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Wait wait, don't tell me: Handedness questionnaires do not predict hand preference for grasping

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ABSTRACT

Handedness questionnaires are a common screening tool in psychology and neuroscience, used whenever a participant's performance on a given task may conceivably be affected by their laterality. Two widely-used examples of such questionnaires are the Edinburgh Handedness Inventory and the Waterloo Handedness Questionnaire. Both instruments ask respondents to report their hand preference for performing a variety of common tasks (e.g., throwing a ball, or opening a drawer). Here we combined questions from the two instruments (E-WHQ; 22 questions total) and asked participants to report their preferred hand for each via a five-point scale. The purpose of this study was to determine whether responses on the E-WHQ are accurate, reliable, and/or predictive of hand-preference for a simple grasp-to-construct task. Regarding accuracy, handedness scores were 5% lower when participants used a scrambled response key versus a consistent one. Test-retest reliability of the questionnaire was weak, with any given inventory item eliciting a different response from 34% of respondents upon retesting. Neither was the E-WHQ predictively useful—although both left- and right-handers preferred their dominant hands, E-WHQ score did not correlate with overall percentage of dominant-hand grasps in either group. We conclude that the E-WHQ is unsuited for predicting hand preference for grasping.

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KEYWORDS Handedness questionnaire; hand preference; grasping; Edinburgh; Waterloo

Introduction

Assessing handedness (i.e., the tendency to use one hand more naturally or skilfully than the other) in research populations is of critical import to investigators, as hand dominance correlates with other lateralized functions, including the hemispheric specialization for language and the lateralization of spatial abilities (Bryden, Hécaen, & DeAgostini, 1983). There are currently dozens of methods in use for assessing handedness in clinical and research populations (if not more; see Edlin et al., 2015). These methods vary, and

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include measures of strength (Clerke & Clerke, 2001; Richards & Palmiter-Thomas, 1996), dexterity or skill [e.g., counting the number of pegs one may insert into holes in a given time (Annett, Annett, Hudson, & Turner, 1979), hand preference for tool use (Bryden, Pryde, & Roy, 2000a), or proficiency in tracing or drawing simple geometric shapes (Derakhshan, 2008)], or observed hand preference for grasping and acting in contralateral space (Bishop, Ross, Daniels, & Bright, 1996; Bryden, Pryde, & Roy, 2000b), among countless others.

Despite these numerous ways to assess hand preference, questionnaires remain the primary tool used in clinical or research settings. Questionnaires provide a comprehensive, non-invasive assessment that is economical to administer with respect to both cost and time. There are several handedness questionnaires in use today, including the Edinburgh Handedness Inventory (EHI) (Edlin et al., 2015; Oldfield, 1971; White & Ashton, 1976; Williams, 1986) and revised Waterloo Handedness Questionnaire (WHQ) (Brown, Roy, Rohr, Snider, & Bryden, 2004; Bryden et al., 2000b). The EHI consists of ten items for which participants index their preferred hand (left, right) as well as the strength of that preference (strong = ++, less strong = +, or indifferent = +/+). The WHQ, developed by Steenhuis and Bryden (Steenhuis & Bryden, 1989; Steenhuis, Bryden, Schwartz, & Lawson, 1990), is a 20-item inventory classifying hand use for everyday tasks on a five-point scale from −2 (left hand always) to + 2 (right hand always). Versions of these questionnaires are common and in widespread use; the EHI in particular has been cited in more than 15,000 papers, and has been modified more than a hundred times by countless research teams (Edlin et al., 2015).

