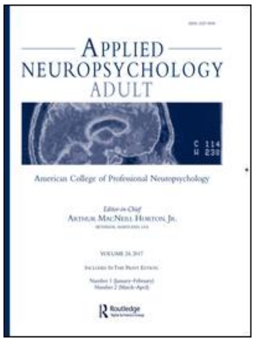

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Factor analysis of the Home Handedness Questionnaire: Unimanual and role differentiated bimanual manipulation as separate dimensions of handedness

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ABSTRACT
Questionnaires are commonly used to measure handedness. However, popular measures do not capture hand preference by skill type, thus reducing handedness to a single dimension. An exception is the Home Handedness Questionnaire (HHQ), an action-based measure developed initially for children, which measures skills across two dimensions of handedness: unimanual actions and role differentiated bimanual manipulation (RDBM). The goal of the current study was to confirm the factor structure of the HHQ in a large sample of adults ($N = 1051$). A secondary goal was to measure RDBM hand preference in adults. To further validate the HHQ, participants also completed the Edinburgh Handedness Inventory (EHI). Confirmatory factor analysis verified the two-factor structure of the HHQ, and a one-factor solution was replicated for the EHI. Individuals that were classified as consistent on the EHI had stronger preferences for unimanual and RDBM hand use on the HHQ. Right hand patterning was reduced for RDBM compared to unimanual on the HHQ, and the EHI. The HHQ was found to be reliable and valid against the EHI. The HHQ offers researchers a tool to examine individual differences across manual skills that comprise the neuropsychological phenomenon handedness, and to more broadly examine laterality patterns with respect to cognition.

KEYWORDS
Factor analysis; hand preference; handedness; laterality; questionnaire

Introduction

Handedness is broadly defined as a bias in the use of one hand over the other. At least 85% of adults are right-handed (Annett, 2002), and this marked right shift at the population level characterizes all studied human cultures past and present (Llaurens, Raymond, & Faurie, 2009). The main goal for researchers studying the neuropsychological phenomenon of handedness has shifted away from being able to detect right-handedness, as congruence across subjects in the general direction of asymmetry has been well established. Rather, the interesting question has become unpacking consistency in hand use within and across subjects and tasks (Marchant & McGrew, 2013) and examining the links between hand use consistency and cognitive performance for understanding brain-behavior relationships (for a review, see Prichard, Propper, & Christman, 2013).

Measurement of hand use is central to being able to ask meaningful questions regarding the relations between handedness and other domains. The most widely used measure in adults based on citation rate is the Edinburgh Handedness Inventory (EHI; Oldfield, 1971). The EHI is a self-report measure that asks subjects which hand they prefer for 10 actions: writing, drawing, throwing, scissors, toothbrush, knife (without fork), spoon, broom (upper hand), striking match (match), and opening box (lid). Subjects are instructed to put a plus in either the left or right column for each item denoting their preference. If their preference is so strong that they would never use the other hand unless forced, two plusses are put in same column. If the subject is truly indifferent, a plus is put in both columns. While the psychometric properties of individual items on the EHI as well as the original instructions have been criticized and modified by individual researchers (for a review, see Edlin et al., 2015), the EHI continues to be widely used across many fields.

A number of investigators have examined the structure of the EHI using factor analysis, which is a tool for examining whether multiple observed variables (i.e., questionnaire items) exhibit a similar pattern of hand use preference because they are associated

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with the latent variable of handedness. A single factor solution has been widely reported for the EHI (Dragovic, 2004; Espirito-Santo et al., 2017; Fazio & Cantor, 2015; McFarland & Anderson, 1980; Milenkovic & Dragovic, 2013; Veale, 2014; Williams, 1986), as well as some modifications of the EHI (Bryden, 1977; Tran, Stieger, & Voracek, 2014); however, see White and Ashton (1976). For researchers looking to screen participants on the basis of handedness for a neuropsychological study, the EHI is likely sufficient. For example, most neuroimaging studies have been conducted on samples of right-handers only and have required a screening tool such as the EHI. However, for researchers directly studying handedness or wishing to use handedness as a main variable, the EHI falls short for two reasons. First, Oldfield's scoring system does not distinguish between a participant who puts 10 plusses in one column versus a participant who puts 20 plusses in one column; they both would receive the same score as exclusively left- or right-handed, despite the difference in consistency patterning. Second, the items on the EHI are not uniform in skill type. While throwing a ball and using a toothbrush are unimanual actions, striking a match requires role-differentiated bimanual manipulation (RDBM), where one hand holds an object for the other hand's manipulation. In RDBM actions, the manipulating hand is recorded as the preferred hand, as indicated by Oldfield (1971) with parentheses. The EHI does not capture this multidimensionality in handedness (e.g., Healey, Liederman, & Geschwind, 1986), as only one overall score is generated. Different dimensions of handedness may tap different patterns of underlying brain asymmetry.

