Handedness Effects of Imagined Fine Motor Movements

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Abstract

Previous studies of movement imagery have found inter-individual differences in the ability to imagine whole-body movements. The majority of these studies have used subjective scales to measure imagery ability, which may be confounded by other factors related to effort. Madan and Singhal (2013) developed the Test of Ability in Movement Imagery (TAMI) to address these confounds by using a multiple-choice format with objectively correct responses. Here we developed a novel movement imagery questionnaire targeted at assessing movement imagery of fine-motor hand movements. This questionnaire included two sub-scales: Functionally-involved Movement (i.e., tool-related) and Isolated Movement (i.e., hand-only). Hand dominance effects were observed, such that right-handed participants were significantly better at responding to right-hand questions compared to left-hand questions for both imagery types. A stronger handedness effect was observed for Functionally-involved Movement imagery, and it did not correlate with the Edinburgh Handedness Inventory. We propose that the Functionally-involved Movement imagery subscale provides an objective hand imagery test that induces egocentric spatial processing and a greater involvement of memory processes, potentially providing a better skill-based measure of handedness.

Keywords: movement imagery; handedness; imagery; tool use; objects

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Lateralization Effects of Imagined Fine Motor Movements of the Hand

Introduction

Mental imagery is broadly defined as the capacity to simulate both sensory processes and motor activity. There are many types of mental imagery, one being designated to the simulation of motoric action, called motor imagery. Motor imagery is distinct from the more common visual imagery – the ability to mentally simulate a single object or scene – both in terms of the frame of reference employed, as well as the use of motion. Specifically, motor imagery typically utilizes an egocentric frame of reference, and has been argued to enhance the degree of kinesthetic feedback (Epstein 1980; Jeannerod 1994; Madan & Singhal 2012; Sirigu & Duhamel 2001). When considering novel ways to measure motor imagery, it is important to first identify the types of movements one is interested in.

Explicit movements can be classified as being either transitive or intransitive. Transitive movements involve the use of objects or tools to achieve particular goals (e.g., using a wrench), whereas intransitive movements are carried out in the absence of object- or tool-use (e.g., waving hand back-and-forth). It has been shown that manual asymmetries exist for tool-use, with right-handed participants performing better for right versus left transitive-limb gestures (Heath et al. 2002). Hand dominance describes the degree to which an individual prefers using their right or left hand when accomplishing typical motor actions (e.g., using a pen, scissors, or spoon). These effects occur because of the functional lateralization of various cognitive processes, including motoric action. Hand dominance may impact higher order cognitive processes as well, with evidence showing that children who are more right-hand dominant perform better on indices of executive function (Mills et al. 2015). The effects of hand dominance also effects the localization of language processes, as there is evidence suggesting an individual's hand preference correlates with their hemispheric lateralization of language processing (Knecht et al. 2000; Pujol et al. 1999). Further, there have been observations of increased activity in lateralized motor regions during language processing for hand-related verbs or functionally manipulable nouns, suggesting such abstract cognitive functions as language may be grounded by constructs of mental simulation such as motoric action and hand dominance (Willems et al. 2011; Just et al. 2010; Rueschemeyer et al. 2010; Saccuman et al. 2006). In the current study, observing greater performance by right-handed participants for right-hand stimuli compared to left-hand stimuli would support these proposed relationships between hand dominance and lateralized increases in cognitive function. To validate these relationships, we measured the correlation between laterality scores, operationalized as the difference between right- and left-hand performance, with the Laterality Quotient (LQ) of the Edinburgh Handedness Inventory (EHI) (Oldfield 1971). The EHI is a well-established questionnaire for evaluating handedness. When relating the novel imagery questionnaire's laterality difference score to the LQ of the EHI, we expected to obtain a moderate to strong correlation due to the unifying focus on objects.

Our ability to recognize and prioritize highly manipulable objects depends on our access to previous knowledge and experiences. One way these representations may be retrieved is by movement imagery. It has been suggested that movement imagery can be evoked automatically, without conscious intent. This has been demonstrated by activations of premotor cortex while participants only viewed images or words of functional objects, as opposed to other stimuli (Chao & Martin 2000; Buccino et al. 2001; Jarvelainen et al. 2004; Just et al. 2010; Madan et al. 2016; Yang & Shu 2013). Such automatic activations of movement imagery support the processing of tool-related stimuli and movement imagery's function in higher-level cognition. In the current study, we set out to determine if imagined hand movements can generalize from the handedness effect observed for explicit transitive movements. We developed a novel movement imagery questionnaire to include two types of hand-related movements: Functionally-involved Movement and Isolated Movement. The Functionally-involved Movement subscale required the participant to imagine transitive hand movements interacting with objects, whereas the Isolated Movement subscale required the participant to imagine intransitive hand movements in the absence of object or tool use. Where other objective tests of movement imagery have focused on whole body and gross limb movements, the novel hand imagery questionnaire provides the ability to measure imagined hand movements specifically, enabling tests to see if hand-dominance predicts movement imagery performance for two different imagery types.

