Hands in mind: learning to write with both hands improves inhibitory control, but not attention

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Abstract

Embodied cognition theories predict that changing motor control would change cognitive control, as cognition is considered to emerge from action in this theoretical approach. We tested this prediction, by examining the attention and cognitive control capabilities of a group of school students (12-13-year-olds) trained to write using both hands (experimental group, N=28), compared to a group of age-matched children (control group, N=33) who did not receive such training. The key tasks used were the attentional network test (ANT) task and the hearts and flowers (HF) task. Results from the ANT task showed that there was no significant difference in the three attentional networks between the groups. However, results from the HF task showed that the experimental group had better inhibitory control. This second result provides support to the embodied cognition prediction that cognitive control and motor control are related, and the former can be changed to some extent by changing the latter.

Keywords: Embodied Cognition; Handedness; Executive Functions; Motor Control.

Introduction

Embodied theories of cognition argue that cognitive processes are shaped by the way the body interacts with the environment (Glenberg et al., 2013). This is because the brain evolved to control coordinated actions in multicellular creatures, and cognitive and affective processes evolved later, to guide action. This evolutionary view is partly based on the work of Rudolfo Llinas (2001), who argues that "A nervous system is only necessary for multicellular creatures (not cell colonies) that can orchestrate and express active movement -- a biological property known as "motricity"".

The embodied cognition position would thus predict that changes in motor control would lead to changes in cognition and affect, as the latter are derivative systems. Supporting this view, a series of studies have linked the manipulation of motor system with changes in executive functions of children as young as 5-year-olds (Stein et al., 2017; Rueda et al., 2012). Motor functions have also been shown to influence inhibition and cognitive flexibility (Livesey et al., 2006). Further, executive functions have been shown to be related to physical activity (Campbell et al., 2002; Becker et al., 2014), and motor functions (Livesey et al., 2006; Davis et al., 2011) in both kindergartners and older children (Stein et al., 2017). These effects of motor functions on cognitive functions are supported by the fact that the biological development of both motor and cognitive functions are closely related (e.g., Sibley and Etnier, 2003), and cognitive functions are stimulated and required when learning and executing new motor skills (Best, 2010; Diamond, 2000).

A related empirical thread has examined the role of handedness, and lack of consistent handedness, on cognitive and affective abilities (Casasanto, 2009; Coren, 1992). It has been shown that handedness (ranging from strongly right-handed to strongly left-handed) predicts whether electrical excitation via transcranial direct current stimulation causes an increase or decrease in the experience of approach-related emotions. (Brookshire and Casasanto, 2012). In such studies, handedness is typically considered a marker of motor training, and thus not explored further. The development of handedness and its results, particularly how training to use both hands at a young age affects cognitive abilities such as attention and executive functions, has not been much explored.

To understand the relation between handedness development and cognitive abilities, we conducted a study based on the Attentional Network Test (ANT) Task and Hearts and Flowers Task (HF). Both ANT and HF tasks are standard psychological tasks that reliably provide independent measures for different attentional networks (i.e. alerting, orienting, and executive control; Fan et al., 2002; Rueda et al., 2004) and executive function components (i.e. working memory, inhibition, and flexibility; Davidson et al., 2006). These tasks were selected as they tap into different types of inhibitory control. The ANT task involves resolving conflict of the stimulus-stimulus type (e.g. both the target and the distractors are visual stimuli in a flanker task). The HF task involves resolving conflict of the stimulus-response type (e.g. overcome the default propensity to make a response matching the stimulus location). These tasks were administered to two student groups (experimental, control) from two schools. The experimental group students studied in a school that provided a school-wide basic training to write using both hands. The control group studied in a school that had no such training.

Methods

Demographics Owing to the uniqueness (only 2 identified schools in India) of the experimental group school[1] in imparting training to write with both hands, this school was assigned to the experimental group by default. Another school which was similar in all other aspects (other than the training) was assigned as the control group school. The criteria for selecting a relevant and comparable control group were multifold: similar parents' profession and annual incomes (migrant laborers), similar school infrastructure (both low-income private schools), similar curricular and extracurricular aspects (including training on physical activities), same age groups (12-13-year-olds), and an equivalent number of languages exposed to the students (each group was familiar with at least three different languages). Apart from the training to write with both hands, the other major difference between the groups was the location: the experimental group school was a village school while the control school was in a slum in the heart of a metropolitan city. The experimental group students were familiar with Kannada, English, and Hindi while the control group students had familiarity with Hindi, English, and Marathi.