In a prior study, we developed the Home Handedness Questionnaire (HHQ), which addresses these two weaknesses in the EHI (Nelson, Gonzalez, El-Asmar, Ziade, & Abu-Rustum, 2018). The HHQ arose from a need for a measure with child-appropriate actions that could be administered outside of a lab setting using common household items. Data are collected by parents as "citizen scientists" on two scales. One scale contains actions designed to be performed unimanually, while the other scale contains actions designed to be performed using RDBM. Hand preference scores are calculated separately for each action type using statistically-driven cutoffs, and patterns between the two types of manual preferences can be compared. Given the multidimensionality of handedness, it matters how hand use is measured. Developmentally, there is a difference in the timing of hand preferences for different manual skills. According to the cascade theory of handedness (Michel, 2002; Michel, 2013), a preference for an earlier skill cascades into a preference for a later skill, meaning that a preference for unimanual manipulation influences a preference for RDBM (Babik & Michel, 2016; Nelson, Campbell, & Michel, 2013). A debate continues in the field regarding when handedness is established in development (e.g., Gesell & Ames, 1947; McManus et al., 1988; Nelson et al., 2013), and the lack of consensus may be driven by differences in the type of preference(s) that have been measured to estimate handedness. In contrast, handedness in adults is considered stable, allowing for comparison across manual skill preferences without the potential variability that may arise in developmental samples. A second advantage of studying handedness in an adult population is increased sample size for analyses, as recruitment for studies with young children is incredibly difficult (e.g., Brand, Gans, Himes, & Libster, 2019).

Thus, the primary aim of this study was to examine the HHQ using confirmatory factor analysis (CFA) in a large convenience sample of adult undergraduate students with established patterns of hand use. We hypothesized that the factor structure of the HHQ would align with its subscales, and we predicted that we would identify two factors: one for unimanual hand preference and a second for RDBM hand preference. We are unaware of any measure that specifically targets RDBM hand preference within the context of understanding adult handedness. Thus, a secondary goal of the current study was to measure RDBM hand preference in adults for the first time for comparison to unimanual hand preference. Using this design, we examined consistency in adult handedness using a novel approach that spans different manual skills. We also collected EHI data from our adult participants to further validate the HHQ.

Materials and method

Participants

A total of 1,216 adults participated in the study. Data were excluded from 30 participants who did not complete the HHQ and 135 participants who did not complete the EHI correctly. Analyses were conducted on a final sample of 1,051 participants. Participants were recruited online from students enrolled in undergraduate psychology courses through the Florida International University Psychology Research Participation system (Sona Systems, Ltd., Bethesda, MD, USA). Data were collected from January 2018 to

November 2018. Eighty-two percent of participants in the final sample identified as female, 17% identified as male, <1% identified their gender as other (e.g., non-binary), and <1% did not report gender. The racial distribution of the final sample was 66% White, 14% Black or African American, 2% Asian or Pacific Islander, <1% Native American, 16% Other (e.g., multiracial), and <1% did not report race. The majority of participants were of Hispanic ethnicity (76%). Participants in the final sample ranged in age with 81% between 18 and 24 years old, 15% between 25 and 34 years old, 2% between 35 and 44 years old, 1% between 45 and 54 years old, <1% 55 or older, and <1% did not report age. The Florida International University Institutional Review Board approved the following procedure, and all participants received extra credit for their time. Informed consent was obtained from all participants, and the work was carried out in accordance with the Declaration of Helsinki.

Home Handedness Questionnaire (HHQ)

The HHQ is an action-based handedness questionnaire intended for use in the home or outside of a typical lab setting (Nelson et al., 2018). The HHQ includes two subscales to assess two distinct domains of manual skill: unimanual manipulation and RDBM. The HHQ includes 30 actions total, with 15 actions corresponding to unimanual skill (e.g., pick up a bottle cap), and 15 actions corresponding to RDBM skill (e.g., hold jar/bottle and unscrew lid). Actions were performed twice in nonconsecutive order. All participants completed the 15 unimanual actions, followed by the 15 RDBM actions and then repeated the sequence. Instructions were provided prior to each block of 15 items. Participants were asked to perform each action and record which hand they used (left or right). Participants were instructed to record the first hand that was used for any prompt where they switched hands during the target action. For RDBM actions, hand use was reported for the portion of the action that appeared in parentheses after the prompt. The hand recorded for RDBM actions was always the hand that performed the active manipulation (i.e., the stabilizing hand in the action was considered the non-preferred hand). Participants who did not complete the HHQ were excluded from statistical analyses ($N = 30$). Additional information on how to score the HHQ can be found in the Calculation of Hand Preference Scores section.

