

Handedness as a Marker of Cerebral Lateralization in Children with and without Autism

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Abstract

We employed a multiple case studies approach to investigate lateralization of hand actions in typically and atypically developing children between 4 and 5 years of age. We report on a detailed set of over 1200 hand actions made by four typically developing boys and four boys with autism. Participants were assessed for unimanual hand actions to both objects and the self (self-directed behaviors). Individual and group analyses suggest that typically developing children have a right hand dominance for hand actions to objects and a left hand dominance for hand actions for self-directed behaviors, revealing a possible dissociation for functional specialization of the left and right hemispheres respectively. Children with autism demonstrated mixed-handedness for both target conditions, consistent with the hypothesis that there is reduced cerebral specialization in these children. The findings are consistent with the view that observed lateralized motor action can serve as an indirect behavioral marker for evidence of cerebral lateralization.

Keywords: cerebral lateralization, handedness, autism, self-directed behaviors

1 **1. Introduction**

2 There are different functional specializations of the left and right hemispheres for processing
3 sensory information [see 1 for a review]. The division of labor between the two hemispheres
4 is proposed to be an advantageous evolutionary adaptation found in both vertebrates [e.g. 2,
5 3] and invertebrates [e.g. 4] providing the brain with increased neural efficiency. Cerebral
6 lateralization allows for disparate specialized processing to operate in parallel within the left
7 and right hemispheres, which decreases the duplication of functioning across hemispheres and
8 eliminates the initiation of simultaneous and incompatible responses [5-7]. Not only do the
9 left and right hemispheres appear to have distinctive roles, the organization of the human
10 brain is such that the innervations of the musculature that originate from the motor cortices
11 extend contralaterally [8]. As a result, the left hemisphere controls the right side of the body
12 and the right hemisphere controls the left side of the body. Thus, hemispheric specialization
13 can manifest as contralateral physical actions [e.g. 9].

14
15 The most prominent examples of a shared lateral bias for human anatomical and functional
16 hemispheric specialization is handedness, and the neural regions associated with speech
17 production [e.g. inferior frontal gyrus: 10] and comprehension [superior temporal gyrus: 11].
18 It is commonly reported that the human population exhibits approximately 90% right-
19 handedness [e.g. 12] and, within the right-handed population, approximately 95% of
20 individuals have language-processing regions situated in the left hemisphere of the brain [13].
21 Therefore, left hemisphere specialization is prominent in right-handed individuals [e.g. 14].
22 However, the existence of a left hemisphere dominance for both language processing and
23 manual activities cannot presume that these cerebral asymmetries are correlated. Some studies
24 have shown weak correlations between the strength of handedness and cerebral specialization
25 for language in adults [15], and even an absence of a significant correlation between
26 handedness for manipulative actions and language performance in very young children [e.g.
27 16, 17]. Additionally, 70% of left-handers also demonstrate left cerebral hemisphere
28 dominance for language [14, 18], indicating a complex relationship between anatomical and

29 functional hemispheric specialism. However, as there is no unified system for measuring
30 handedness, it is also possible that differences in handedness patterns across studies may be
31 symptomatic of the vast range of measurement techniques [e.g. 19].

32

33 Handedness is often assessed through subjective self-reporting and surveys [e.g. Edinburgh
34 Handedness Inventory; 20], and has been defined using a variety of terms and measures
35 across fields of study. Handedness is commonly considered to be the hand that is preferred for
36 a specific task, regardless of performance, however it can also reflect hand efficiency with
37 respect to speed and accuracy [e.g. 21]. Handedness can be categorized as right, left or mixed
38 along a gradient that ranges from strongly left-handed to strongly right-handed [e.g. 19, 22]. It
39 is generally established by the time typically developing children start school [23-25]. As in
40 adult populations, associations have been drawn between hemispheric asymmetries associated
41 with language and hand biases in children [26]

42

43 Some investigations of child handedness suggest that left-handedness can be an indicator of
44 decreased cerebral lateralization [e.g. 27-30]. However, other studies involving children,
45 suggests that stronger hand dominance (left or right) correlates with both earlier language
46 acquisition [31] and the successful hemispheric specialization for language [1]. For example,
47 hand dominance (left or right) for manipulative tasks (e.g. drawing) has been associated with
48 typical neurodevelopment, whereas inconsistent hand dominance has been associated with
49 significantly lower developmental assessment scores in children, using the Viennese
50 Development Test (WET) [32]. A growing body of evidence now indicates that reduced
51 cortical lateralization is associated with impaired cognitive function and can manifest
52 behaviorally as mixed-handedness [e.g. 33-37].