Methods

Participants

A total of 79 right-handed undergraduate students with the average age of 19.14 (*SD* = 1.74) participated for partial credit towards an introductory undergraduate psychology course. All participants provided written consent and the research protocol was approved with the consent of the University of Alberta research ethics board.

Along with obtaining the degree of the student's handedness score using the Edinburgh Handedness Inventory [M (SD) LQ = 78.69 (16.09)] (Oldfield, 1971), object experience was recorded. Participants rated each object on a 9-point Likert-scale from low experience (1) to high proficiency (9). Of the 79 individuals who participated, 70 subjects were used in data analysis (49 female), with seven students excluded in all analysis due to having a LQ less than 50 (not right-handed), and two excluded due to a lack of compliance with instructions. One student was excluded only from the object experience/performance analyses due to incomplete responses.

Objective movement imagery questionnaires

Many movement imagery questionnaires rely on a participant's subjective self-report of the vividness of their imagery. Although this technique can be useful in conjunction with other imagery questionnaires, it is confounded by inflated confidence or social desirability bias, especially when comparing specific populations such as athletes. The introduction of objective imagery tests, such as the Test of Ability in Movement Imagery (TAMI), addressed this problem by using a multiple-choice format to explicitly test for an individual's imagery ability (Madan & Singhal 2013, 2014). Where TAMI presented whole-body images, the present study used images of hands, and images of highly manipulable objects under the Functionally-involved Movement imagery questions. We related these subscales to the Florida Praxis Imagery Questionnaire (FPIQ) (Ochipa et al. 1997), the original TAMI, as well as the EHI to assess how our novel questionnaire relates to extant measures of movement imagery. The FPIQ has four subscales: kinesthetic, position, action, and object. We predicted that the Isolated Movement subscale should correlate strongly with the position, kinesthetic, and action subscales, however we do not expect a high correlation with the object subscale. The Functionally-involved Movement subscale should correlate greatest with the object and position subscales of the FPIQ, as the position subscale requires one to imagine their relative finger positions when using different objects, and the object subscale requires an adequate degree of previous experience with the objects. Functionally-involved Movement imagery should also correlate to a lesser degree with the kinesthetic and action subscales, since imagining the initial hand shape still requires an ability to imagine finger joint movements. We also predicted a high correlation between Isolated Movement imagery and whole-body movements from TAMI, since both are not object-oriented, and thus a low correlation is predicted between Functionally-involved Movement imagery and TAMI.

<u>*Materials*</u>

Novel Hand Imagery Questionnaire

Our questionnaire provided an objective test of movement imagery focused on hand-related movements. Each question began with an image of an open hand, to depict the initial starting position. Five simple instructions followed, in which the participant was required to read and mentally construct the final hand position. An example of the five finger-movement instructions is as follows: “1. Lay your hand open, palm up, with your fingers together. 2. Spread your fingers apart. 3. Cross your pinky finger in front of your ring finger. 4. Point your middle finger perpendicular to the palm. 5. Touch the tip of your thumb midway up your middle finger.” The full questionnaire along with the instructions participants were provided with can be found in the Appendix. While reading these five instructions, each participant held a tennis ball in the corresponding hand in question to prevent overt hand movements from occurring. Holding the tennis ball kept the hand in a uniform, natural position, acting to prevent any motor commands involved in maintaining an unnatural hand position from arising. Such subtle attention and unconscious planning required to keep the hand in an unnatural position, such as flat against a table, could interfere with an individual’s ability to imagine movements.

The hand imagery questionnaire contained 44 questions, and used a 2 x 2 x 2 design of the between-subject factor Perspective (FPV, uninstructed), and the within-subject factors Laterality (Right, Left) and Imagery Type (Functionally-involved Movement, Isolated Movement). The questionnaire was divided into four booklets: two tested the imagined movements of the right hand, and the other two tested the imagined movements of the left hand. All four booklets contained both imagery types. Participants completed the battery of questionnaires in a classroom setting, seated at a desk. The order in which participants completed the four booklets changed across experimental session to control for order effects, and egocentric perspective instruction was manipulated between experimental sessions.