Training Process An ethnographic study of the experimental group school showed that students start their training by using their dominant hand to write during the first six months after being admitted into the school. Thus, students may start the training as early as 3 years (kindergarten) or as late as 12 years (7th grade) depending on when they join the school. They are then instructed to use the non-dominant hand for the next six months. The training starts with making lines and curves, then progresses to writing alphabets and numbers, and concludes with words and sentences. Instruction is given in small, often mixed-age groups (4-5 students per group). A teacher first demonstrates the techniques by writing on a blackboard. She then allows students to practice on the board and on their notebooks. After 3rd grade, however, these practice sessions are considered an extracurricular activity (optional) that students are free to pursue before/after school hours. Students who participated in our experiment had an average of 2.1 years (S.D. = 0.69 years) experience writing with both hands.

Attention Network Task (Child Version)

Participants 27 students (Mean age = 12.5 years, S.D. = 0.57, 12 male, 15 female) from the experimental group and 32 students (Mean age = 12.8 years, S.D. = 0.80, 19 male, 13 female) from the control group participated in the experiment. The school principal and teachers were communicated in advance about the purpose and nature of the study. Participants were explained in detail about the consent process (including the option to discontinue whenever they wanted) and the tasks, following which signed consent was obtained from each participant and school principal prior to the study. All communication between participants and experimenters was in the language that participants understood most clearly (Kannada for the experimental group and Hindi for the control group).

Stimuli and apparatus The stimuli were presented using Inquisit 5's ANT (Child version), a commercial application by Millisecond[2], run on laptops (all 15.6-inch screens: 34.54 cm x 19.41 cm) with Windows 10 OS. Participants viewed the screen from a distance of 53 cm (approx.), and responded to the stimuli by pressing two keys on the laptop keypad.

The stimuli consisted of a central fixation (+ sign) that appeared at the beginning of each trial, presented against a constant blue-green (0, 255, 255) screen background. This was followed by one of four warning cue conditions: no-cue, center-cue, double-cue, or spatial-cue. A black dot (cue) appeared in the center instead of the + sign for the center-cue condition. The double-cue condition involved the cue being presented on target locations both above and below the + sign. In the spatial-cue condition, the cue appeared either above or below the + sign. The no-cue condition did not provide any warning about the forthcoming stimulus, while the center-cue and double-cue conditions warned the participants when the target will appear. The spatial-cue condition alerted as well as indicated the locations of the target stimulus (see Fan et al., 2002; Rueda et al., 2004 for more details). (See link for a schematic diagram)

The target stimuli were a yellow color-filled line drawing of either a single fish or an array of five fish that appeared above or below the central fixation. Each fish projected a visual angle of 1.6° and the contours of adjacent fish were at a distance of 0.06° from each other. The total visual angle projected by the array of 5 fish was 8.4°. The target stimuli were presented at 1.08° above or below the central fixation.

Procedure Participants were instructed to focus on the hungry central fish and feed them by pressing the "E" (when the fish facing left) or "I" (when the fish facing right) key. While receiving the instructions, participants were asked clarifying questions to ensure that they understood the context and task requirements.

Each session lasted ~30 minutes and consisted of one practice block (24 trials) and three experimental blocks (48 trials). The trials in the experimental blocks had one of the following combinations: 4 cue conditions (no-cue, center-cue, double-cue, spatial-cue) x 3 flanker conditions (congruent, incongruent, neutral) x 2 target stimuli positions (up, down) x 2 target stimuli directions (left, right). (See link for a schematic diagram). The order of the trials was random.

Each trial sequence had the following trial structure: fixation period with randomly chosen presentation time (between 400-1600 ms), followed by a warning cue for 100 ms, followed by a fixation period of 400 ms after the disappearance of the cue, and concluding with the appearance of the target stimulus, either alone or along with

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[1] https://www.youtube.com/watch?v=PDVDw60sG5c

[2] https://www.millisecond.com/

flankers for 1700 ms. Participants had to respond within this 1700 ms duration, after which the stimulus disappeared. The inter-trial interval was set at 1000 ms. Participants received audio-visual feedback for both correct and incorrect responses during the practice block. The experimental blocks did not have any feedback.