53

54 The frequency of mixed-handedness appears to rise within populations of individuals with
55 autism (autistic spectrum disorder, ASD). ASD is a Pervasive Developmental Disorder [38],
56 marked by symptoms that commonly include reduced language and social skills. Most

57 children with ASD present impairments in receptive and expressive language [39], which can
58 be the most obvious behavioral symptom of the disorder leading to a diagnosis [40].
59 Diagnosis is generally established in early childhood, but can be severely delayed when
60 symptoms are subtle presenting alongside relatively intact language [e.g. 41]. While mixed-
61 handedness makes up approximately 3-4% of the general population [e.g. 42], populations
62 with ASD reveal mixed-handedness at proportions of between 17% and 47% [for a review see
63 43]. However, it has been reported that children with ASD who possess either left or right
64 hand dominance, generally tend to have stronger language capabilities, compared with mixed-
65 handed children with ASD. A further investigation suggests that in addition to language
66 difficulties, mixed-handed children have a greater likelihood of having scholastic and mental
67 health problems that persist into adolescence [44]. While a causal relationship between hand
68 dominance and cognitive performance remains uncertain, measures of mixed-handedness
69 could facilitate the recognition of children who are at risk for reduced cognitive function.
70
71 Recent evidence suggests that ASD is likely to have an early developmental onset
72 characterized by hypo-lateralization of brain function for expressive and receptive language
73 processes [45] long before there is visible behavioral evidence of language impairment [46].
74 Motor behaviors provide one possible area of exploration for further investigation. Motor
75 capabilities have become a topical issue in the study of overt behavioral symptoms of children
76 with ASD. It is now suspected that aberrant pruning during the development of ASD disrupts
77 early sensory and motor processes [47], causing anomalies within these domains to become
78 visible first. For example, infants with a familial risk for developing ASD have demonstrated
79 significantly lower motor scores as early as 7 months of age [48]. A firm understanding of
80 handedness strength across development for functionally specific tasks may afford a new
81 approach to indirectly assess hypo-lateralization of brain function in children at risk for ASD.
82
83 Hand dominance has traditionally focused on school-aged children and left hemisphere
84 dominant functions (e.g. object manipulation, right-handedness). In general, these studies

85 have identified putative associations between hand dominance and cognitive performance on
86 the basis of subjective parent-report, self-report or surveys for handedness. However,
87 observational studies of naturalistic hand actions have demonstrated that hand dominance can
88 be objectively revealed much earlier than pre-school age [e.g. 24]. For example, right-handed
89 dominance for manual tasks has been observed in typically developing infants between 6
90 months and 18 months of age [49, 50 51]. Studies of observed naturalistic hand dominance in
91 children, have observed actions such as pointing gestures, unimanual grasping of objects and
92 bimanual tasks. However, hand dominance for different functional behaviors (e.g.
93 communicative and non-communicative) have not been previously shown to be correlated in
94 young children [e.g. 17, 49, 52-54]. In fact, a disparate range of experimental paradigms for
95 assessing handedness in children has resulted in a variety of patterns of asymmetries
96 depending hand action function [e.g.16]. These studies showcase an opportunity for broader
97 investigations of handedness across ages, revealing more complex patterns of handedness
98 across development than previously found employing traditional reporting approaches.
99 However, these studies also highlight the possibility that differences in handedness patterns
100 across studies may be in part due to the vast range of paradigms and measurement techniques
101 employed [e.g. 19].

102

103 In addition to early handedness evaluation, observing naturalistic handedness behaviors
104 allows for the exploration of a more comprehensive range of hand behaviors. For example,
105 the study of three preliterate cultures, using methods developed in ethology, revealed that the
106 only condition under which spontaneous hand actions were preferentially lateralized across a
107 pooled dataset of naturalistic hand actions was for object manipulation during tool use.
108 Handedness for non tool-use actions, pooling a range of hand actions to both social partners
109 (e.g. embrace) and to the self (e.g. nose wipe), demonstrated a propensity towards mixed-
110 handedness [55]. The authors noted that traditional studies of handedness were narrowly
111 defined and did not represent the naturalistic actions of daily life. A recent study of children
112 also found that hand dominance varied across targets, even in those who are otherwise

113 considered right-hand dominant by parent report [56]. The authors demonstrated that while
114 typically developing right-handed boys (aged 4 to 5 years) expressed a significant right hand
115 dominance for object manipulation, no hand preference was found for hand actions directed
116 towards social partners and the self. The authors proposed that in typically developing
117 children, hand actions to object and hand actions to the self /social partners are functionally
118 different behaviors and as thus are associated with different patterns of hemispheric
119 specialization. Specifically, the authors posited that while object manipulation revealed the
120 expected left hemisphere/right hand dominance, hand actions directed to social partners and
121 the self (pooled) incorporated additional right hemisphere resources for processing social-
122 emotional content. This interpretation is consistent with prevailing theories of social-
123 emotional processing in humans. In humans, the right hemisphere hypothesis considers the
124 right hemisphere to be dominant in all forms of emotional expression and perception [e.g. 57],
125 while the valence theory posits that the left hemisphere dominance is dominant for positive
126 affect and right hemisphere dominance for negative affect [e.g. 58, 59].