Edinburgh Handedness Inventory (EHI)

The EHI was administered in its original format, as recent literature has described multiple instances of altered use of the EHI that limits comparisons across studies (Edlin et al., 2015). Participants were instructed to indicate their hand preference for the listed EHI activities by typing a "+" in the appropriate column (right or left). If a participant's preference was so strong that they would never use the other hand unless forced to, they were instructed to type "++" in the appropriate column of right or left. If participants were indifferent to the hand they would use to complete the action, they were instructed to type a "+" in both columns. As per the original EHI instructions, participants were encouraged to try to answer all the questions, and told to only leave a blank if they had no experience at all with the object or task. Participants with EHI data who typed in responses that were uninterpretable or did not lend themselves to calculation using the "+" and "++" system (e.g., typing "right hand" into response boxes, typing "++" for both right hand and left hand columns for an action, or using a symbol other than "+"/"++") were excluded from the final sample ($N = 135$). Further information regarding scoring the EHI can be found in the Calculation of Hand Preference Scores section.

Procedure

After giving informed consent to be in the study, participants completed the handedness measures online via Qualtrics (Qualtrics, Provo, UT, USA). All participants completed the HHQ first, followed by the EHI. This decision of task order was made to reduce attrition for the HHQ, given our primary objective was to conduct a factor analysis on the HHQ. Prior to starting the HHQ, participants were given a list of required materials and asked to find someone to help them with tasks that required a partner. Participants were then instructed to sit at a flat table or surface and complete the listed actions with the items that they collected. For the EHI, participants were instructed to base their answers from memory, rather than from trying to produce the actions with the items they collected for the HHQ. On average, participants spent 91 ± 25 minutes completing the entire study online. Completion was calculated on time elapsed between the first click to give informed consent, and the final click to submit responses. Participants were allowed to complete the study at their own pace, thus time spent likely includes participant breaks and returning to the survey link after extended periods of time.

Analytical procedures

Confirmatory factor analysis of the HHQ and the EHI

A two-factor confirmatory factor analysis (CFA) was used to confirm the structural validity of the HHQ, indicating that the HHQ measures hypothesized latent constructs of unimanual and RDBM hand preference. The HHQ presents the 15 unimanual and the 15 RDBM actions twice to achieve 30 data points per subscale. Thus, in order to conduct the CFA, the raw HHQ data were reduced by re-coding participant responses. Participants who reported left hand use across the two iterations of a given action received a score of 0 for that action on the HHQ. Participants who reported mixed hand use (i.e., one right response and one left response) across the two iterations of an HHQ action received a score of 1 for that action. Participants who reported right hand use across the two iterations of an action received a score of 2 for that action on the HHQ. Compressing the data in this manner adequately addresses the relation between repeated actions during CFA analysis. Items on the HHQ from the unimanual subscale were loaded onto Factor 1, and items from the RDBM subscale were loaded onto Factor 2. A one-factor CFA was conducted on the EHI data in order to compare the factor structure from an established handedness measure to that of the HHQ within the same participant pool. Reponses on the EHI were re-coded into Likert scale responses ranging from 1 (exclusively left) to 5 (exclusively right; see Dragovic, 2004).

Analyses were conducted using robust weighted least squares estimation utilizing polychoric correlations given the categorical nature of the HHQ and EHI data (Jöreskog, 1994; Muthén, 1984; Muthén, Du Toit, & Spisic, 1997; Muthén & Kaplan, 1985). MPlus (version 6.12) was used to conduct both CFA analyses (Muthén & Muthén, 1998). The following measures were used to assess model fit: (1) Satorra-Bentler Scaled chi-square statistic (S-B χ^2) with $p < .05$ indicating good fit (note: achieving $p < .05$ in large sample sizes is difficult; see Bentler & Bonett, 1980; Hu & Bentler, 1999; Tanaka, 1993); (2) the Tucker–Lewis coefficient (TLI) with values above .90 indicating acceptable fit and values above .95 indicating good fit; (3) comparative fit index (CFI) with values above .90 indicating acceptable fit and values above .95 indicating good fit; and (4) the root mean square error of approximation (RMSEA) with values lower than .08 indicating acceptable model fit and values lower than .06 indicating good model fit (Browne & Cudeck, 1993; Hu & Bentler, 1999; Kline, 2005; Lei & Wu, 2007; Marsh, Hau, & Grayson, 2005). Factor loadings per item were also assessed for significance and loading value. Factor loadings indicate the relationship between the item and the latent construct. Items with loadings below .3 were flagged for exclusion (Comrey & Lee, 1992; Costello & Osborne, 2005; Tabachnick & Fidell, 2001).