Hearts and Flowers Task

Participants The participants for this experiment were the same as those in the ANT experiment.

Stimuli and apparatus The stimuli were presented through Inquisit 5's Hearts and Flowers Task (Child-friendly version). Other apparatus remained the same as the previous task.

The stimuli consisted of a central fixation (+ sign) followed by a heart or a flower (target stimuli) that appeared on the left or the right of the fixation cross. The fixation sign was constantly present on the white background screen while the stimuli appeared in red. The hearts/flowers appeared at a visual angle of 5.6° to the left or right of the central fixation. A heart subtended a visual angle of 2.04° whereas a flower subtended a visual angle of 2.16° (Davidson et al., 2006). (See link for a schematic diagram)

Procedure Each session lasted for ~20 minutes and consisted of three sequential blocks: Congruent-only block (Hearts as stimulus) followed by Incongruent-only (Flowers as stimulus) followed by Mixed (both Hearts and Flowers as stimulus). Each block had 8 practice trials and 20 experimental trials. The experimental trials were initiated only if participants reached an accuracy of minimum 75% in the practice trials. Participants received audio-visual feedback during the practice trials for both correct and incorrect responses. The experimental trials did not have any audio-visual feedback.

Each trial sequence in the experiment block started with the presentation of the target stimulus. The maximum response time was 5000 ms (for congruent-only and incongruent-only) and 6000 ms (for mixed block). The inter-trial interval was set at 1000 ms. Participants were required to press "A" for a heart appearing on the left of the + sign and "L" for a heart appearing to the right of the + sign (congruent trials). For the flower stimulus, participants had to press the "A" key for a flower appearing on the right of the + sign and "L" for the flower appearing to the left of the + sign (incongruent trials). Both congruent-only and incongruent-only blocks had the stimulus on the left of + sign for ten trials and on the right for the remaining ten, appearing in random order. In the mixed block, there were 10 hearts (5 right, 5 left) and 10 flowers (5 right, 5 left) that appeared in a random order, with the following constraint: a maximum of 3 trials of the same type (congruent or incongruent) could be run consecutively, and the number of switch trials (i.e. from congruent to incongruent and vice-versa) would vary from trial to trial (with a minimum of 6 per trial).

Edinburgh Handedness Inventory (EHI)

26 participants (Mean age = 12.5 years, S.D. = 0.58, 11 male, 15 female) from the experimental group and 28 (Mean age = 12.9, S.D. = 0.85, 18 male, 10 female) from the control group were provided with the EHI questionnaire (Oldfield, 1971). Participants were asked to respond orally to a 12-item questionnaire, using one of five responses: always right, usually right, both equally, usually left, always left. Since the participants were not familiar with surveys, concrete everyday examples were provided for clarification of each questionnaire item, along with the response categories. Participants were asked to act out how they would perform each of the items in the questionnaire while reporting their response. The Laterality Quotient (LQ) score for each participant was calculated as below:

$$LQ = 100\frac{(\sum \text{number of positives} - \sum \text{number of negatives})}{(\sum \text{number of positives} + \sum \text{number of negatives})}$$

Where "always right" was assigned ++ (2 positives), "usually right" was + (1 positive), "both equally" was +- (one positive, one negative), "usually left" was - (1 negative), and "always left" was -- (2 negatives). An LQ score closer to +100 denoted strongly right-handed, -100 denoted strongly left-handed, and a 0 represented an equal preference for both hands in the tasks. Scores other than the above represent the use of both hands but not in an equal measure.

Results

One-way ANCOVA using group (experimental, control) as the fixed factor and age and gender as covariates on LQ scores showed a significant main effect of group [*F*(1,50) = 6.481, *p* = 0.014, η_p^2 = 0.115]. Results revealed that the experimental group (*M* = 65.62, *S.D.* = 23.63) had significantly lower LQ score compared to control group (*M* = 83.14, *S.D.* = 13.75) (see Fig 1a). This suggests that training to use both hands might have influenced the participants to use both their hands for motor activities other than writing, as the LQ score in EHI is calculated by taking into consideration the handedness preference in various everyday general motor activities.