127

128 Self-directed behaviors (SDBs) have been labeled by a host of names (e.g. self-adaptors [60],
129 body manipulators [61]) and have a long history within the field of psychiatry. Evidence
130 suggests a link between stress and SDBs. Specifically, the frequency of SDBs have been
131 correlated with ratings of anxiety and guilt [62]. SDBs are considered to be adaptive
132 responses to counteract stressors and facilitate a return to homeostasis [63]. To date, the
133 influence of cerebral dominance associated with hand dominance for SDBs in humans has not
134 been investigated. Compared with object manipulation, SDBs may represent a functionally
135 different type of manual behavior and would benefit from further investigation separate from
136 hand actions to social partners.

137

138 Observed naturalistic assessment of hand dominance presents certain challenges akin to that
139 of the dense data approaches required for acquiring detailed observational information from
140 individual cases of early language development [64]. Additionally, the fine-grained coding of

141 corpus data sets is a time-consuming process that typically relies on small samples and case
142 studies. Nevertheless, this approach is a data-rich process, necessary to advance our
143 understanding of the association between neurodevelopment, behavior and prognosis. To
144 date, disparities in findings from handedness studies highlight the fact that there is no existing
145 systematic approach for the assessment for handedness. Additionally, there is a paucity of
146 studies that observe naturalistic hand actions for different functional target-types across child
147 populations, hindering our understanding of any underlying relationships between cerebral
148 lateralization and hand preference.

149

150 The current study employed a behavioral observation technique (MultiDimensional Method,
151 MDM) to investigate if handedness is influenced by target type, in typically and atypically
152 developing boys. The MDM is a standardized, objective, coding framework to assess physical
153 action within space, time and context [65]. The study was designed to systematically assess
154 and compare the handedness actions of typically developing boys and boys with autism. We
155 examined how the target type of a manual action influenced the hand with which a child
156 chooses to interact with that target for both groups. Based on a previous naturalistic study
157 child handedness [e.g. 56], we hypothesized that right-handed typically developing children
158 hand choice of would vary depending on the targets type. Additionally, we hypothesized that
159 children with autism would demonstrate a weaker pattern of hand dominance consistent with
160 neuroscientific evidence of decreased lateral specialization in these individuals [45].

161

162 **2. Methods**

163

164 ***2.1 Participants***

165

166 Four typically developing (TD) boys (mean age 57.8, SD 5.25 months; range 53–65 months)
167 and four boys diagnosed with autism (mean age 60.8, SD 3.86 months; range 57–65 months)
168 participated in the study. Chronologically age-matched children participated as part of an

169 opportunity sampling of children who were all attending the same school. The test
170 environment was unique in that the TD boys attended the mainstream portion of a primary
171 school, and the boys diagnosed with autism attended the adjoining special needs section of the
172 same school, dedicated to children with a clinical diagnosis of ASD. Based on a subjective
173 report, parents were asked by letter to subjectively classify the children as left, right or mixed-
174 handed. Additionally, teachers were verbally asked to corroborate parent classification of
175 child handedness. All children chosen to participate in the study were classified as right-
176 handed. Children of this age range were chosen because evidence suggests stable handedness
177 [e.g. 24] and the cerebral processes associated with hand preference for unimanual actions
178 have been established by three years of age [49, 66]. However, strength of hand bias may
179 continue to increase until approximately seven years of age [e.g. 67]. It is not unusual that our
180 sample consisted of all boys, as there is strong evidence to suggest that more boys than girls
181 are diagnosed with ASD. The ratio of male to females diagnosed with ASDs is at least 4:1, if
182 not higher [e.g. 68]. All participants with ASD had an existing diagnosis of autism; a
183 prerequisite for admittance to the special needs school. Original diagnoses were made through
184 a variety of clinical assessments.

185

186 ***2.2 Data Capture***

187

188 The Multidimensional Method (MDM) was employed for data capture, coding and analyses
189 in order to reveal structure from signals elicited through organism-environment interactions
190 [65] and to facilitate direct comparisons with previous investigations [e.g. 56]. The MDM is
191 based on the idea that physical actions are embedded within space, time and situational
192 variables. It considers behavior as multimodal and builds on concepts of distributed cognition
193 [69-71] to provide a bottom-up, noninvasive approach to the investigation of behavior. The
194 current investigation employed a focal video sampling approach [72] in which one camera
195 recorded a close-up view of a focal individual in order to capture fine-grained manual actions.
196 Digital video cameras (Panasonic NVGS11B: UK; Sony DCR – TRV900E, IT) were tripod

197 mounted, but mobile, and followed a child's activity using zoom, tilt and swivel to optimize
198 their view. Video footage was collected at 24 frames per second. Video streams were
199 compressed to 15 frames/s for subsequent coding.

200

201 All participants were filmed during the administration of the standardized Autism Diagnostic
202 Observational Schedule (ADOS), conducted by a licensed clinician. The ADOS is a
203 standardized diagnostic assessment that addresses the developmental level and age of the
204 child through activities designed to elicit social interactions, communication and repetitive
205 behaviors for the purpose of diagnosing ASD [73]. Although the ADOS was not designed to
206 assess typical development, TD children were given the ADOS to standardize the situational
207 environment within which the observational data were collected. Experimental data collection
208 involved one continuous focal sampling session of each child during the participation of the
209 clinical assessment. The time taken to assess each child varied depending on the performance
210 of the child. All children completed the diagnostic assessment module whilst seated at a table
211 in a quiet room and in the presence of only the clinician and the cameraperson. Observation
212 times were between 20-35 minutes (Mean = 25.6, SD = 4.2).