Calculation of hand preference scores

Hand preference scores for the HHQ were calculated with handedness indices (HI). Separate HI scores were calculated for the unimanual scale (HI_{UNI}) and the RDBM scale (HI_{RDBM}) of the HHQ using the formula $HI = (R - L)/(R + L)$, where R is the total number of right hand actions, and L is the total number of left hand actions. HI scores range from -1.00 (exclusive left hand use) to 1.00 (exclusive right hand use). Hand preference direction was determined using binomial z-scores where $z < -1.96 =$ left preference, $z > 1.96 =$ right preference, and all other z scores = no preference. These binomial z-score cutoffs correspond to $p < .05$ for two-tailed t-tests (Gonzalez & Nelson, 2015; Hopkins, 2013a, 2013b). Hand preference scores for the EHI were calculated with a laterality quotient (LQ). The LQ is similar to the HI except for that the remainder is multiplied by 100. The LQ is calculated by the following formula, $LQ = ((R - L)/(R + L)) \times 100$, where R is the number of plusses in the right column and L is the number of plusses in the left column. LQ scores range from -100 (all left plusses) to 100 (all right plusses). Hand preference direction was determined per Oldfield's (1971) original specifications where scores greater than 0 indicate a right preference and scores less than 0 indicate a left preference. We opted to label EHI scores of 0 as no preference. HI and LQ scores were tested for population-level biases using one-sample Wilcoxon Signed Rank tests against a value of 0. Spearman's correlations were used to examine the relation between HI_{UNI} and HI_{RDBM} scores. Independent samples Mann-Whitney U tests were used to test for differences between self-identified males and females on hand preference scores. Participants who did not report gender ($N = 2$), and participants who marked "other" as their gender ($N = 5$) were excluded from all gender related analyses.

Validity and reliability of the HHQ

Spearman's correlations between HI and LQ scores were used to test the convergent validity of the HHQ. Internal reliability of the HHQ was examined with Kuder-Richardson-20 analysis (KR-20). KR-20 is similar to Cronbach's alpha, but appropriate for use with binary responses (Cortina, 1993). Internal reliability of the EHI was tested using Cronbach's alpha because of the "+/++" scoring system. Unlike the HHQ, responses were not binary on the EHI. To further test the discriminatory power of the HHQ, independent samples Mann-Whitney U tests were conducted on HI_{UNI} and HI_{RDBM} scores by EHI consistency groups using cutoffs from Christman, Prichard, and Corser (2015). The strength of the EHI score was first computed by taking the absolute value of the LQ score. Participants with a score of |85–100| on the EHI were considered consistent, and participants with a score |1–84| were considered inconsistent in their hand use. Individuals with an EHI LQ score of 0 ($N = 19$) were excluded from these analyses.

Results

Confirmatory factor analyses

Table 1 displays the model fit for the two-factor CFA on the HHQ, and Table 2 displays the factor loadings for the unimanual and RDBM subscales of the HHQ. Model fit was acceptable, and all factor loadings were significant ($p < .05$). However, factor loadings for the unimanual action items "put a bracelet on own arm" and "put a ring on own finger" were below the established loading cutoff of .3 indicating that these two items contribute a minimal amount to the latent variable of unimanual hand preference. Data from these two items were subsequently excluded, and a two-factor CFA was conducted once more. Table 1 illustrates the fit for the reduced model, and factor loadings for the reduced model appear in Table 2. Model fit improved slightly after removal of the two items. Overall, acceptable to good fit was identified using the two-factor structure, supporting the hypothesis that the HHQ measures two distinct hand preference domains: unimanual hand preference and RDBM. HI_{UNI} scores were calculated using the reduced HHQ unimanual scale.

A one-factor CFA was conducted using EHI responses. EHI model fit is displayed in Table 1, and factor loadings are displayed in Table 3. The EHI demonstrates acceptable to good model fit with a single factor solution. All factor loadings were significant and above the loading cutoff, suggesting that all items should be retained for calculating EHI LQ scores.

Table 1. Model fit indices.

Model	S-B χ^2(df); p-value	TLI	CFI	RMSEA
HHQ Original Items	$\chi^2(435) = 10774.524$; $p > .05$	.93	.92	.04
HHQ Reduced Model	$\chi^2(378) = 10545.54$; $p > .05$	.92	.93	.04
EHI	$\chi^2(45) = 20939.73$; $p > .05$	.99	.99	.08

Note. S-B χ^2 = Satorra-Bentler Scaled Chi-Square Statistic; df = Degrees of freedom; TLI = Tucker–Lewis Coefficient; CFI = Comparative Fit Index; RMSEA = Root Mean Square Error of Approximation; HHQ = Home Handedness Questionnaire; EHI = Edinburgh Handedness Inventory.

Hand preference scores

After excluding the two items on the HHQ unimanual subscale with low factor loadings, HI_{UNI} and HI_{RDBM} scores were calculated. HI_{UNI} scores ranged from −1.00 to 1.00 ($M = .66$, $SD = .45$; Figure 1a). HI_{RDBM} scores ranged from -1.00 to 1.00 ($M = .59$, $SD = .49$; Figure 1b). For the EHI, LQ scores ranged from −100 to 100 ($M = 64.64$, $SD = 50.73$; Figure 1c).