Isolated Movement imagery questions required the participant to recognize and select the correct final hand shape in a multiple-choice format (Figure 1A). Hand articulations were constructed by first generating a bank of possible movement instructions, followed by assembling subsets of these instructions in ways that led to distinct hand shapes. All hand images were produced by taking multiple photos of real hands in the selected articulations. Using Adobe Photoshop CS6 (Adobe Systems Inc.; San Jose, CA), photos were then converted to line drawings and scaled to a consistent size.

Functionally-involved Movement imagery questions required the participant to judge which of the presented objects they would most likely use with their imagined hand shape (Figure 1B). To see whether Functionally-involved Movement imagery differentiates from Isolated Movement imagery, we first selected 27 line drawings of highly manipulable objects from the Bank of Standardized Stimuli (BOSS) (Brodeur et al. 2010, 2014; Guérard et al., 2015). The BOSS is a dataset of photos and line drawings of objects that have been normed across a number of dimensions including manipulability. From the 274 line drawings included in version 2.0 of the BOSS, we selected objects based on several criteria: primarily ensuring that each object required a unique hand shape, while also selecting objects with high manipulability scores. In addition to the normed dimension of manipulability, we also considered how familiar participants were with each object, the degree of detailed lines each object possessed (visual complexity), as well as the congruency between the object stimuli and the participants' mental image (object agreement). For our chosen items, the mean (SD) scores of these normed dimensions, where 1 corresponded to low and 5 corresponded to high, were as follows: $M_{\text{Manipulability}}$ = 3.23 (.723), $M_{\text{Familiarity}}$ = 4.14 (.467), $M_{\text{VisualComplexity}}$ = 2.35 (.471), and $M_{ObjectAgreement}$ = 4.14 (.478). Mirrored images of objects were incorporated to enhance the congruency between object orientation and mental simulations of either the left or right hand. No object was keyed as the correct answer more than once.

Object experience questionnaire

The object experience questionnaire required participants to self-assess how much experience they had using each of the 27 objects appearing in the Functionally-involved Movement subscale. Assessments were made using a 9-point Likert-scale, where 1 indicated no experience, and 9 indicated very high proficiency. Participants were provided with the same line-drawn images that appear in the right-hand, Functionally-involved Movement imagery questions.

Test of Ability in Movement Imagery (TAMI)

The TAMI is a movement imagery questionnaire comprised of 10 questions that assess an individual's ability to imagine whole body movements, including manipulations of the head, arms, torso, and legs (Madan & Singhal, 2013). Questions begin with a set of 5 instructions, each describing a single body movement, with the first instruction fixed across questions to re-orient the participant, for example: "1. Stand up straight with your feet together and your hands at your sides. (See image.) 2. Place both of your hands on top of your head. 3. Step your left foot 30 cm to the side. 4. Turn your torso 60˚ to the right. 5. Tilt your head downward, towards your chest.” Following are 5 line drawings of final body positions for the participant to choose from, as well as options for “None” and “Unclear”. Answers designed to be decoys differed by a minimum of two movements. See Figure 1 of Madan and Singhal (2015) for an example. Participants were instructed to imagine the movements as their own, and to refrain from moving in any way. A practice question was provided with immediate feedback, as well as an opportunity to flip back and reread the instructions. We used the alternate scoring method (TAMIw), which reduced ceiling effects by assigning more weight to the more difficult questions, making the test out of 24 points (Madan & Singhal, 2014).

Florida Praxis Imagery Questionnaire (FPIQ)

The FPIQ is a clinical tool used to assess mental imagery ability in patients with apraxia and other movement disorders (Ochipa et al. 1997). Four subscales (position, kinesthetic, object, and action) comprise the FPIQ, each out of 12 points. The position subscale requires the participant to imagine the spatial position of their hand in relation to either an object or their other body parts during some action. For example, “Imagine you are using a fingernail clipper. Which is bent, the index finger or the thumb?” The kinesthetic subscale requires the participant to judge which joint moves the most in a given action. For example, “Imagine you are using an ice pick. Which joint moves more, your elbow or your wrist?” The object subscale requires the subject to make judgments based off of different parameters. For example, “Which is wider, the eraser at the end of a pencil, or the point?” Lastly, the action subscale requires the participant to imagine the motion of a limb when performing an action. For example, “Imagine you are using a handsaw. Does your hand move up and down, or front to back?”

Edinburgh Handedness Inventory (EHI)

The EHI was developed by Oldfield (1971) and is a 10-item questionnaire designed to measure handedness. Participants indicate whether they would prefer to complete a task using their right, left, or either hand by placing checkmarks in either hand column, or both. Further, if there is a hand preference, the strength of this preference is indicated by placing either one or two checkmarks in the respective hand column, where two checkmarks indicate the participant would never use the other hand unless forced to. The Laterality Quotient (LQ) here was calculated as the sum of the number of right-hand checkmarks, divided by the total number of checkmarks provided, and multiplied by 100, resulting in a percentage of right-handedness. The 10 items were: writing, drawing, throwing, scissors, toothbrush, knife (without fork), spoon, broom, striking a match (match), and opening a box (lid).