213

214 Each participant was administered the module of the ADOS that was considered appropriate
215 for their level of verbal communication abilities. Modules ranged from 1 to 3 (1 for little or
216 no phase speech, 2 for some phase speech but verbally non-fluent, 3 for verbally fluent).

217 Three of four boys with autism were administered Module 1, while one boy with autism
218 completed Module 2. Three of four TD boys completed module 2, while one TD boy
219 completed Module 3. All participants completed all elements of the ADOS test procedure.

220 ADOS results confirmed a diagnosis of autism for all four boys placed within the ASD
221 participation group.

222

223 ***2.3 Behavioral Coding***

224

225 Handedness assessments generally consist of either or both unimanual manipulations and
226 bimanual activities. In bimanual activities, both hands are employed in a coordinated manner
227 and are sensitive to task complexity. Bimanual activities have been reported to elicit stronger
228 patterns of hand biases in children, adults [49; 74-76] and non-human primates [for a review
229 see 77]. However, unimanual actions have been shown to be sufficient to elicit patterns of
230 hand bias for functionally different targets types in both non-human primates [78, 79] and in
231 children [56] and were most suitable in order to accommodate both of the target types for the
232 present study. Unimanual actions were classified as single-handed lateralized (left, right)
233 actions that acted upon, and made physical contact with the self or and inanimate object
234 targets, while the other hand remained at rest. Any action where one hand was already
235 engaged or was performing an act of posture support was excluded from the dataset.

236

237 Two types of unimanual hand actions were considered. First, contact with the self (self-
238 directed behaviors; SDBs) consisted exclusively of manual actions directed towards and
239 making contact with the individual's own body (e.g. supporting the head, scratching actions,
240 nose wipes, eye rubs, hair and face and body manipulations). Manual actions directed towards
241 other individuals in the room (e.g. the camera person, the clinician) were excluded. Actions to
242 social partners combined with actions to the self have previously resulted in mixed-
243 handedness in gorillas [78], chimpanzees [79] and children [56]. As the present testing
244 environment did not afford social partners, the investigation provided a unique opportunity to
245 isolate and investigate SDBs as separate from actions to social partners. Second, inanimate
246 object targets comprised of all forms of manual contact with objects in the room (e.g.
247 touching, grasping, pushing). Object targets were classified as either loose or fixed non-living
248 items. However, manual contact with the table at which participants were seated was
249 excluded from analysis due to the high probability of manual contact being made with this
250 target whilst interacting with objects situated on the table. Additionally, communicative hand
251 actions, where a gesture was performed but no physical contact was made with the self or an

252 object, were also excluded from data capture (e.g. pointing). The task performed by the hand
253 was not considered, only the nature of the target itself.

254

255 There is some discussion within the primate literature about whether bouts or frequencies
256 (events) of hand actions constitute the most accurate measure of manual bias for statistical
257 analysis [80, 81]. Frequencies have raised concerns for experiments investigating bimanual
258 actions, (e.g. bimanual feeding) because these actions tend to develop into sequences, thus
259 violating an independent choice of two hands for actions subsequent to the initial dominant
260 hand choice [e.g. pseudo-replication: see 82, 83]. Because both hands were required to be ‘at
261 rest’ for the coding of unimanual actions, we preserved independence of the two hands. Thus,
262 the measures reported here represent the more conservative measure of bouts. A unimanual
263 hand frequency count was attributed to an action in which the child reached and made contact
264 with the target.

265

266 ***2.4 Data Analyses***

267

268 Analyses focused on the handedness of individual children using a dense data set of
269 naturalistic manual actions. Though participant numbers were small due to the dense data
270 approach, group comparisons were also considered.

271

272 ***2.4.1 Case Analyses***

273

274 Handedness index (HI) scores and binomial approximations to the z-scores were calculated to
275 highlight individual participant patterns. Handedness Index (HI) scores were calculated using
276 the formula $[HI = (R-L)/(R+L)]$, with R and L being the frequency counts for right and left
277 hand dominance for unimanual actions respectively. HI values vary on a continuum between -
278 1.0 and +1.0, where the sign indicates the direction of hand preference. When $R=L$, then HI is
279 zero. Positive values reflect a right hand preference while negative values reflect a left hand

280 preference. The absolute value depicts the strength of hand preference. The directional
281 strength of hand preference for each participant was calculated using z-scores such that
282 children were left handed when $z \leq -1.96$, right handed when $z \geq 1.96$ and ambiguously
283 handed when $-1.96 < z < 1.96$. Binomial tests were performed for each individual, in order to
284 indicate whether the use of the left and right hands significantly differed for SDBs and actions
285 towards inanimate objects. Alpha was set at 0.05 and all tests were two-tailed.