Based on HI_{UNI} scores, 81.4% of participants had a right hand preference, 5.7% had a left hand preference, and 12.9% had no preference. For HI_{RDBM} scores, 61.2% of participants had a right hand preference, while 4.1% demonstrated a left hand preference, and 34.7% had no preference. For EHI LQ scores, 88% of participants had a right hand preference, 10.2% had a left hand preference, and 1.8% had no preference. One-sample Wilcoxon Signed Rank tests were conducted on HHQ HI_{UNI} and HI_{RDBM} scores. A significant right hand preference for HI_{UNI} scores was found, $Z = 510{,}088$, $p < .001$, $r = .77$. Similarly, a significant right hand preference for HI_{RDBM} was also identified, $Z = 493{,}260$, $p < .001$, $r = .73$. Additionally, a significant right hand preference was found for EHI LQ scores, $Z = 485{,}908$, $p < .001$, $r = .77$. Moreover, HHQ HI_{UNI} and HI_{RDBM} scores were significantly positively correlated, $r_s = .531$, $p < .001$, indicating that hand preference direction was related across manual skill type. No significant gender difference was found for HI_{UNI} scores, $U = 80{,}243$, $p > .05$, $r = .03$ ($Mdn_{MALES} = .77$; $Mdn_{FEMALES} = .85$). No significant gender difference was found for HI_{RDBM} scores, $U = 81{,}340$, $p > .05$, $r = .04$ ($Mdn_{MALES} = .73$; $Mdn_{FEMALES} = .73$). No significant gender difference was found for EHI LQ scores, $U = 80{,}631$, $p > .05$, $r = .03$ ($Mdn_{MALES} = .80$; $Mdn_{FEMALES} = .83$).

Validity and reliability of the HHQ

HI_{UNI} scores were correlated with EHI LQ scores, $r_s = .42$, $p < .05$. HI_{RDBM} scores were also correlated

Table 2. HHQ factor loadings.

	Original Items Factor loadings	Reduced Model Factor Loadings
Unimanual Latent Factor		
1. Pick up a bottle cap	.43	.43
2. Bang or slap on a surface	.53	.53
3. Brush/comb hair	.75	.75
4. Tap a cup with a spoon	.61	.61
5. Pick up a bottle	.39	.39
6. Hand someone a bottle	.35	.35
7. Hold a toothbrush when brushing teeth	.74	.74
8. Throw a ball	.72	.72
9. Open a drawer/closet	.45	.45
10. Pick up a sheet of paper off a table	.34	.34
11. Pick up a cloth off a table	.38	.38
12. Pat/pet a stuffed animal	.41	.41
13. Put a bracelet on own arm	.19	–
14. Hand someone a bracelet	.34	.34
15. Put ring on own finger	.16	–
RDBM Latent Factor		
1. Hold bag and retrieve a toy from inside (record hand that takes toy)	.49	.49
2. Hold someone's hand and put a ring on it (record hand that places ring)	.42	.42
3. Hold someone's hand and put a bracelet on it (record hand that places bracelet)	.45	.45
4. Hold toothpaste and open top (record hand that opens top)	.37	.36
5. Hold brush/comb and remove hair (record hand that picks hair)	.31	.31
6. Hold jar/bottle and unscrew lid (record hand that unscrews lid)	.49	.49
7. Hold paper and write/draw (record the hand that writes/draws)	.78	.78
8. Hold book and turn a page (record hand that turns the page)	.44	.44
9. Hold bottle and place a rubber band on it (record hand that places rubber band)	.50	.49
10. Hold a cup and retrieve a snack inside (record hand that takes food)	.46	.46
11. Hold hair and pretend to cut (record hand that "cuts")	.65	.65
12. Hold plate and wash with a sponge (record hand that uses sponge)	.58	.58
13. Hold cup and pour or stir sugar inside (record hand that pours/stirs)	.63	.63
14. Hold someone's foot and put a shoe on it (record hand that places shoe)	.50	.50
15. Hold purse/bag and retrieve a wallet from inside (record hand that retrieves wallet)	.48	.48

Note. HHQ = Home Handedness Questionnaire; RDBM = Role Differentiated Bimanual Manipulation. All factor loadings were significant at $p < .05$ in the original and reduced models.

Table 3. EHI factor loadings.

EHI Items	Factor Loadings
1. Writing	.96
2. Drawing	.95
3. Throwing	.75
4. Scissors	.90
5. Toothbrush	.83
6. Knife (without fork)	.57
7. Spoon	.86
8. Broom (upper hand)	.62
9. Striking a match (match)	.81
10. Opening box (lid)	.66

Note. EHI = Edinburgh Handedness Inventory. All factor loadings were significant at $p < .05$.