Procedure

All participants completed the questionnaires in the following fixed order: novel hand imagery questionnaire, TAMI, FPIQ, EHI, and object experience questionnaire.

Prior to beginning the hand imagery questionnaire, participants were given an initial instruction package containing a between-subject manipulation of frame of reference. Half of the participants were explicitly asked to imagine the movement instructions from a first-person perspective (FPV), while the other half were not given an explicit perspective instruction (uninstructed). Examples of either pointing your thumb "*parallel*" or "*perpendicular to the plane of your palm*" were provided to reduce potential confounds due to participants misunderstanding the instructions. The instructions emphasized the importance of holding the tennis ball while reading each question's movement instructions, in an attempt to prevent any overt movements. If the experimenter noticed that the participants were not holding the tennis ball while reading the movement instructions, they were reminded to do so.

After completing all imagery questionnaires, participants were given the object experience questionnaire asking them to rate their familiarity with each object from the Functionally-involved Movement subscale.

Data Analyses

Statistical analyses

A three-way mixed ANOVA was conducted to compare movement imagery accuracy as a function of the between-subject factor Perspective (FPV, uninstructed), and the within-subject factors Laterality (Right-Hand, Left-Hand), and Imagery Type (Isolated Movement, Functionally-involved Movement). Correlations were calculated between the accuracy of the imagery types and the other imagery questionnaires (TAMIw, FPIQ). Laterality difference scores were obtained by subtracting the Left-Hand accuracy from the Right-Hand accuracy, within each imagery type, and then correlated with the EHI.

Functionally-involved movement imagery

To ensure the questions were reasonably difficult, each functionally-involved movement imagery question included objects that involved closely related interactions to prevent the detection of obvious distractors. Questions were designed such that there was always one object that would be more intuitive and natural for the participant, however it is possible that these fit our own judgments, and may not represent the majority's preferences. To address this, we used participants' performance to re-calibrate the scoring of the Functionally-involved Movement imagery questions, as well as eliminate ambiguous questions. First we calculated the proportion of selected responses for each question. This indicated whether responses for a question were relatively consistent across participants or distributed across several options. To establish which questions had low variability in response (i.e., high consistency), versus an even distribution of selection (i.e., ambiguous), a root-mean-squared-deviation (RMSD) score was obtained using questions with scores near 0 representing low consistency and larger RMSD scores denoting high consistency.

To methodically determine where a cutoff point should be for the removal of poor questions, we used an Ordering Points to Identify the Clustering Structure (OPTICS) clustering algorithm (Ankerst et al. 1999; Daszykowski et al. 2002), similar to the approach used by Madan and Singhal (2014). Briefly, RMSD scores were sorted from largest to smallest, and the differences were calculated between adjacent scores. Large differences indicated a wide gap in the consistency for a question. Based on this gap, the lower bound RMSD score and all questions with lower RMSD scores were removed (7 questions). Additionally, because some questions were found to have two high occurrence responses, we divided the remaining questions into those that had only one correct answer, worth 1 point, and others with two correct answers, worth half a point. To do so, we calculated again using a clustering approach. Large difference scores represented questions in which one answer was highly favored, whereas low differences corresponded to questions in which the two most chosen responses had similar selection rates. Based on the cluster analysis, 11 questions were assigned to have one correct answer, and 4 questions assigned to have 2 correct answers (each worth 0.5 points). In the end, this led to a total score of 13, with a maximum score of 6.5 for each Laterality (left, right).

Object Performance and Experience

The mean performance across all objects was 59% (S.D.=8.0%), with the maximum of 79%, and a minimum of 45%. The mean object experience (out of 9) was 6.30 (S.D.=1.86), with a maximum of 8.56, and a minimum of 3.67. The performance and experience for each object was recorded, with the means displayed in Table 1. The correlation between participants' mean experience and performance with each object was not significant, suggesting that for these objects, a participant's experience does not relate to their performance [$r(25) = .088$, $p =.471$]. (Table 1 about here).

Differences between left-hand and right-hand question scores are depicted using cumulative distribution functions, depicting the total probability of obtaining a specific score, and all scores less than it. The abscissa is the range of scores, and the ordinate is the total probability for a given score. Curves that are shifted to the right have less data points (participants) producing lower scores, and therefore their mean score would be higher than a curve that is shifted to the left.