Attention Network Task

Overall Accuracy Analysis An 80% overall accuracy criterion led to the elimination of five participants (1 in experimental and 4 in the control group), giving 54 participants' data for further analysis. JASP software was used to perform statistical analysis. One-way ANCOVA using group (experimental, control) as the fixed factor and age and gender as the covariate on accuracy showed a main effect of group [*F*(1,50) = 6.52, *p* = 0.014, η_p^2 = 0.115] while the effect of gender and age were not significant, suggesting that the experimental group (*M* = 95.78, *S.D.* = 2.90) had significantly higher overall accuracy in the ANT task, compared to control group (*M* = 92.71, *S.D.* = 5.44) (see Fig. 1b). However, when participants' LQ score was used as a covariate, it could explain the difference in overall accuracy between the two groups [$F(1,51) = 4.446$, $p = 0.04$, $\eta_p^2 = 0.08$]. To further understand the relationship between LQ scores and overall accuracy scores, Pearson's correlation analysis was performed. Results indicated a significant negative association between LQ score and overall accuracy ($r(52) = -0.383$, $p = 0.004$), suggesting that participants with low LQ scores performed better compared to those with high LQ scores. Low LQ scores indicate more usage of both hands for everyday motor activities, whereas high LQ scores indicate more usage of a single or dominant hand.

Flanker type x Cue type x Group Analysis We performed 3 (*Flanker type:* congruent, incongruent, neutral) x 4 (*Cue type:* no-cue, center-cue, double-cue, spatial-cue) x 2 (*Group:* experimental, control) mixed ANOVA with flanker type and cue type as within subject factors and group as between subject factor on the median RTs. The main effect of flanker type [$F(1.46, 76.27) = 77.67$, $p < .001$, $\eta_p^2 = 0.599$] and cue type [$F(2.56, 133.55) = 66.30$, $p < .001$, $\eta_p^2 = 0.56$] were found to be significant. However, the main effect of group was not significant [$F(1, 52) = 0.701$, $p = 0.406$, $\eta_p^2 = 0.013$]. Planned comparisons showed that participants were significantly faster [$t(53) = 3.52$, $p < 0.001$] in the congruent flanker condition ($M = 625.33$ ms, $S.E. = 15.23$) compared to the incongruent one ($M = 697.46$ ms, $S.E. = 16.71$), showing the standard flanker effect (Ericksen & Ericksen, 1974).

Planned comparisons for different cue conditions showed that participants were significantly [$t(53) = 4.026$, $p < 0.001$] faster in the double-cue condition ($M = 633.08$ ms, $S.E. = 15.39$) compared to the no-cue condition ($M = 675.97$ ms, $S.E. = 15.08$) demonstrating the typical alerting effect of the cue on RT. Also, the difference between center-cue ($M = 645$ ms, $S.E. = 14.38$) and spatial-cue ($M = 596.63$ ms, $S.E. = 13.86$) was significant [$t(53) = 4.541$, $p < 0.001$], demonstrating the orienting effect of the spatial-cue. The difference between center-cue and no-cue was also significant [$t(53) = 2.907$, $p < 0.05$] suggesting that even the single cue had an alerting effect, though the magnitude was less compared to the double cue. There was a significant interaction between cue type and group [$F(2.56, 133.55) = 3.04$, $p = 0.031$, $\eta_p^2 = 0.055$]. Post-hoc analyses showed no significant difference between experimental and control group for each cue type.

Alerting, Orienting, and Conflict Analysis The measures of effects for the three networks were calculated by subtracting different cue type and flanker type conditions. The altering effect was calculated by subtracting the double-cue condition RT from the no-cue condition RTs. The orienting effect was calculated by subtracting the spatial-cue condition RT from center-cue condition RTs. The conflict or executive function effect was calculated by subtracting congruent flanker condition RT from incongruent flanker condition RT (Rueda et al., 2004).

Pearson's correlation analysis revealed that there was no significant correlation between any of these three networks [alerting and orienting, $r(52) = 0.081$, $p = .562$; alerting and conflict, $r(52) = 0.173$, $p = .211$; orienting and conflict, $r(52) = 0.212$, $p = .124$], thus supporting the finding in previous studies that the three networks are independent.