with EHI LQ scores, $r_s = .41$, $p < .05$. The HHQ unimanual subscale demonstrated high internal reliability ($KR_{20} = .93$), as did the HHQ RDBM subscale ($KR_{20} = .94$). The EHI also demonstrated high internal reliability ($\alpha = .93$). An independent samples Mann-Whitney *U* test comparing individuals with a consistent hand preference on the EHI ($N = 526$) to individuals with an inconsistent hand preference on the EHI ($N = 506$) found a significant difference in HI_{UNI} scores, $U = 170{,}342$, $p < .001$, $r = .25$ ($Mdn_{CONSISTENT} = .85$; $Mdn_{INCONSISTENT} = .69$). A significant difference between EHI LQ consistency groups was also found in relation to HI_{RDBM} scores, $U = 168{,}336$, $p < .001$, $r = .23$ ($Mdn_{CONSISTENT} = .87$; $Mdn_{INCONSISTENT} = .67$). Figure 2 displays the means and standard errors for HI_{UNI} and HI_{RDBM} scores by EHI consistency group.

Discussion

The CFA confirmed the two-factor structure of the HHQ, indicating that the HHQ measures two latent constructs for hand preference: unimanual and RDBM. To our knowledge, this is the first action-based measure of hand preference that explicitly measures both of these manual skills with sufficient trials to make a statistical determination of hand preference per skill type in adults. In comparison, a CFA of the EHI replicated previous findings of a one-factor structure (Bryden, 1977; Dragovic, 2004; Espirito-Santo et al., 2017; Fazio & Cantor, 2015; McFarland & Anderson, 1980; Milenkovic & Dragovic, 2013; Tran et al., 2014; Veale, 2014; Williams, 1986). A significant population-level right bias was found for both unimanual and RDBM skill on the HHQ, and also on the