286

287 *2.4.2 Group Analyses*

288

289 Group analyses were conducted using Fisher's exact tests. Paired-sample t tests were used to
290 test simple effects. Because all participants were observed during the same diagnostic
291 assessment, statistical calculations were performed on raw frequencies of manual actions.
292 However, proportions were also calculated for each participant to equalize the weighting that
293 each participant contributed to the data set. Proportions were calculated by dividing the
294 frequency of left or right hand actions by the total frequency of actions.

295

296 **3. Results**

297

298 *3.1 Case Analyses*

299

300 Based on parent and teacher reports, all 8 participants were right-handed. Raw frequencies,
301 binomial approximations of z-scores for each participant (P) by lateralized target condition
302 (object, SDBs), HI scores and hand classification are presented in Table 1.

303

304 Table 1. Frequencies, binomial approximations of the z-score and HI scores of unimanual
305 lateralized hand actions to the self and to objects.

306

307 -Insert table 1-

308

309 *3.1.1 Unimanual Actions to Inanimate Targets*

310

311 *3.1.1.1 Typically Developing Children: Case Analyses*

312

313 TD1 produced 28 left-handed and 105 right-handed actions towards inanimate objects
314 resulting in a right hand HI score of 0.58 and a significant right hand bias ($p < .001$), based
315 upon the binomial approximation of the z-score ($z = 6.59$). Results from analyses of TD2,
316 TD3 and TD4 handedness followed the same pattern. TD2 produced 35 left-handed and 83
317 right-handed actions towards inanimate objects resulting in a right hand HI score of 0.41 and
318 a significant right hand bias ($p < .001$), based upon the binomial approximation of the z-score
319 ($z = 4.33$). TD3 produced 55 left-handed and 101 right-handed actions towards inanimate
320 objects resulting in a right hand HI score of 0.29 and a significant right hand bias ($p < .001$),
321 based upon the binomial approximation of the z-score ($z = 3.61$). TD4 produced 43 left-
322 handed and 86 right-handed actions towards inanimate objects resulting in a right hand HI
323 score of 0.33 and a significant right hand bias ($p < .001$), based upon the binomial
324 approximation of the z-score ($z = 3.70$).

325

326 *3.1.1.2 Children with Autism Spectrum Disorder: Case Analyses*

327

328 AS1 produced 51 left-handed and 68 right-handed actions towards inanimate targets resulting
329 in a mixed-handedness HI score of 0.14 and no significant hand preference ($p < .142$), based
330 upon the binomial approximation of the z-score ($z = 1.47$). AS2 produced 49 left-handed and
331 53 right-handed actions towards inanimate objects resulting in a mixed-handedness HI score
332 of 0.04 and no hand preference significant ($p < .764$), based upon the binomial approximation
333 of the z-score ($z = 0.30$). AS3 produced 69 left-handed and 42 right-handed actions towards
334 inanimate objects resulting a left-handed HI score of -0.24 and a significant left hand bias (P
335 < 0.014), based upon the binomial approximation of the z-score ($z = -2.47$). AS4 produced 11

336 left-handed and 26 right-handed actions towards inanimate objects resulting in a right hand HI
337 score of 0.41 and a significant right hand bias ($p < 0.021$), based upon the binomial
338 approximation of the z-score ($z = 2.30$).

339

340 ***3.1.2 Unimanual Self-Directed Behaviors***

341

342 *3.1.2.1. Typically Developing Children: Case Analyses*

343

344 TD1 produced 40 left-handed and 6 right-handed SDBs resulting in a left-handed HI score of
345 -0.54 and a significant left hand bias ($p < .001$), based upon the binomial approximation of the
346 z-score ($z = -3.74$). TD3 and TD4 followed the same pattern. TD3 produced 68 left-handed
347 and 28 right-handed SDBs resulting in a left-handed HI score of -0.42 and a significant left
348 hand bias ($p < .001$), based upon the binomial approximation of the z-score ($z = -3.98$). TD4
349 produced 31 left-handed and 5 right-handed SDBs resulting in a left-handed HI score of -0.72
350 and a significant left hand bias ($p < .001$), based upon the binomial approximation of the z-
351 score ($z = -4.17$). TD2 produced 22 left-handed and 14 right-handed SDBs resulting in a
352 mixed-handedness HI score of -0.22 and a non-significant left hand preference ($p = 0.242$)
353 based upon the binomial approximation of the z-score ($z = -1.17$).

354

355 *3.1.2.2 Children with Autism Spectrum Disorder: Case Analyses*

356

357 AS1 produced 21 left-handed and 24 right-handed SDBs resulting in a mixed-handedness
358 HI score of 0.07 and no significant hand preference ($p = .764$), based upon the binomial
359 approximation of the z-score ($z = 0.30$). AS2 produced 10 left-handed and 13 right-handed
360 SDBs resulting in a mixed-handedness HI score of 0.13 and no significant hand preference (p
361 $= .674$), based upon the binomial approximation of the z-score ($z = 0.42$). AS3 produced 10
362 left-handed and 9 right-handed SDBs resulting a mixed-handedness HI score of -0.05 and no
363 significant hand preference ($p = 1.000$), based upon the binomial approximation of the z-score

364 ($z = 1.00$). AS4 produced 12 left-handed and 10 right-handed SBDs resulting in a mixed-
365 handedness HI score of -0.09 and no significant hand preference ($p = .834$), based upon the
366 binomial approximation of the z-score ($z = -0.21$).