A series of one-way ANOVA were performed to examine the effect of group, age, and gender on the mean of median RTs and errors for the alerting, orienting and conflict quotients. None of the comparisons reached significance, except for a group difference in percentage error for alerting quotients [$F(1,49) = 4.891$, $p = 0.032$, $\eta_p^2 = 0.091$].

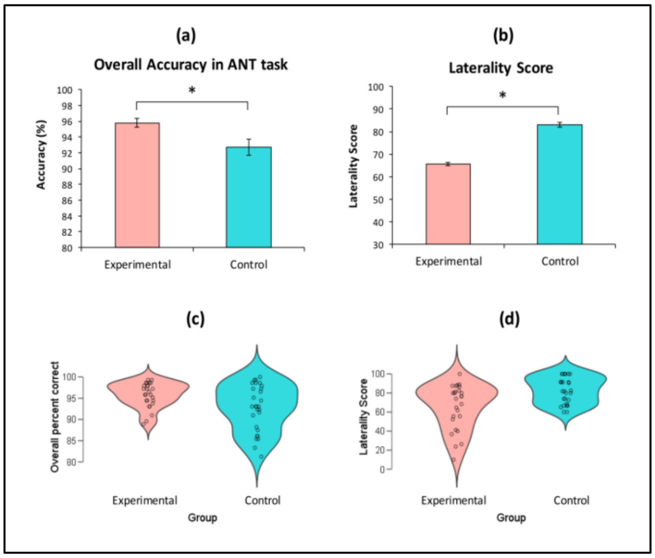

Figure 1. The top panel shows the bar plot for (a) overall accuracy in the ANT task, and (b) LQ score for both groups. The bottom panel shows the corresponding violin plot. Error bar represents S.E. of mean. * indicates <0.05

Hearts and Flowers Task

Overall Accuracy and Reaction Time An 80% overall accuracy criterion led to the elimination of five participants (3 in experimental, 2 in control). Additionally, two participants from the control group didn't complete the task. This resulted in a total of 52 participants' data for further analysis. One-way ANCOVA using group (experimental, control) as the fixed factor and age, gender, and LQ score as covariates showed no significant difference in overall accuracy between the two groups [experimental group 92%, control group 91.4%; $F(1, 48) = 0.225$, $p = 0.637$, $\eta_p^2 = 0.005$]. Similarly, there was no significant difference in overall mean RT as a function of group [$F(1, 48) = 0.388$, $p = 0.536$, $\eta_p^2 = 0.008$; experimental group, $M = 636.3$ ms, $S.E. = 28.11$; control group, $M = 660.9$ ms, $S.E. = 26.48$].

Block x Group Analysis Two-way 3 (*block type:* congruent, incongruent, mixed) x 2 (*group:* experimental, control) mixed ANOVA with block type as within subject factor and group as between subject factor on the mean RTs showed a significant main effect of block type [$F(1.64, 83.83) = 164.33$, $p < .001$, $\eta_p^2 = 0.763$]. However, the main effect of group and interactions were not significant. Planned comparisons showed the expected significant differences between congruent, incongruent and mixed block types. That is, participants were significantly faster in the congruent block ($M = 497.1$ ms, $S.E. = 18.20$) compared to both incongruent block [$M = 590.22$ ms, $S.E. = 20.26$; $t(52) = 3.642$, $p < .001$] and mixed blocks [$M = 899.194$ ms, $S.E. = 31.51$; $t(52) = 15.72$, $p < .001$]. Also, the difference between incongruent block and mixed block was significant [$t(52) = 12.08$, $p < .001$].

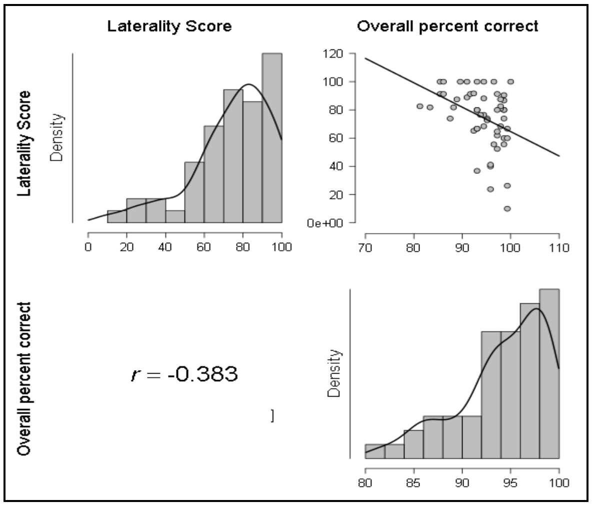

Figure 2. The correlation matrix between overall accuracy in ANT and LQ score.

