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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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47 Lateralization Effects of Imagined Fine Motor Movements of the Hand

48 **Introduction**

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

58 Explicit movements can be classified as being either transitive or intransitive. Transitive
59 movements involve the use of objects or tools to achieve particular goals (e.g., using a wrench),
60 whereas intransitive movements are carried out in the absence of object- or tool-use (e.g., waving
61 hand back-and-forth). It has been shown that manual asymmetries exist for tool-use, with right-
62 handed participants performing better for right versus left transitive-limb gestures (Heath et al.
63 2002). Hand dominance describes the degree to which an individual prefers using their right or
64 left hand when accomplishing typical motor actions (e.g., using a pen, scissors, or spoon). These
65 effects occur because of the functional lateralization of various cognitive processes, including
66 motoric action. Hand dominance may impact higher order cognitive processes as well, with
67 evidence showing that children who are more right-hand dominant perform better on indices of
68 executive function (Mills et al. 2015). The effects of hand dominance also effects the localization
69 of language processes, as there is evidence suggesting an individual's hand preference correlates

70 with their hemispheric lateralization of language processing (Knecht et al. 2000; Pujol et al.
71 1999). Further, there have been observations of increased activity in lateralized motor regions
72 during language processing for hand-related verbs or functionally manipulable nouns, suggesting
73 such abstract cognitive functions as language may be grounded by constructs of mental
74 simulation such as motoric action and hand dominance (Willems et al. 2011; Just et al. 2010;
75 Rueschemeyer et al. 2010; Saccuman et al. 2006). In the current study, observing greater
76 performance by right-handed participants for right-hand stimuli compared to left-hand stimuli
77 would support these proposed relationships between hand dominance and lateralized increases in
78 cognitive function. To validate these relationships, we measured the correlation between
79 laterality scores, operationalized as the difference between right- and left-hand performance,
80 with the Laterality Quotient (LQ) of the Edinburgh Handedness Inventory (EHI) (Oldfield 1971).
81 The EHI is a well-established questionnaire for evaluating handedness. When relating the novel
82 imagery questionnaire's laterality difference score to the LQ of the EHI, we expected to obtain a
83 moderate to strong correlation due to the unifying focus on objects.

84 Our ability to recognize and prioritize highly manipulable objects depends on our access
85 to previous knowledge and experiences. One way these representations may be retrieved is by
86 movement imagery. It has been suggested that movement imagery can be evoked automatically,
87 without conscious intent. This has been demonstrated by activations of premotor cortex while
88 participants only viewed images or words of functional objects, as opposed to other stimuli
89 (Chao & Martin 2000; Buccino et al. 2001; Jarvelainen et al. 2004; Just et al. 2010; Madan et al.
90 2016; Yang & Shu 2013). Such automatic activations of movement imagery support the
91 processing of tool-related stimuli and movement imagery's function in higher-level cognition. In
92 the current study, we set out to determine if imagined hand movements can generalize from the

93 handedness effect observed for explicit transitive movements. We developed a novel movement
94 imagery questionnaire to include two types of hand-related movements: Functionally-involved
95 Movement and Isolated Movement. The Functionally-involved Movement subscale required the
96 participant to imagine transitive hand movements interacting with objects, whereas the Isolated
97 Movement subscale required the participant to imagine intransitive hand movements in the
98 absence of object or tool use. Where other objective tests of movement imagery have focused on
99 whole body and gross limb movements, the novel hand imagery questionnaire provides the
100 ability to measure imagined hand movements specifically, enabling tests to see if hand-
101 dominance predicts movement imagery performance for two different imagery types.

102

103

Methods

Participants

104 A total of 79 right-handed undergraduate students with the average age of 19.14 ($SD =$
105 1.74) participated for partial credit towards an introductory undergraduate psychology course.
106 All participants provided written consent and the research protocol was approved with the
107 consent of the University of Alberta research ethics board.