Results

Novel Hand Imagery Questionnaire

Table 2 provides raw-score descriptive statistics to compare the movement imagery questionnaires and subscales. Participants' overall mean (SD) accuracy was .673 (.018). Using a 2 x 2 x 2 mixed ANOVA with the between-subjects factor of Perspective (FPV, uninstructed) and the within-subjects factors of Laterality (Right-Hand, Left-Hand) and Imagery Type (Isolated Movement, Functionally-involved Movement), a main effect of Laterality was found, demonstrating a hand-dominance effect with mean Right-Hand accuracy significantly greater than mean Left-Hand [$M_{\text{Righ-Hand}}$ = .724 (.017), $M_{\text{Left-Hand}}$ = .622 (.025); $F(1,68) = 18.29$, $p <$

.001, $\eta_p^2 = .212$] . There was a main effect of Imagery Type, with greater accuracy for Isolated Movement compared to Functionally-involved Movement [$M_{\text{Isolated Movement}} = .757$ (.019), $M_{\text{Functionally-involved}} = .588$ (.021); $F(1,68) = 70.74$, $p < .001$, $\eta_p^2 = .510$]. The main effect of Perspective was not significant [$p > .1$]. A significant interaction between Laterality and Imagery Type was observed, such that there was a stronger hand-dominance effect for Functionally-involved Movement compared to Isolated Movement [$M_{\text{Functionally-involved Right-Left Difference}} = .141$ (.026), $M_{\text{Isolated Hand Right-Left Difference}} = .062$ (.023); $F(1,68) = 5.83$, $p < .05$, $\eta_p^2 = .079$] (Figure 2).

(Figure 2 around here)

Relating the two subscales of isolated and functionally-involved movement imagery produced a relatively strong correlation, indicating that these two imagery processes do share some common source of variation [$r(68) = .52$, $p < .001$]. However, this correlation corresponds to only 27% of overall shared variance (i.e., r^2), indicating that these two processes still substantially differ from each other, which is evident from the interaction between Laterality and Imagery Type, with Functionally-involved Movement imagery having a stronger hand-dominance effect. To ensure that the consistency in imagery ability between the two subscales is not entirely due to a shared relationship with any of the other questionnaires, we controlled for the four FPIQ subscales, as well as TAMIw, which produced a weaker, albeit significant correlation, eliminating the severity of a shared source of variability [$r_p(63) = .38$, $p < .01$].

(Table 2 around here).

FPIQ and TAMI

Scores for each of the FPIQ subscales were as follows: $M_{\text{kinesthetic}} = 8.67$ (1.37), $M_{\text{position}} = 10.46$ (1.82), $M_{\text{action}} = 10.61$ (1.35), and $M_{\text{object}} = 10.40$ (1.60). Though scores were near ceiling, participants performed worse on the kinesthetic subscale compared to the other three (all *p's* < .001). This pattern of results replicate the pattern of results reported in Madan and Singhal (2013) and the controls in Ochipa et al. (1997). The mean score on TAMIw was 16.90 (5.46).

<u>*Relationships between questionnaires*</u>

Hand Imagery Questionnaire and FPIQ

Both the FPIQ and our novel hand imagery questionnaire involved examining how people interact with objects. However, in our novel hand imagery questionnaire, only the Functionally-involved Movement subscale involved objects, whereas the Isolated Movement subscale did not. In looking at how our novel questionnaire relates to the FPIQ, we correlated each of our subscales to the four subscales of the FPIQ (Table 3). Measuring the degree to which these relationships could be the result of shared covariance was accomplished by running separate partial correlations. To differentiate Isolated Movement and Functionally-involved Movement imagery, partial correlations for the position and object subscales of the FPIQ were performed based on our prediction that functionally-involved movement imagery would strongly relate to these two FPIQ subscales. The partial correlation between Isolated Movement imagery and the position and object subscale was not significant [Isolated Movement-position: $r_p(66) = .043$ $p = .729$; Isolated Movement-object: $r_p(66) = .222$, $p = .069$]. When comparing Isolated Movement imagery to the object subscale of the FPIQ, the Functionally-involved Movement subscale was included as a control, since it also involved an understanding of various object parameters. (Table 3 about here).

Only the kinesthetic and object subscales of the FPIQ produced significant correlations with Functionally-involved Movement imagery (Table 3). Neither of the partial correlations between the Functionally-involved Movement suhscale and the position or object subscales of the FPIQ were significant [Functionally-involved-position: $r_p(66)= .017$, $p = .890$; Functionally-involved-object: $r_p(66)= .212$, $p = .084$].