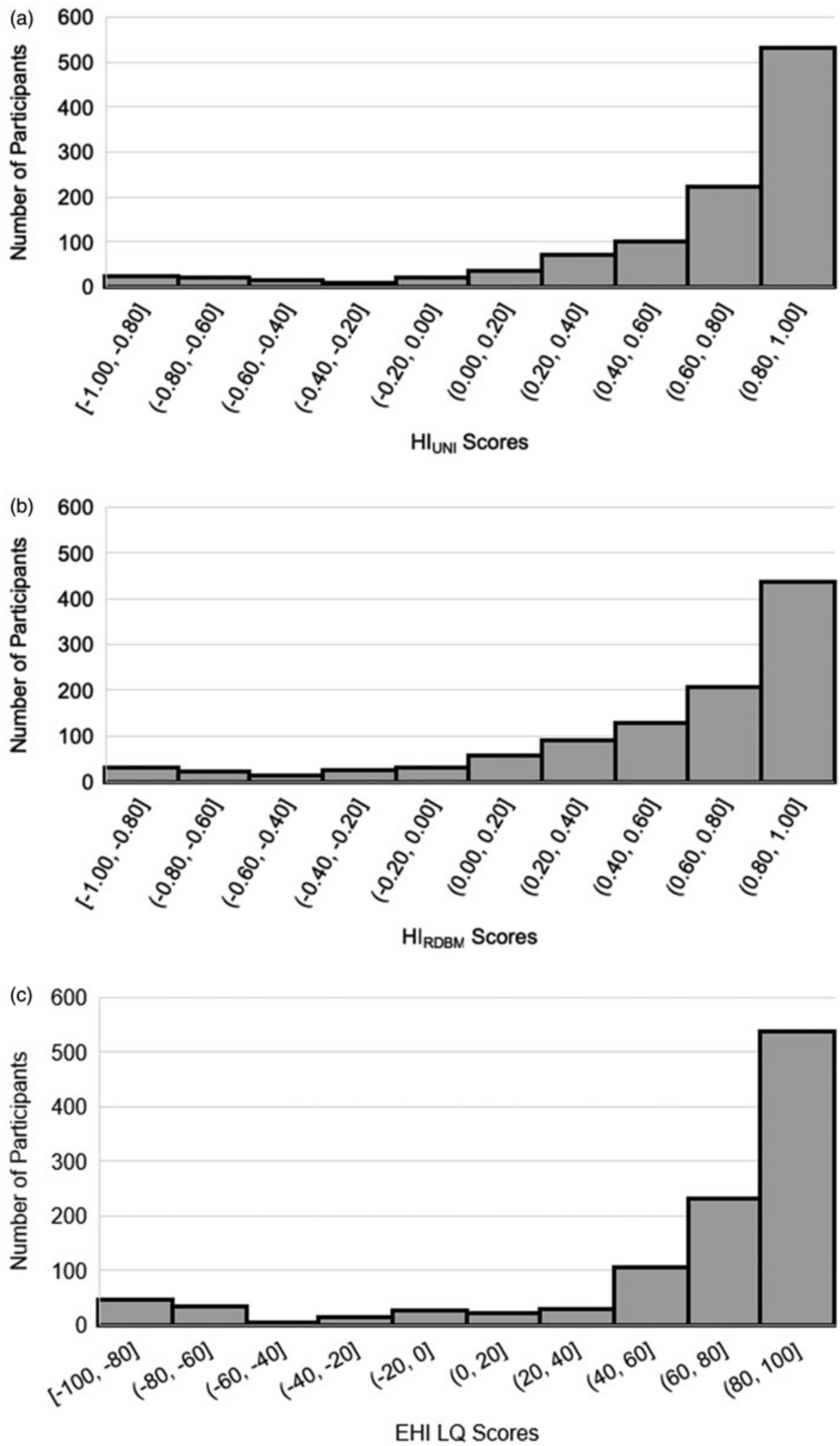

Figure 1. Distribution of hand preference scores for (a) HHQ Unimanual, (b) HHQ RDBM, and (c) EHI. *Note.* HHQ = Home Handedness Questionnaire; RDBM = Role-differentiated bimanual manipulation; EHI = Edinburgh Handedness Inventory; HI = Handedness Index; LQ = Laterality Quotient.

EHI. When the sample was divided into EHI consistency groups, there were significant differences in the strength of specific hand preference skills as measured by the HHQ. Participants in the consistent EHI group had stronger preferences for both unimanual and RDBM hand use as compared to the inconsistent EHI group. Sex differences were not found in the current sample. Overall, findings support the use of the HHQ

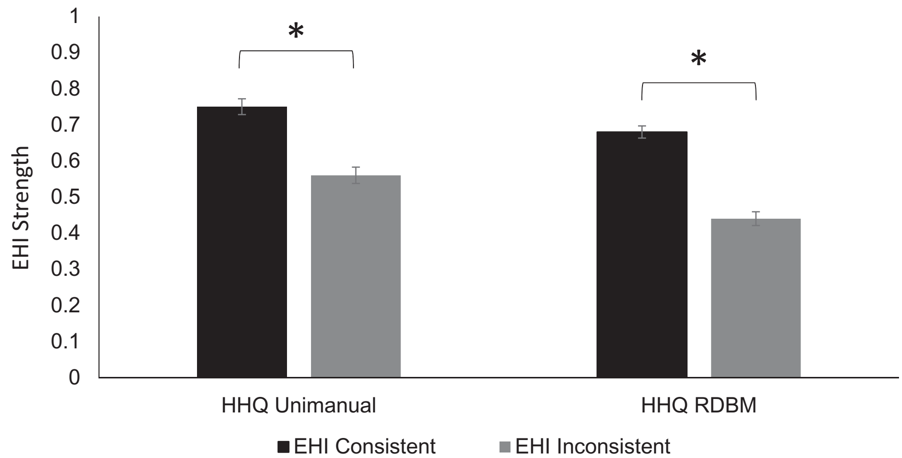

Figure 2. Mean HHQ Unimanual and HHQ RDBM scores by EHI consistency. Bars denote standard error. EHI strength was computed by taking the absolute value of EHI LQ scores. *Note.* HHQ = Home Handedness Questionnaire; RDBM = Role-differentiated bimanual manipulation; EHI = Edinburgh Handedness Inventory; LQ = Laterality Quotient.

as a reliable and valid measurement of the neuropsychological construct of handedness across more than one dimension of hand preference in adults.

Factor structure has been widely examined in handedness measures. In addition to the EHI, a one-factor structure has been reported for the Dutch Handedness Questionnaire (van Strien, 2002), the Fazio Laterality Inventory (Fazio, Dunham, Griswold, & Denney, 2013), the Flinders Handedness Survey (FLANDERS; Nicholls, Thomas, Loetscher, & Grimshaw, 2013), and others (e.g., Richardson, 1978). Two or more factors based on skill type have been identified previously for handedness questionnaires as well (Bryden, 1977; Fazio & Cantor, 2015; Ida & Bryden, 1996), indicating that it is possible to capture more than one dimension of handedness. Notably, some measures of handedness have found multiple factors, but opted to reduce to one factor for theoretical reasons (Bryden, 1977; White & Ashton, 1976). However, as measurement of handedness has changed over time, it is clear that handedness has multiple dimensions rather than a single construct and how handedness is measured matters (Brown, Roy, Rohr, & Bryden, 2006; Liu, Forrester, & Whitall, 2006; Massy-Westropp, Gill, Taylor, Bohannon, & Hill, 2011). In particular, scales with greater discriminatory power may yield more factors (Christman et al., 2015; Peters, 1998). In this regard, the HHQ may be a more discriminating scale than the EHI, and other one-factor measures of handedness.

It is worth noting that two items on the HHQ unimanual subscale did not load adequately on to the unimanual factor. These items were “put a bracelet on own arm” and “put a ring on own finger.” Upon further review of these items, each action involved simultaneous use of both hands where the participant was required to use one hand to place an item on the opposite hand. Involvement of both hands may have caused confusion when responding, as it may have been unclear to participants which hand was the dominant hand in the action. Given the results of the factor analysis, we excluded these two items for further analysis. A goal for future work is to replace the items with two new actions where the hands are not used in combination and the action can be clearly performed with one hand. Possible replacement actions that would not require participants to acquire additional objects are “wipe a surface with a cloth” and “point to your nose with one finger.” Additionally, researchers interested in using the HHQ may reword the RDBM item “hold someone’s hand and put a bracelet on it” to “hold someone’s wrist and put a bracelet on it” to clarify the optimal position for participants to execute the action.