108 Along with obtaining the degree of the student's handedness score using the Edinburgh
109 Handedness Inventory [M (SD) LQ = 78.69 (16.09)] (Oldfield, 1971), object experience was
110 recorded. Participants rated each object on a 9-point Likert-scale from low experience (1) to high
111 proficiency (9). Of the 79 individuals who participated, 70 subjects were used in data analysis
112 (49 female), with seven students excluded in all analysis due to having a LQ less than 50 (not
113 right-handed), and two excluded due to a lack of compliance with instructions. One student was
114 excluded only from the object experience/performance analyses due to incomplete responses.

115

116

117 *Objective movement imagery questionnaires*

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

139 and thus a low correlation is predicted between Functionally-involved Movement imagery and
140 TAMI.

141

142 Materials

143 *Novel Hand Imagery Questionnaire*

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

158 The hand imagery questionnaire contained 44 questions, and used a 2 x 2 x 2 design of
159 the between-subject factor Perspective (FPV, uninstructed), and the within-subject factors
160 Laterality (Right, Left) and Imagery Type (Functionally-involved Movement, Isolated
161 Movement). The questionnaire was divided into four booklets: two tested the imagined

162 movements of the right hand, and the other two tested the imagined movements of the left hand.
163 All four booklets contained both imagery types. Participants completed the battery of
164 questionnaires in a classroom setting, seated at a desk. The order in which participants completed
165 the four booklets changed across experimental session to control for order effects, and egocentric
166 perspective instruction was manipulated between experimental sessions.

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

174 Functionally-involved Movement imagery questions required the participant to judge
175 which of the presented objects they would most likely use with their imagined hand shape
176 (Figure 1B). To see whether Functionally-involved Movement imagery differentiates from
177 Isolated Movement imagery, we first selected 27 line drawings of highly manipulable objects
178 from the Bank of Standardized Stimuli (BOSS) (Brodeur et al. 2010, 2014; Guérard et al., 2015).
179 The BOSS is a dataset of photos and line drawings of objects that have been normed across a
180 number of dimensions including manipulability. From the 274 line drawings included in version
181 2.0 of the BOSS, we selected objects based on several criteria: primarily ensuring that each
182 object required a unique hand shape, while also selecting objects with high manipulability
183 scores. In addition to the normed dimension of manipulability, we also considered how familiar
184 participants were with each object, the degree of detailed lines each object possessed (visual

185 complexity), as well as the congruency between the object stimuli and the participants' mental
186 image (object agreement). For our chosen items, the mean (SD) scores of these normed
187 dimensions, where 1 corresponded to low and 5 corresponded to high, were as follows:
188 $M_{\text{Manipulability}} = 3.23 (.723)$, $M_{\text{Familiarity}} = 4.14 (.467)$, $M_{\text{VisualComplexity}} = 2.35 (.471)$, and
189 $M_{\text{ObjectAgreement}} = 4.14 (.478)$. Mirrored images of objects were incorporated to enhance the
190 congruency between object orientation and mental simulations of either the left or right hand. No
191 object was keyed as the correct answer more than once.

192

193 *Object experience questionnaire*

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

199

200 *Test of Ability in Movement Imagery (TAMI)*

201 The TAMI is a movement imagery questionnaire comprised of 10 questions that assess
202 an individual's ability to imagine whole body movements, including manipulations of the head,
203 arms, torso, and legs (Madan & Singhal, 2013). Questions begin with a set of 5 instructions, each
204 describing a single body movement, with the first instruction fixed across questions to re-orient
205 the participant, for example: "1. Stand up straight with your feet together and your hands at your
206 sides. (See image.) 2. Place both of your hands on top of your head. 3. Step your left foot 30
207 cm to the side. 4. Turn your torso 60° to the right. 5. Tilt your head downward, towards your

208 chest.” Following are 5 line drawings of final body positions for the participant to choose from,
209 as well as options for “None” and “Unclear”. Answers designed to be decoys differed by a
210 minimum of two movements. See Figure 1 of Madan and Singhal (2015) for an example.
211 Participants were instructed to imagine the movements as their own, and to refrain from moving
212 in any way. A practice question was provided with immediate feedback, as well as an
213 opportunity to flip back and reread the instructions. We used the alternate scoring method
214 (TAMIw), which reduced ceiling effects by assigning more weight to the more difficult
215 questions, making the test out of 24 points (Madan & Singhal, 2014).