Another similar 3 (block) x 2 (group) mixed ANOVA on the mean accuracy revealed a significant main effect of block type [$F(1.41, 71.99) = 54.02$, $p < .001$, $\eta_p^2 = 0.514$]. However, the main effect of *group* [$F(1, 51) = 0.119$, $p = 0.731$, $\eta_p^2 = 0.002$] and interaction [$F(1.41, 71.99) = 2.704$, $p = 0.091$, $\eta_p^2 = 0.05$] were not significant. Planned comparisons for the different block types revealed significant differences between all the groups [congruent vs. incongruent, $t(52) = 2.933$, $p < 0.05$; congruent vs. mixed, $t(52) = 8.624$, $p < 0.01$; incongruent vs. mixed, $t(52) = 5.69$, $p < 0.01$]. Results replicated the expected effects of block type on reaction time and accuracy, wherein participants became slower and less accurate as the task demand increased from congruent to incongruent to mixed block.

Inhibitory Control and Cognitive Flexibility To measure inhibitory control, the congruent block RTs (working memory) were subtracted from the incongruent block (working memory + inhibition control), and to measure cognitive flexibility the incongruent block RTs were subtracted from the mixed block (working memory + inhibition + cognitive flexibility). The switching score was obtained by subtracting the non-switch trials from the switch trials in the mixed block.

Pearson's correlation analysis was used to evaluate the association between inhibitory control, cognitive flexibility, and switching scores. Results showed a negative association ($r(52) = -0.464$, $p < .001$) between inhibitory control and cognitive flexibility, whereas other correlations were not significant [inhibitory control and switching, $r(52) = 0.162$, $p = 0.247$; cognitive flexibility and switching, $r(52) = -0.138$, $p = 0.325$]. Further analysis is needed to understand this relationship. (See link for correlation matrix)

We performed a series of one-way ANCOVAs for all the three subtraction scores, with group as the between subject variable and laterality as covariate. The only significant main effect of group was in the inhibition control for both reaction time [$F(1, 51) = 8.749$, $p = 0.005$, $\eta_p^2 = 0.146$] and accuracy [$F(1, 51) = 6.431$, $p = 0.014$, $\eta_p^2 = 0.112$]. These results suggest that participants with training to write with both hands were better in inhibitory control, compared to participants in the control group (see figure 3). (See http://handedness.surge.sh/ for more tables, figures, and a detailed analysis)

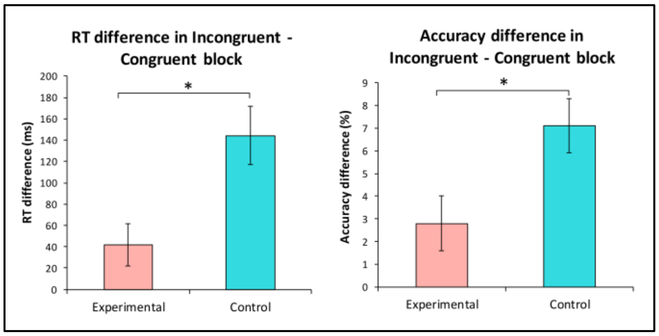

Figure 3. The bar plot displaying the difference in RT between incongruent and congruent block (left), and difference in accuracy between incongruent and congruent block (right).

Discussion

In both ANT and HF tasks, standard effects were observed, suggesting that the tasks were executed successfully. The central result was the significant group difference observed in inhibitory control, as measured by the HF task. The ANT results revealed that training to write with both hands improved overall accuracy, without significantly hampering response time. However, participants from the experimental group were slower in response (though not significantly) compared to the control group, suggesting a kind of speed-accuracy trade-off. This group difference in accuracy covaried with the differences in the LQ score. Laterality and overall accuracy were negatively correlated, suggesting that participants with low LQ scores had higher accuracy, while participants with high LQ scores had lower accuracy.

