoupling develops in children and adolescents differently for standard and non-standard mapping tasks (Dalecki, Gorbet, & Sergio, 2019), and that eye-hand decoupling is sensitive to aging (Hawkins & Sergio, 2014). Moreover, left-handed individuals appear less lateralized and more variable than right-handed individuals (Goble & Brown, 2008; McManus, 2009; Perelle & Ehrman, 2005) which may in turn lead to differences in hand asymmetries during cognitive-motor integration tasks in left-handed individuals.

Conclusions

The present study revealed performance differences between the dominant and non-dominant hand during visually guided pointing on touchscreens during cognitive-motor integration tasks with different levels of eye-hand decoupling. General hand differences were found for trajectory but not for endpoint accuracy related measures. The level of eye-hand decoupling altered only trajectory execution related measures, revealing deteriorate non-dominant hand performance in the rather simple task conditions with no or only one level of eye-hand decoupling. In contrast, the most challenging cognitive-motor integration task condition that included two levels of eye-hand decoupling did not affect performance differently when using the non-dominant and dominant hand. Therefore, we conclude that cognitive-motor integration performance differences between the non-dominant and dominant hand is inversely affected by eye-hand decoupling complexity. This finding might be relevant for study approaches focusing on hand use and neurological populations where task sensitivity is of particular importance.

Conflict of interest

Declarations of interest: none

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Supplementary file I: Overall descriptive statistics (Mean ±SD) of the four conditions (Direct, Feedback Reversal, Plane Change, Plane Change + Feedback Reversal); Abbreviations: RT = Reaction time, MT = Movement time, PV = Peak Velocity, PL = Pathlength, AE = Absolute endpoint error, IDE = Absolute initial direction error; FR = Feedback Reversal, PC = Plane Change, PL+FR = Plane Change + Feedback Reversal.

Variable	**Condition**	**Dominant**	**Non-dominant**
		[ms]	
RT	Direct	307.1 ± 50.8	305.8 ± 44.5
	FR	410.6 ± 98.7	446.0 ± 41.3
	PC	334.8 ± 59.5	345.7 ± 58.5
	PL+FR	436.5 ± 81.4	426.8 ± 80.2
MT	Direct	429.8 ± 101.6	466.8 ± 109.4
	FR	754.5 ± 282.1	837.9 ± 349.4
	PC	681.8 ± 197.5	724.1 ± 207.4
	PL+FR	932.1 ± 407.0	998.8 ± 326.2
		[mm/s]	
PV	Direct	182.4 ± 43.0	174.1 ± 38.3
	FR	132.7 ± 44.9	130.8 ± 49.0
	PC	137.2 ± 36.7	128.9 ± 36.1
	PL+FR	106.2 ± 35.6	102.7 ± 30.3
		[mm]	
PL	Direct	74.1 ± 1.8	74.9 ± 2.3
	FR	74.9 ± 2.8	77.1 ± 3.6
	PC	73.2 ± 1.9	74.2 ± 2.0
	PL+FR	76.0 ± 4.1	76.1 ± 4.4
AE	Direct	4.4 ± 0.8	4.7 ± 0.7
	FR	5.5 ± 1.1	5.6 ± 1.0
	PC	5.3 ± 0.8	5.3 ± 0.8
	PL+FR	6.1 ± 0.8	6.1 ± 1.1
		[°]	
IDE	Direct	9.5 ± 3.9	10.7 ± 3.6
	FR	11.4 ± 5.8	13.6 ± 6.2
	PC	8.6 ± 3.8	11.9 ± 5.5
	PL+FR	12.9 ± 6.2	15.0 ± 6.6

Supplementary File II: Statistics of the mixed ANOVA for Hand (Dominant, Non-dominant), Plane (Vertical, Horizontal), and Cursor Feedback (Direct, Reversed). Abbreviations: RT = Reaction time, MT = Movement time, PV = Peak Velocity, PL = Pathlength, AE = Absolute endpoint error, IDE = Initial direction error.

Variable	**Hand**			**Cursor Feedback (CF)**			**Plane (*finger movement*)**		
	(Dominant, Non-dominant)			(Direct, Reversed)			(Vertical, Horizontal)		
	F (1,22)	**p - value**	**η^2**	**F (1,22)**	**p - value**	**η^2**	**F (1,22)**	**p - value**	**η^2**
RT	0.012	0.914	0.001	116.104	0.000	0.841	9.057	0.006	0.292
MT	4.011	0.058	0.154	47.496	0.000	0.683	40.456	0.000	0.740
PV	2.191	0.153	0.091	49.830	0.000	0.694	89.982	0.000	0.804
PL	10.735	0.003	0.328	12.437	0.002	0.361	1.089	0.308	0.047
AE	0.922	0.347	0.040	37.219	0.000	0.628	46.576	0.000	0.679
IDE	24.753	0.000	0.529	13.826	0.001	0.386	0.903	0.352	0.039

Variable	**CF x Plane**			**Hand x CF**			**Hand x Plane**			**Hand x CF x Plane**		
	F (1,22)	**p - value**	**η^2**	**F (1,22)**	**p - value**	**η^2**	**F (1,22)**	**p - value**	**η^2**	**F (1,22)**	**p - value**	**η^2**
RT	1.982	0.173	0.083	0.001	0.973	0.000	2.066	0.165	0.086	2.038	0.139	0.081
MT	2.335	0.141	0.096	1.903	0.405	0.032	0.030	0.865	0.001	0.104	0.750	0.005
PV	5.378	0.030	0.196	1.666	0.210	0.070	0.034	0.855	0.002	0.033	0.858	0.001
PL	1.623	0.216	0.069	0.562	0.462	0.025	2.393	0.136	0.098	5.925	0.023	0.212
AE	2.335	0.141	0.096	0.722	0.141	0.096	0.030	0.865	0.001	0.104	0.750	0.005
IDE	1.528	0.229	0.065	0.023	0.882	0.001	0.520	0.478	0.023	0.569	0.459	0.025