216

217 *Florida Praxis Imagery Questionnaire (FPIQ)*

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

230

231 *Edinburgh Handedness Inventory (EHI)*

232 The EHI was developed by Oldfield (1971) and is a 10-item questionnaire designed to
233 measure handedness. Participants indicate whether they would prefer to complete a task using
234 their right, left, or either hand by placing checkmarks in either hand column, or both. Further, if
235 there is a hand preference, the strength of this preference is indicated by placing either one or
236 two checkmarks in the respective hand column, where two checkmarks indicate the participant
237 would never use the other hand unless forced to. The Laterality Quotient (LQ) here was
238 calculated as the sum of the number of right-hand checkmarks, divided by the total number of
239 checkmarks provided, and multiplied by 100, resulting in a percentage of right-handedness. The
240 10 items were: writing, drawing, throwing, scissors, toothbrush, knife (without fork), spoon,
241 broom, striking a match (match), and opening a box (lid).

242

243 *Procedure*

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

246 Prior to beginning the hand imagery questionnaire, participants were given an initial
247 instruction package containing a between-subject manipulation of frame of reference. Half of the
248 participants were explicitly asked to imagine the movement instructions from a first-person
249 perspective (FPV), while the other half were not given an explicit perspective instruction
250 (uninstructed). Examples of either pointing your thumb “*parallel*” or “*perpendicular to the plane*
251 *of your palm*” were provided to reduce potential confounds due to participants misunderstanding
252 the instructions. The instructions emphasized the importance of holding the tennis ball while
253 reading each question’s movement instructions, in an attempt to prevent any overt movements. If

254 the experimenter noticed that the participants were not holding the tennis ball while reading the
255 movement instructions, they were reminded to do so.

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

259

260 Data Analyses

261 *Statistical analyses*

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

269

270 *Functionally-involved movement imagery*

271 To ensure the questions were reasonably difficult, each functionally-involved movement
272 imagery question included objects that involved closely related interactions to prevent the
273 detection of obvious distractors. Questions were designed such that there was always one object
274 that would be more intuitive and natural for the participant, however it is possible that these fit
275 our own judgments, and may not represent the majority's preferences. To address this, we used
276 participants' performance to re-calibrate the scoring of the Functionally-involved Movement

277 imagery questions, as well as eliminate ambiguous questions. First we calculated the proportion
278 of selected responses for each question. This indicated whether responses for a question were
279 relatively consistent across participants or distributed across several options. To establish which
280 questions had low variability in response (i.e., high consistency), versus an even distribution of
281 selection (i.e., ambiguous), a root-mean-squared-deviation (RMSD) score was obtained using
282 questions with scores near 0 representing low consistency and larger RMSD scores denoting
283 high consistency.

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

299

300 *Object Performance and Experience*

301 The mean performance across all objects was 59% (S.D.=8.0%), with the maximum of
302 79%, and a minimum of 45%. The mean object experience (out of 9) was 6.30 (S.D.=1.86), with
303 a maximum of 8.56, and a minimum of 3.67. The performance and experience for each object
304 was recorded, with the means displayed in Table 1. The correlation between participants' mean
305 experience and performance with each object was not significant, suggesting that for these
306 objects, a participant's experience does not relate to their performance [$r(25) = .088, p = .471$].
307 (Table 1 about here).