TAMIw, Hand Imagery Questionnaire, and Edinburgh Inventory Scale

TAMIw and its correlation with the entirety of the hand imagery questionnaire was ($r(68) = .490$, $p < .001$). The relationship between TAMIw and the two types of hand movement imagery is presented in Table 3. The relationship between the participants' Edinburgh Handedness score and their Laterality difference scores for both types of hand movement imagery depicted differences, notably that the Isolated Movement subscale had a significant correlation with the EHI, whereas the Functionally-involved Movement subscale did not [$r_{\text{Isolated-EHI}}(68) = .246$, $p < .05$; $r_{\text{Functionally-involved-EHI}}(68) = -.042$, $p > .05$].

Discussion

The present study sought to investigate two types of hand-related movement imagery. Functionally-involved Movement imagery required participants to imagine hand-object interactions, whereas more abstract imagery processes required participants to imagine themselves making isolated hand-articulations. A significant laterality effect was observed for both types of imagery processes, such that right-handed participants demonstrated greater performances for right-hand questions compared to left-hand questions. An interaction between Laterality and Imagery Type further indicated that while both imagery types involve hand-related movements, differences exist between these two types of imagery, with Functionally-involved Movement imagery producing a greater hand-dominance effect.

In Sirigu and Duhamel's (2001) study with inferotemporal and left-parietal patients, they were unable to observe any immediate lateralization effects, and it is possible that this was due to the simplicity of the hand rotation task employed. There is supporting evidence to suggest imagined hand movements are in fact lateralized. Nico et al. (2004) demonstrated that amputee patients who underwent amputation of their preferred limb had higher latencies and made more errors on a left-right hand judgment task as compared to amputees of the non-dominant limb. Research employing hand laterality tasks have shown that right-handers recognize their dominant hand more easily compared to their non-dominant hand (Conson et al. 2011; Gentilucci et al. 1998; Ionta & Blanke 2009; Nì Choisdealbha et al. 2011). Further, it has been suggested that right-handers exhibit a heightened sense of ownership of their dominant hand (Hoover & Harris 2012, 2015). Moreover, when participants are required to imagine another person performing a motoric action, they imagine a significantly higher proportion of actions performed with their dominant rather than non-dominant hand, that is, right-handers report more right-handed actions compared to left-handers (Marzoli et al. 2011a; Marzoli et al. 2011b; Marzoli, et al. 2013). Not all studies produce such simple findings however. Sabate et al. (2004) found lateralization in motor planning, but left-brain lesions affected the velocity of imagined movements in both hands, whereas right-brain lesions only affected left-hand imagined movements. Our results support their findings that suggest the left hemisphere dominates in planning complex sequences of movements in right-handed individuals. To further support the laterality effect that we observed, a mirrored version of the hand imagery questionnaire could be created, such that all left-hand questions become right-hand and vice-versa. Doing so would eliminate the possibility that right-hand questions happened to be easier than left-hand questions.

The moderately strong correlation between our novel hand-imagery questionnaire and TAMI reflects the similarity between the two movement imagery questionnaires, but also demonstrates differences in the scale of body movement (hand vs. body) and degree of functional involvement (transitive vs. intransitive). This latter distinction is further demonstrated by the stronger relationship between TAMI and isolated movement imagery, compared to Functionally-involved Movement imagery. Both isolated hand and whole-body movement imagery are free of any transitive processes related to goal intention, which could reflect the unique variance in Functionally-involved Movement imagery ability. The observation that no significant partial correlations existed between either of the imagery types and the FPIQ subscales suggests that the FPIQ subscales highly co-vary, making it difficult to further distinguish between Isolated Movement imagery and Functionally-involved Movement imagery. Because the EHI is related to some degree with the mental simulations involving hands, we suggest that it may be thought of as a subjective movement imagery questionnaire itself. Subjective movement imagery questionnaires, such as the Vividness of Movement Imagery Questionnaire revised version (VMIQ-2; Roberts et al. 2008), require the participant to rate how vividly they can imagine themselves performing actions. Similarly, the EHI requires the participant to rate the degree to which they prefer using their right or left hand when performing certain actions. The relationship between the EHI and the isolated movement imagery Laterality score had a significant correlation as opposed to the relationship between the EHI and the Functionally-involved Movement imagery Laterality scores, which at first glance appears to be problematic. One would expect that imagined transitive movements oriented towards object interaction should be more sensitive to hand dominance, and therefore produce a better indication of handedness. Marzoli et al. (2017) found that when required to imagine another person performing a manual action, right-handers imagining complex actions reported a larger proportion of right-handed actions compared with imagining simple actions, demonstrating a preference towards the dominant hand with increases in motor complexity. In fact, the Functionally-involved Movement imagery questions did produce a stronger handedness effect than the Isolated Movement imagery questions, suggesting that Functionally-involved Movement imagery utilizes additional factors predicting handedness.