367

368 **3.2 Group Analyses:**

369

370 *3.2.1. Typically Developing Children*

371

372 Mean Handedness Index scores (MHI) were calculated for target categories and overall
373 strength of handedness (Figure 1). Typically developing children (who were reported by
374 parents to be right-handed individuals) demonstrated the following scores: Overall MHI = -
375 0.036, SDB MHI = -0.475, Object MHI = 0.403. A Fisher's exact test of frequencies revealed
376 a significant interaction of handedness and target type ($p < .0001$).

377

378 *3.2.2 Children with Autism Spectrum Disorder*

379

380 Mean Handedness Index scores (MHI) were calculated for target categories and overall
381 strength of handedness. Typically developing children who were reported by parents and
382 teachers to be right-handed individuals demonstrated the following scores: Overall MHI =
383 0.051, SDB MHI = 0.015, Object MHI = 0.051. A Fisher's exact test revealed no significant
384 interaction of handedness and target type ($p = 1.0$).

385

386 - Insert Figure 1-

387

388 Figure 1. Group results for the interaction of hand and action type (self, object). Mean
389 frequencies for typically developing child results are displayed in the left panel and results
390 from children with autism are displayed in the right panel.

391

392 **3.3 Total Frequencies of Hand Actions**

393

394 For TD children, SDBs accounted for 29.1% of unimanual actions, while object actions
395 accounted for 70.9% of total unimanual actions. Similarly, for children with ASD, SDB
396 targets accounted for 22.8% of unimanual actions, while object targets accounted for 77.2%
397 of unimanual actions. These percentage of actions for objects and the self were not
398 significantly different between the two experimental groups, $\chi^2(1) = 0.65, p = .42$.

399

400 **4. Discussion**

401

402 **4.1 Unimanual Actions to Objects**

403

404 Based on the findings from the present study, right-handed TD boys and right-handed boys
405 with ASD expressed different patterns of actions to objects. All TD boys demonstrated a
406 significant right-handed dominance for actions to objects at both the individual level,
407 replicating previously reported findings in both great apes [78, 79] and children [56]. One
408 interpretation of this seemingly robust pattern is that it represents an early evolutionary neural
409 division of labor, such that the left hemisphere and right hand are preferentially engaged for
410 hand actions for skilled sequences of hand actions (e.g. tool use) and language processes. A
411 left hemisphere dominance for action sequences that underlie both tool use and language
412 processes may be related to why stronger hand dominance has often been reported to correlate
413 with earlier language acquisition [31] and the successful hemispheric specialization for
414 language [1]. However, regardless of any causal relationship underlying hand preference, the
415 results suggest that for typically developing boys, hand preference is influenced by the target
416 to which the manual action is directed.

417

418 In contrast to the TD boys, only two of the four boys with ASD demonstrated a significant
419 hand dominance for actions to objects and the direction of bias was split. While one boy with

420 ASD expressed a relatively strong right-handed bias for actions to objects (HI = .41), the
421 other expressed a relatively weak left-handed preference (HI = -.24). The two remaining boys
422 with ASD showed no lateral preference for actions for objects. This result is consistent with
423 arguments that ASD is characterized by reduced cerebral lateralization [e.g. 84, 85] and
424 marked by reduced strength of handedness for object manipulation [e.g. 33-37].

425

426 ***4.2 Unimanual Actions to Self***

427

428 Few studies have investigated hand behaviors outside of object manipulation. The studies that
429 have considered hand actions for different target types have revealed mixed-handedness for
430 unimanual actions to animate targets that pooled actions to the self and to social partners [55,
431 56, 78, 79]. However, the present study addressed SDBs in isolation, considering the
432 possibility that hand actions to social partners and hand actions to the self, may be driven by
433 different processes. In humans, SDBs are often used as an index of emotional arousal with
434 regards to the stress response and have been considered the manifestation of ‘emotional
435 leakage’ [86] and as a result may have invoked more right hemisphere processing compared
436 with actions associated with objects. Analyses revealed that three of the four TD boys
437 demonstrated a significant left hand bias for SDBs, while one TD boy expressed no
438 significant lateral preference, although a non-significant right hand preference was recorded.
439 One interpretation of this pattern of results is that SDBs are preferentially controlled by the
440 right hemisphere in typically developing children. These findings are consistent with studies
441 that have reported a left-handed preference for self-directed face touching in adults who were
442 otherwise right-handed [87], and a further study that revealed that individuals reflexively raise
443 their non-dominant hand to protect their faces [88]. Although untested in the current study, it
444 is possible that SDBs might represent displacement behaviors found to be correlated with
445 levels of stress in studies of both human and nonhuman primates [89].