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

314 **Results**

315 *Novel Hand Imagery Questionnaire*

316 Table 2 provides raw-score descriptive statistics to compare the movement imagery
317 questionnaires and subscales. Participants' overall mean (SD) accuracy was .673 (.018). Using a
318 2 x 2 x 2 mixed ANOVA with the between-subjects factor of Perspective (FPV, uninstructed)
319 and the within-subjects factors of Laterality (Right-Hand, Left-Hand) and Imagery Type
320 (Isolated Movement, Functionally-involved Movement), a main effect of Laterality was found,
321 demonstrating a hand-dominance effect with mean Right-Hand accuracy significantly greater
322 than mean Left-Hand [$M_{\text{Right-Hand}} = .724 (.017), M_{\text{Left-Hand}} = .622 (.025); F(1,68) = 18.29, p <$

323 .001, $\eta_p^2 = .212$] . There was a main effect of Imagery Type, with greater accuracy for Isolated
324 Movement compared to Functionally-involved Movement [$M_{\text{Isolated Movement}} = .757 (.019)$,
325 $M_{\text{Functionally-involved}} = .588 (.021)$; $F(1,68) = 70.74$, $p < .001$, $\eta_p^2 = .510$]. The main effect of
326 Perspective was not significant [$p > .1$]. A significant interaction between Laterality and Imagery
327 Type was observed, such that there was a stronger hand-dominance effect for Functionally-
328 involved Movement compared to Isolated Movement [$M_{\text{Functionally-involved Right-Left Difference}} = .141$
329 $(.026)$, $M_{\text{Isolated Hand Right-Left Difference}} = .062 (.023)$; $F(1,68) = 5.83$, $p < .05$, $\eta_p^2 = .079$] (Figure 2).
330 (Figure 2 around here)

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

342

343 *FPIQ and TAMI*

344 Scores for each of the FPIQ subscales were as follows: $M_{\text{kinesthetic}} = 8.67 (1.37)$, $M_{\text{position}} =$
345 $10.46 (1.82)$, $M_{\text{action}} = 10.61 (1.35)$, and $M_{\text{object}} = 10.40 (1.60)$. Though scores were near ceiling,

346 participants performed worse on the kinesthetic subscale compared to the other three (all p 's <
347 .001). This pattern of results replicate the pattern of results reported in Madan and Singhal
348 (2013) and the controls in Ochipa et al. (1997). The mean score on TAMiw was 16.90 (5.46).

349

350 *Relationships between questionnaires*

351 *Hand Imagery Questionnaire and FPIQ*

352 Both the FPIQ and our novel hand imagery questionnaire involved examining how
353 people interact with objects. However, in our novel hand imagery questionnaire, only the
354 Functionally-involved Movement subscale involved objects, whereas the Isolated Movement
355 subscale did not. In looking at how our novel questionnaire relates to the FPIQ, we correlated
356 each of our subscales to the four subscales of the FPIQ (Table 3). Measuring the degree to which
357 these relationships could be the result of shared covariance was accomplished by running
358 separate partial correlations. To differentiate Isolated Movement and Functionally-involved
359 Movement imagery, partial correlations for the position and object subscales of the FPIQ were
360 performed based on our prediction that functionally-involved movement imagery would strongly
361 relate to these two FPIQ subscales. The partial correlation between Isolated Movement imagery
362 and the position and object subscale was not significant [Isolated Movement-position: $r_p(66) =$
363 $.043$ $p = .729$; Isolated Movement-object: $r_p(66) = .222$, $p = .069$]. When comparing Isolated
364 Movement imagery to the object subscale of the FPIQ, the Functionally-involved Movement
365 subscale was included as a control, since it also involved an understanding of various object
366 parameters. (Table 3 about here).

367 Only the kinesthetic and object subscales of the FPIQ produced significant correlations
368 with Functionally-involved Movement imagery (Table 3). Neither of the partial correlations

369 between the Functionally-involved Movement subscale and the position or object subscales of
370 the FPIQ were significant [Functionally-involved-position: $r_p(66) = .017, p = .890$; Functionally-
371 involved-object: $r_p(66) = .212, p = .084$].

372

373 *TAMIw, Hand Imagery Questionnaire, and Edinburgh Inventory Scale*

374 TAMIw and its correlation with the entirety of the hand imagery questionnaire was ($r(68)$
375 = .490, $p < .001$). The relationship between TAMIw and the two types of hand movement
376 imagery is presented in Table 3. The relationship between the participants' Edinburgh
377 Handedness score and their Laterality difference scores for both types of hand movement
378 imagery depicted differences, notably that the Isolated Movement subscale had a significant
379 correlation with the EHI, whereas the Functionally-involved Movement subscale did not [$r_{\text{Isolated-}}$
380 $\text{EHI}(68) = .246, p < .05$; $r_{\text{Functionally-involved-EHI}}(68) = -.042, p > .05$].