There are several reasons why Functionally-involved Movement imagery does not closely relate to the EHI. The first regards the frame of reference evoked in both tasks. The EHI provides a single word for each object or action with no component evoking a particular reference frame, whereas the Functionally-involved Movement imagery subscale provides images of objects, which have been shown to induce egocentric spatial processing (Ruggiero et al. 2009). Promoting an egocentric frame of reference may allow more precise coordinate frames to be tapped into during imagery of hand movements, and could facilitate a stronger handedness effect. The Functionally-involved Movement imagery subscale may also differ from the EHI in terms of depth of processing. While the EHI simply requires participants to read a word and make a hand-preference judgment, the functionally-involved imagery subscale requires participants to not only imagine a series of finger movements to arrive at a final hand-shape, but to keep this final form in mind, and apply it to several objects in view. Functionally-involved Movement imagery may rely on more goal-oriented, lateralized motor imagery processes, and thus relate more strongly to handedness. Here, right-handed participants performed relatively poorer on the more memory demanding Functionally-involved Movement subscale than on the Isolated Movement subscale, which could also explain the correlation observed between the Functionally-involved Movement subscale and the EHI. Depth of processing could also explain part of the distinction between the Isolated Movement and Functionally-involved Movement imagery subscales. The Isolated Movement subscale enables participants to match their imagined hand to an image of a hand that is visible, reducing the degree of working memory required. An interesting question going forward would involve modifying the Isolated Movement subscale to include questions where none of the images of hands were the correct final hand-shape, and thus the correct response would be “E” for “None”. Would participants be more likely to incorrectly pick one of the available options (using lower depth of processing) for non-dominant hand questions, and more likely to accurately select “None” (higher depth of processing) when imagining their dominant hand? Such a study would provide evidence to determine if a relationship exists between handedness and depth of processing.

Whether an individual is consciously aware of it or not, imagining a motoric action is done from either an egocentric (first-person) or allocentric (third-person) frame of reference. Movement imagery studies manipulating frame of reference can explicitly instruct the participant to use a particular perspective, or they can ask the participant after the experiment to report which imagery perspective they used. In the current study, we manipulated imagery perspective by either the presence or absence of an egocentric instruction. We manipulated frame of reference based on previous depictions of first-person instruction promoting an individual to primarily use motor resources, compared to third-person instructions which promote the use of visual resources when completing a mental rotation task (Sirigu & Duhamel 2001). Imagery perspective can interact with the lateralization of motor imagery on hand laterality tasks, such that an egocentric perspective speeds up the recognition of one’s own dominant hand (Conson et al. 2010, 2012; Ni Choisdealbah et al. 2011). The relative contribution of motor and visual representation elicited as a function of imagery perspective has been depicted while individuals imagined others' actions (Marzoli et al. 2011a; Marzoli et al. 2013). Specifically, a stronger activation of motor representation was elicited while a back-view/ egocentric perspective was used, compared to a front-view/allocentric perspective (Marzoli et al. 2011a). Further, perspective has been shown to influence the severity of such clinical disorders and post-traumatic stress disorder and social anxiety disorder, and can therefore pose as a new strategy for current therapeutic imagery interventions (Moran et al. 2015).

We did not observe any significant main effects when manipulating the frame of reference, however there are several explanations for this null result. The significance and strength of the effect may have been affected by the saliency of the manipulation. The egocentric instruction only appeared in the initial instruction package, and it is possible that increasing the salience by additional verbal instruction could have increased compliance. More likely, however, is the possibility that when given "uninstructed" instructions, individuals naturally imagine in an egocentric frame of reference, preventing a main effect from occurring. This is especially true if presenting images of objects or hands evokes an egocentric frame of reference. Lastly, it is possible that imagery perspective does not have an effect on imagery ability, however Roberts et al. (2008) demonstrated a higher correlation between external visual imagery (third-person) and the Movement Imagery Questionnaire (MIQ; Hall & Pongrac 1983; most recently the MIQ-RS [Movement Imagery Questionnaire - Revised, second version]; Gregg, Hall, & Butler 2010) compared to internal visual imagery (first-person). The MIQ-RS relies on incorporating information about form to accurately accomplish movements, and this information has been shown to be more readily acquired using external visual imagery (Callow & Hardy 2004). With such evidence suggesting perspective influences imagery ability, future studies could require the participant to report which perspective they used at the end of the study. Such a method would still allow the main effect or any interactions to be observed, and the issue of compliance would be resolved.