446

447 Although there is a paucity of human studies relating to this subject, SDBs have been
448 associated with frustration, uncertainty and anxiety in social conflict situations in a variety of
449 primate species [for a review see 90]. One study of chimpanzee SDBs demonstrated a
450 significant group-level increase in self-scratching with increased task complexity [91].
451 Interestingly, lateral patterns associated with SDBs have also been identified in non-human
452 primates. For example, rehabilitated orangutans exhibited a significant group-level lateralized
453 preference for left-handed scratching and for the fine manipulation of parts of the face [92]. A
454 further study of chimpanzees reported that while self-directed scratching showed no hand
455 preference, there was a significant bias for scratching on the left side of the body. The authors
456 postulated that this behavior was the manifestation of a right hemisphere dominant role in the
457 regulation of the autonomic nervous system during arousal [93, but see 94 for complementary
458 methodological approaches].
459
460 The left hand bias for SDBs in TD children who are otherwise right-handed children, could be
461 acting as a biomarker for heightened emotional processing. Tasks undertaken as part of the
462 ADOS involved active role-play with the clinician and timed problem solving. Increased
463 levels of task complexity or novel challenges (e.g. improvisation) may have increased stress
464 levels, resulting in an increase of right hemisphere emotional processing, eliciting left-handed
465 actions directed to the self. This interpretation is consistent with the prevailing theories of
466 social-emotional processing in humans. The right hemisphere hypothesis considers the right
467 hemisphere to be dominant in all forms of emotional expression and perception [e.g. 56].
468 Additionally, the valence theory [e.g. 57, 58] has garnered support in a number of
469 noninvasive behavioral studies including dichotic listening tasks using affective stimuli [95,
470 96] and in divided visual field studies using facial emotion stimuli [97-99], revealing a left
471 hemisphere dominance for positive affect and a right hemisphere dominance for negative
472 affect [e.g. 100, 101].
473

474 The results of the boys with ASD were markedly different from those of the TD boys. While
475 three of the four TD boys revealed handedness index (HI) scores for SDBs indicating strong
476 left hand biases (ranging between -0.42 and -0.72). All four boys with ASD revealed no hand
477 preference for SDBs with almost equal proportions of left and right hand actions directed to
478 the self and HI scores ranging from -0.09 to +0.07. Common symptoms of ASD include
479 impairments with language and social processes yet to date, research of cerebral asymmetries
480 for function tends to be devoted almost exclusively to understanding structural
481 asymmetries in language association areas [for a review see 35]. The influence of cerebral
482 dominance for emotive processing associated with hand dominance has not been thoroughly
483 investigated. These findings suggest that handedness for SDBs may engage the opposite
484 hemisphere to that controlling object manipulation and language processing and as such, can
485 provide an additional and complementary marker of cognitive function and a further indirect
486 measure of strength of cerebral lateralization.

487

488 ***4.3 Target-Dependent Unimanual Handedness***

489

490 Although the present study could not assess whether left hand biased SDBs and right hand
491 biased actions for objects in typically developing boys were a direct manifestation of right
492 and left hemisphere processing respectively, it is an important consideration for future
493 functional imaging studies. A functional dissociation between hand preference for controlling
494 hand actions for object manipulation and SDBs is consistent with an evolutionary functional
495 distinction between the two hemispheres such that the left hemisphere is dominant for
496 structured sequences of actions (e.g. tool use and language), and the right hemisphere is
497 dominant for actions that are the manifestation of emotive processing (fight or flight) [2]. As
498 such, handedness strength measures across functionally different targets may be a valuable
499 behavioral marker of successful hemispheric functional lateralization across both
500 hemispheres. Additionally, a lack of hand preference for functionally distinct targets may

501 serve as a useful biomarker for atypical lateralization of cerebral function and thus decreased
502 cognitive function.

503

504 **5. Conclusions**

505

506 The systematic observation of spontaneous naturalistic behavior across functionally disparate
507 target-types remains a largely un-tapped area of investigation. To date, studies of handedness
508 have been confounded by disparate investigative approaches across fields of study hindering
509 comparative studies and reproducibility of findings. While we highlight a lack of consistency
510 in approaches to studies of handedness, we purport that naturalistic hand actions provide a
511 rich, observable behavior that may be a valuable marker of decreased cognitive function.

512 Observational approaches of naturalistic hand behavior allow for flexible data capture across
513 different contexts allowing for the study of an ethologically valid set of hand activities.

514 Additionally, studies of naturalistic behavior afford greater flexibility for collecting data from
515 participants of all ages, allowing for the early detection of children's weak hand dominance
516 patterns.

517

518 In the future, functional imaging of the neural processing underpinning hand actions in
519 humans and a systematic inventory of typical behavioral patterns could be used to elucidate
520 the trajectory of typical hand strength development from birth to adulthood. Additionally, the
521 investigation of lateralized motor behaviors of children with different cognitive disorders and
522 delays may help to identify early disruptions to the typical development of cerebral
523 lateralization of basic sensory motor processes that have cascading consequences for the
524 development of higher cognitive functions. Because early motor deficits are not specific to
525 autism, a systematic analysis of behavioral observations of typically developing children and
526 children with developmental delays and/or disorders is necessary to understand the interaction
527 between neurodevelopment, behavior and prognosis. This study introduces one quantitative,
528 objective approach to the investigation of handedness that can be employed to evaluate

529 handedness across different human and non-human primate populations, offering an
530 opportunity to further both developmental and evolutionary aspects of human handedness.