381

382

Discussion

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

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

414 The moderately strong correlation between our novel hand-imagery questionnaire and
415 TAMI reflects the similarity between the two movement imagery questionnaires, but also
416 demonstrates differences in the scale of body movement (hand vs. body) and degree of
417 functional involvement (transitive vs. intransitive). This latter distinction is further demonstrated
418 by the stronger relationship between TAMI and isolated movement imagery, compared to
419 Functionally-involved Movement imagery. Both isolated hand and whole-body movement
420 imagery are free of any transitive processes related to goal intention, which could reflect the
421 unique variance in Functionally-involved Movement imagery ability. The observation that no
422 significant partial correlations existed between either of the imagery types and the FPIQ
423 subscales suggests that the FPIQ subscales highly co-vary, making it difficult to further
424 distinguish between Isolated Movement imagery and Functionally-involved Movement imagery.
425 Because the EHI is related to some degree with the mental simulations involving hands, we
426 suggest that it may be thought of as a subjective movement imagery questionnaire itself.
427 Subjective movement imagery questionnaires, such as the Vividness of Movement Imagery
428 Questionnaire revised version (VMIQ-2; Roberts et al. 2008), require the participant to rate how
429 vividly they can imagine themselves performing actions. Similarly, the EHI requires the
430 participant to rate the degree to which they prefer using their right or left hand when performing
431 certain actions. The relationship between the EHI and the isolated movement imagery Laterality
432 score had a significant correlation as opposed to the relationship between the EHI and the
433 Functionally-involved Movement imagery Laterality scores, which at first glance appears to be
434 problematic. One would expect that imagined transitive movements oriented towards object
435 interaction should be more sensitive to hand dominance, and therefore produce a better
436 indication of handedness. Marzoli et al. (2017) found that when required to imagine another

437 person performing a manual action, right-handers imagining complex actions reported a larger
438 proportion of right-handed actions compared with imagining simple actions, demonstrating a
439 preference towards the dominant hand with increases in motor complexity. In fact, the
440 Functionally-involved Movement imagery questions did produce a stronger handedness effect
441 than the Isolated Movement imagery questions, suggesting that Functionally-involved Movement
442 imagery utilizes additional factors predicting handedness.

443 There are several reasons why Functionally-involved Movement imagery does not
444 closely relate to the EHI. The first regards the frame of reference evoked in both tasks. The EHI
445 provides a single word for each object or action with no component evoking a particular
446 reference frame, whereas the Functionally-involved Movement imagery subscale provides
447 images of objects, which have been shown to induce egocentric spatial processing (Ruggiero et
448 al. 2009). Promoting an egocentric frame of reference may allow more precise coordinate frames
449 to be tapped into during imagery of hand movements, and could facilitate a stronger handedness
450 effect. The Functionally-involved Movement imagery subscale may also differ from the EHI in
451 terms of depth of processing. While the EHI simply requires participants to read a word and
452 make a hand-preference judgment, the functionally-involved imagery subscale requires
453 participants to not only imagine a series of finger movements to arrive at a final hand-shape, but
454 to keep this final form in mind, and apply it to several objects in view. Functionally-involved
455 Movement imagery may rely on more goal-oriented, lateralized motor imagery processes, and
456 thus relate more strongly to handedness. Here, right-handed participants performed relatively
457 poorer on the more memory demanding Functionally-involved Movement subscale than on the
458 Isolated Movement subscale, which could also explain the correlation observed between the
459 Functionally-involved Movement subscale and the EHI. Depth of processing could also explain

460 part of the distinction between the Isolated Movement and Functionally-involved Movement
461 imagery subscales. The Isolated Movement subscale enables participants to match their imagined
462 hand to an image of a hand that is visible, reducing the degree of working memory required. An
463 interesting question going forward would involve modifying the Isolated Movement subscale to
464 include questions where none of the images of hands were the correct final hand-shape, and thus
465 the correct response would be “E” for “None”. Would participants be more likely to incorrectly
466 pick one of the available options (using lower depth of processing) for non-dominant hand
467 questions, and more likely to accurately select “None” (higher depth of processing) when
468 imagining their dominant hand? Such a study would provide evidence to determine if a
469 relationship exists between handedness and depth of processing.