A secondary aim of the current study was to measure adult hand preference for RDBM. Results indicated that adults demonstrated a predominantly right-hand preference for RDBM. Additionally, hand preference for unimanual and RDBM skills was significantly correlated, indicating stability in hand preference between both action types. To our knowledge, the HHQ is the first measure that targets RDBM in adults. Results also indicated a lower rate of right hand preference for RDBM (61.2%) compared to unimanual hand preference (81.4%), and for hand preference measured from the EHI (88%). Data collected with the HHQ in a child sample found similar results, with children demonstrating lower levels of right hand preference for RDBM skills compared to unimanual skills (Nelson et al., 2018). Recent work by

Christman et al. (2015) found a single factor for consistent right-handers, and two factors for inconsistent right-handers using the EHI. It is possible that the second factor identified by Christman and colleagues was driven by variability in hand preference for RDBM skill. Out of 10 items on their modified version of the EHI, six actions could be performed with RDBM: writing, drawing, using a knife, using scissors, striking a match, and opening a jar. Moreover, the Christman et al. (2015) sample excluded left-handers, whereas both left- and right-handers were included in our sample. Further research is required to understand population-level patterns of adult hand preference for RDBM skill along a continuum of handedness. Overall, future work should also aim to elucidate why RDBM may show a less pronounced right hand preference across development (e.g., Gonzalez & Nelson, 2015).

Principally, what distinguishes the HHQ from the EHI is that the HHQ can capture more variability in hand preference. As demonstrated in Figure 1, both the HHQ unimanual and RDBM subscales exhibit the J-shaped right shift pattern typically seen in adult handedness (e.g., Annett, 2002). However, compared to the EHI, the HHQ was more sensitive in detecting individual differences in the strength and directionality of hand use patterns. It is crucial that research on handedness continue to measure hand preference across skill types, as in order to truly study handedness, studies must investigate consistency in manual behavior across subjects and tasks (Marchant & McGrew, 2013). The discriminatory power of the HHQ situates it as an excellent measure to investigate the relation between individual differences in hand preference for unimanual and RDBM actions and cognitive abilities (cf., Nelson, Campbell, & Michel, 2014; Nelson et al., 2017). Importantly, how hand preference is measured matters for disentangling its relation to other cognitive domains, as recent work finds that not all measures of hand preferences relate equally to cognitive outcomes. For example, Pietsch and Jansen (2019) reported that the EHI was not predictive of mental rotation performance, but other handedness measures such as visuomotor control and manipulation skill were significantly related to speed in solving mental rotation tasks.

Potential limitations to the current study should be noted. Firstly, the HHQ is longer than typical questionnaire measures of handedness. Additionally, because it is a performance-based measure, its length may mean that it takes longer to complete than a pen and paper questionnaire. However, a shorter questionnaire would likely not capture the same multidimensionality of handedness (e.g., Peters, 1998). We suggest that researchers interested in screening for handedness (i.e., handedness is not an independent or dependent variable for their research question) should opt for the EHI or another shorter measure. Alternatively, researchers interested in handedness as a central research question, or those who are interested in the role of individual differences in laterality in relation to other measures, would greatly benefit from adopting the HHQ. An additional limitation of the current study is reliance on participant self-report. However, self-report is an issue in general with questionnaires. Future work will utilize the HHQ in a controlled research setting in order to compare participant actions in person when completing the HHQ to their online responses. Finally, because a main goal for the HHQ is ease of use outside of traditional research settings and across ages, standardization across objects was not a focus of the current study. Differences in object size may influence hand preference measurement (Bryden, Mayer, & Roy, 2011; Potier, Meguerditchian, & Fagard, 2013). Additional studies will collect data from participants on the objects used at home, and will recruit participants to complete the HHQ in person with a standardized set of objects to investigate potential effects of object size. Also, while we did not find significant sex differences, our sample may not be representative of the general population given the higher proportion of females to males in our available participant pool. Papadatou-Pastou, Martin, Munafo, and Jones (2008) conducted a meta-analysis confirming a sex difference in left handedness favoring males. Future work will need to address potential sex differences in the HHQ in other samples.

In conclusion, the HHQ is a valid and reliable measure of handedness. The HHQ was explicitly created to measure hand preference across two distinct domains: unimanual and RDBM, and these domains were confirmed by factor analysis. Overall, we recommend the HHQ for researchers interested in a measure of handedness that can be used across a variety of settings and participant ages, who aim to study handedness on its own or in relation to other variables.

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