531

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538

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886 Table 1

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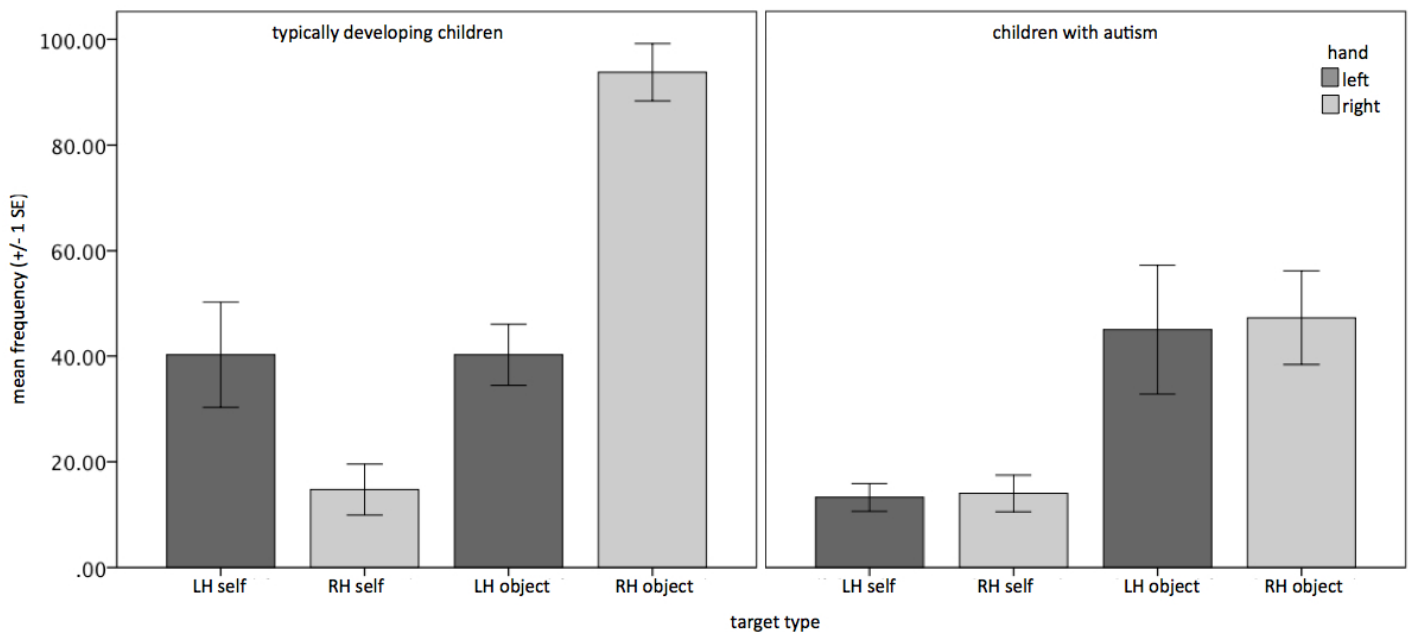
Participant	unimanal actions to objects						unimanual actions to self					
	Left F(P)	Right F(P)	Binomial Score	Z-score	HI Score	Hand Class.	Left F(P)	Right F(P)	Binomial Score	Z-score	HI Score	Hand Class.
TD 1	28(.15)	105(.57)	<0.001*	6.59	0.58	Right	40(.22)	12(.06)	<0.001*	-3.74	-0.54	Left
TD 2	35(.23)	83(.54)	<0.001*	4.33	0.41	Right	22(.14)	14(.09)	0.242	-1.17	-0.22	Mixed
TD 3	55(.22)	101(.40)	<0.001*	3.61	0.30	Right	68(.27)	28(.11)	<0.001*	-3.98	-0.42	Left
TD 4	43(.26)	86(.52)	<0.001*	3.70	0.33	Right	31(.19)	5(.03)	<0.001*	-4.17	-0.72	Left
ASD 1	51(.31)	68(.41)	0.142	1.47	0.14	Mixed	21(.13)	24(.15)	0.764	0.30	0.07	Mixed
ASD 2	49(.39)	53(.42)	0.764	0.30	0.04	Mixed	10(.08)	13(.10)	0.674	0.42	0.13	Mixed
ASD 3	69(.53)	42(.32)	0.014*	-2.47	-0.24	Left	10(.08)	9(.07)	1.000	1.00	-0.05	Mixed
ASD 4	11(.19)	26(.44)	0.021*	2.30	0.41	Right	12(.20)	10(.17)	0.834	-0.21	-0.09	Mixed

* significant <math>P < 0.05</math>, TD = typically developing, ASD = autism spectrum disorder, F = frequency, P = proportion, HI score = handedness index, Hand Class. = hand classification based on binomial significance

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890 Figure 1

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