470 Whether an individual is consciously aware of it or not, imagining a motoric action is
471 done from either an egocentric (first-person) or allocentric (third-person) frame of reference.
472 Movement imagery studies manipulating frame of reference can explicitly instruct the participant
473 to use a particular perspective, or they can ask the participant after the experiment to report
474 which imagery perspective they used. In the current study, we manipulated imagery perspective
475 by either the presence or absence of an egocentric instruction. We manipulated frame of
476 reference based on previous depictions of first-person instruction promoting an individual to
477 primarily use motor resources, compared to third-person instructions which promote the use of
478 visual resources when completing a mental rotation task (Sirigu & Duhamel 2001). Imagery
479 perspective can interact with the lateralization of motor imagery on hand laterality tasks, such
480 that an egocentric perspective speeds up the recognition of one’s own dominant hand (Conson et
481 al. 2010, 2012; Ni Choisdealbah et al. 2011). The relative contribution of motor and visual
482 representation elicited as a function of imagery perspective has been depicted while individuals

483 imagined others' actions (Marzoli et al. 2011a; Marzoli et al. 2013). Specifically, a stronger
484 activation of motor representation was elicited while a back-view/ egocentric perspective was
485 used, compared to a front-view/allocentric perspective (Marzoli et al. 2011a). Further,
486 perspective has been shown to influence the severity of such clinical disorders and post-
487 traumatic stress disorder and social anxiety disorder, and can therefore pose as a new strategy for
488 current therapeutic imagery interventions (Moran et al. 2015).

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

506 still allow the main effect or any interactions to be observed, and the issue of compliance would
507 be resolved.

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

524 Here we demonstrated that hand dominance influenced movement imagery ability for
525 both isolated and functionally-involved hand movements. Our observation of a handedness effect
526 in both types of imagery processes is not surprising, due to the common involvement of hand-
527 related movements. The moderate correlation between the two imagery types further indicates
528 that although they share a common source of variability, these two types of movement imagery

529 differ in some way. With the stronger handedness effect seen for Functionally-involved
530 Movement imagery, it is possible that these two methods of measuring imagined hand
531 movements differ in the degree of sensitivity to handedness. We propose that the Functionally-
532 involved Movement subscale differs from both the Isolated Movement subscale and the EHI in
533 terms of requiring greater depth of processing, adding the construct of manipulability to the
534 mental simulation of a hand movement by using object stimuli, and from the EHI alone by
535 evoking an egocentric reference frame. It is possible that the EHI does not go far enough to elicit
536 egocentric spatial processing, as the words presented in the EHI may in fact interfere with praxis.
537 An objective hand imagery questionnaire that induces egocentric spatial processing and greater
538 involvement of memory processes may act as a better skill-based measure of handedness.

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739 **Table 1.** Mean object experience and performance for each of the objects. Mean accuracy score
 740 determined as unique proportion of obtained versus total points accumulated from each question
 741 involving the object. Objects are listed based on their names in the BOSS (Brodeur et al. 2014)
 742 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
computerouse(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

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

	<i>M</i>	<i>SD</i>	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

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

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

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

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783 **Figure 1:** Example of Isolated Movement (A) and Functionally-involved Movement (B)

784 question types.

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786 **Figure 2:** Proportion of participants' accuracy on Isolated Movement (IM)-Right versus IM-Left

787 subscales (A). Proportion of participants' accuracy on Functionally-involved Movement

788 (FM)-Right versus FM-Left subscales (B).

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