Overall, the writing training did not significantly improve performance in any of the attentional networks. Similar results were obtained by Rueda et al., (2012), where computer-based attentional training provided to school children did not significantly improve the alerting and orienting networks. However, there was an enhancement in the executive network, which overlapped with the domain of training provided to participants. Similarly, even though we did not find any significant group difference for alerting, orienting and conflict networks in ANT, we observed a significant group difference in inhibitory control as measured by the HF task.

The Hearts and Flowers task can be viewed as a child version of the Simon task, which tracks a standard tendency to inhibit the prepotent impulse when the stimulus location overlaps with the response side. People with better inhibitory control would be able to resolve this conflict faster, and would thus be less prone to the Simon effect. It has been shown that playing video games, but not visual training, improves inhibitory control, and reduces the cost of Simon effect (Hutchinson, Barrett, Nitka, &Raynes, 2016).

These results suggest that learning to write with both hands could be understood as leading to the improvement of inhibitory control. However, it is not clear how this improvement in inhibitory control is related to writing with both hands. One possibility is a heightened activation model, where writing with both hands leads to both hands getting activated by motor plans for writing, and active inhibition of one is required to write with the other. This process requires, and improves inhibitory control.

This model fits well with our ethnographic data, which showed that when students were asked to write a novel paragraph using both their hands, they did so with only with one hand at a time i.e., they did not write *simultaneously* with both hands. Some students wrote one character with one hand and the next with the other. Others wrote a word or multiple characters of a word with one hand before moving to write the next word or the remaining characters with the other hand. Based on this data and the heightened activation model, learning to write with both hands could be understood as having effects similar to learning to speak in more than one language, where all the known languages get activated when planning to speak. The speaker thus needs to inhibit the other activated languages when choosing to speak in one, and also when trying to understand speech, as many candidate words will be activated. This choosing process requires, and supports, heightened inhibitory control, whose effects would be seen in other control situations. Supporting this model, bilingualism studies show that executive function improves through learning more than one language (see Bialystok, 2001, 2011). Although these studies show that bilingualism improves cognitive control (the “bilingual advantage”), there exists a debate regarding the main effect (Anton et al., 2014). Some studies show that bilingual training only provides a domain-specific advantage (i.e. improves inhibition and control of perceptual or stimulus-stimulus type representations), and no drastic improvement in inhibition and control of motor or habitual or stimulus-response type representations (Blumenfeld & Marian, 2014; Martin-Rhee & Bialystock, 2008; Poarch, 2018). This fits well with our findings, as which show benefits of motor training on inhibitory control in the HF task but not in the ANT task. The growing literature on the cognitive control effects of *changes* in motor control (Stein et al., 2017; Stuhr et al., 2018; for a review see Diamond & Ling, 2016) -- to which our study contributes -- shows that training motor control abilities might have global effects, which are reflected in tasks wider than the immediate context of training. Apart from our results on inhibitory control, our Edinburgh Handedness Inventory (to determine handedness or the level of hand preferences for various everyday motor tasks) also found that participants who had received training to write with both hands used both hands for other everyday motor tasks, suggesting that hand preferences change in a global fashion with such training. These, and related results showing the role of action in language and imagination (Pulvermuller, 2001; Glenberg, 1997), open up the possibility of using the motor system as an intervention channel, particularly to change higher-order cognitive and affective systems.

However, this intervention possibility needs to be approached with caution, as the relationship between higher-order systems (such as imagination and language) and motor control is not straightforward, as higher-order systems typically draw on, *and recombine*, many networks, including from frontal regions of the brain. Further, tasks in higher-order cognition, such as physics problem-solving, requires bringing together many cognitive components, such as reading, imagining, calculating, reasoning, etc. Whether these processes and their integration, are improved by motor control is currently unclear.

Thus, even though schools that train students to write with both hands do so with possible educational effects in mind, the results related to wider control capabilities we report here cannot be taken as an indication of training to write with both hands improving problem-solving abilities. Further studies need to be done to investigate whether such improvements could follow from motor training. While this study leveraged the opportunity provided by a particular school that trains students to write with both hands, future studies would benefit if the above experiments are conducted as part of a controlled intervention study. This study provides a good starting point in demonstrating the effect of bimanual writing on cognitive flexibility. However, a more extensive and controlled study is required to replicate as well as extend the results.

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