Movement imagery, which is specific to imagining motoric actions, is just one type of imagery that belongs to the greater cognitive processes known as mental simulation, which encompasses all internally-driven sensorimotor activation. Mental simulation thus affords the ability to assess manipulability, or how readily an object can be manipulated. Rueschemeyer et al. (2010) distinguished two types of manipulability: functional manipulation for instances when the object can be used in a tool-like fashion, and volumetric manipulation involving those objects that cannot be used as a tool, but are still susceptible to interaction. The same group ran an fMRI study using a lexical decision task to investigate the differences between these two types of manipulability. By showing participants names of objects that fall under each manipulability type, they found differential neural activation of areas involved in movement imagery. Hand preference itself could be another construct of mental simulation, likely involving automatic processes of simpler sensory and motor networks to establish one’s handedness. Our finding of an enhanced handedness effect for Functionally-involved Movement imagery, which incorporates more information such as the manipulability of objects, converges with the ideas surrounding embodied cognition, that our abstract cognitive processes arise from simpler and deeper processes such as our senses and ability to move.

Here we demonstrated that hand dominance influenced movement imagery ability for both isolated and functionally-involved hand movements. Our observation of a handedness effect in both types of imagery processes is not surprising, due to the common involvement of hand-related movements. The moderate correlation between the two imagery types further indicates that although they share a common source of variability, these two types of movement imagery differ in some way. With the stronger handedness effect seen for Functionally-involved Movement imagery, it is possible that these two methods of measuring imagined hand movements differ in the degree of sensitivity to handedness. We propose that the Functionally-involved Movement subscale differs from both the Isolated Movement subscale and the EHI in terms of requiring greater depth of processing, adding the construct of manipulability to the mental simulation of a hand movement by using object stimuli, and from the EHI alone by evoking an egocentric reference frame. It is possible that the EHI does not go far enough to elicit egocentric spatial processing, as the words presented in the EHI may in fact interfere with praxis. An objective hand imagery questionnaire that induces egocentric spatial processing and greater involvement of memory processes may act as a better skill-based measure of handedness.

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Table 1. Mean object experience and performance for each of the objects. Mean accuracy score determined as unique proportion of obtained versus total points accumulated from each question involving the object. Objects are listed based on their names in the BOSS (Brodeur et al. 2014) database.

Objects	Average Experience (0-9)	Average Score (0-1)
calculator(01)	8.3	0.56
bagel(01)	6.8	0.79
rearviewmirror	5.3	0.67
binoculars(01b)	4.3	0.59
dropper(01)	6.0	0.68
scissors(01)	8.2	0.57
pencil(01)	9.0	0.64
computermouse(06)	8.4	0.61
mousetrap	2.3	0.65
dice(05a)	6.5	0.71
carkey	6.4	0.63
cigarette	1.9	0.53
gamepiece	5.8	0.58
spraybottle(01)	6.7	0.66
weight(01)	6.3	0.58
soapdispenser(01)	7.9	0.51
plate(01b)	8.7	0.57
hammer(01)	5.7	0.51
iron(01b)	4.9	0.52
eraser	8.4	0.58
envelope(03a)	7.0	0.64
deodorant(02a)	7.1	0.65
nailclipper(03b)	8.0	0.45
thumbtack(02a)	6.3	0.45
lunchbox	5.8	0.51
punchingbag	4.2	0.51
syringe(01)	4.0	0.51

Table 2. Descriptive statistics of raw scores for all movement imagery measures and subscales.

	M	*SD*	Possible range	Observed range
Isolated Movement	8.329	1.886	0 – 11	2 – 11
Functionally-involved	3.825	1.415	0 – 6.5	0 – 6.5
FPIQ-Kinesthetic	8.671	1.372	0 – 12	4 – 12
FPIQ-Position	10.457	1.815	0 – 12	5 – 12
FPIQ-Action	10.614	1.354	0 – 12	4 – 12
FPIQ-Object	10.400	1.598	0 – 12	6 – 12
TAMIw	16.857	5.462	0 – 24	4 – 24

Table 3. Correlations (*r*) between the Isolated Movement (IM) and Functionally-involved Movement (FM) subscales with the FPIQ, TAMIw, and EHI.

	Isolated (IM) ***r*-coefficients**	**Functionally-Involved (FM)** ***r*-coefficients**
FPIQ-Kinesthetic	.257*	.337*
FPIQ-Position	.255*	.194
FPIQ-Action	.335*	.211
FPIQ-Object	.436**	.353*
TAMIw	.529**	.288*

* = $p < .05$; ** = $p \leq .001$.

Figure 1: Example of Isolated Movement (A) and Functionally-involved Movement (B) question types.

Figure 2: Proportion of participants' accuracy on Isolated Movement (IM)-Right versus IM-Left subscales (A). Proportion of participants' accuracy on Functionally-involved Movement (FM)-Right versus FM-Left subscales (B).