One such modification, a combination of the EHI and WHQ, has been used by us and a number of our colleagues for over a decade. The Edinburgh-Waterloo Handedness Questionnaire (E-WHQ), uses the simple five-point scoring system of the WHQ to answer questions of hand preference pulled from both inventories. The E-WHQ asks participants to rate their preferred hand for 22 simple everyday tasks (e.g., which hand do you use to open a drawer, or turn a key in a lock?) on the WHQ's five-point Likert scale, from −2/−1 (Always/Usually Left) to + 1/+2 (Usually/Always Right); a score of 0 would indicate no preference, or equal preference. These preferences are summed, revealing a handedness score ranging from −44 (exclusively left handed) to 44 (exclusively right handed). The questionnaire also includes six open-ended short-answer questions used for screening purposes (e.g., *do you consider yourself right handed, left handed, or ambidextrous?* and *is there any reason (e.g., injury) why you have changed your hand preference for an extended period of time for any of the above activities?*); participant responses to these questions do not affect the calculation of handedness score (see Stone, Bryant, and Gonzalez (2013) for the full questionnaire). This test has been used extensively by our lab and others' in dozens of published investigations involving hand-use for grasping and other everyday behaviours (Bryant, de Bruin, & Gonzalez, 2013; Bryant & Gonzalez, 2013; de Bruin & Gonzalez, 2013; Flindall, De Bruin, & Gonzalez, 2014; Flindall, Doan, & Gonzalez, 2014; Flindall & Gonzalez, 2013, 2014, 2015, 2016, 2017; Flindall, Stone, & Gonzalez, 2015; Gonzalez, Flindall, & Stone, 2014; Gonzalez, Ganel, & Goodale, 2006; Gonzalez, Ganel, Whitwell, Morrissey, & Goodale, 2008; Gonzalez & Goodale, 2009; Gonzalez, Mills, et al., 2014; Gonzalez, Whitwell, Morrissey, Ganel, & Goodale, 2007; La Mantia, Gonzalez, & Brown, 2013; Maclean & Gonzalez, 2013; Mills, Gibb, MacLean, Netelenbos, & Gonzalez, 2015; Mills & Gonzalez, 2013; Netelenbos & Gonzalez, 2012, 2015; Rousseau, Mills, & Gonzalez, 2013; Sacrey, Arnold, Whishaw, & Gonzalez, 2013; Stone & Gonzalez, 2013, 2014; Stone et al., 2013), and no-doubt countless more pilot studies and unpublished experiments.

However, to our knowledge the E-WHQ has never been validated, and recent evidence from our lab has begun to cast doubts on both its usefulness for predicting *actual* hand-preference for grasping, and on the reliability of participant responses. With respect to hand preference for grasping, one would assume that hand preference for simple or skilled tasks would naturally extend to grasping; however, several studies in our lab, assessing both kinematics and simple preference, have found no correlation between either advantage or preference and E-WHQ handedness scores (Flindall et al., 2015; Gonzalez et al., 2007). With respect to reliability, we find (anecdotally) that handedness scores of + 44/−44 are not uncommon, despite the improbability of someone *always* using one hand over the other in the absence of a physical or neurological disability. As such, a handedness score of + 44/−44 suggests that either the participant misunderstands the meaning of the answer format (in particular, their definition of "always" may be subjective), is casually reporting their already-decided hand preference with little or no thought for their *actual* behaviour (or worse, actively attempting to deceive, as in the case of "mischievous responders;" see Fish & Russell, 2017; Robinson-Cimpian, 2014). More likely, participants are simply *mistakenly* reporting their behaviour, demonstrating a difficulty in self-reflection rather than an active lack of concern for the truth. In any case, such reports are taken seriously by the researcher, as they must always be; to preserve the brevity of testing sessions, questionnaires are presented in lieu of in-depth interviews, tests, and direct observations, and their results cannot be disregarded upon an investigator's hunches or whims. The benefit of questionnaires is that they save time, but the inevitable downside is that they are vulnerable to inaccuracy and manipulation, whether intentional or unintentional.

Several studies have been conducted to assess the validity of such questionnaires (Brown, Roy, Rohr, & Bryden, 2006; Bryden, 1977; Cavill & Bryden, 2003; Chapman & Chapman, 1987; Coren & Porac, 1978; Dragovic, 2004; Dragovic, Milenkovic, & Hammond, 2008; Peters, 1998; Raczkowski, Kalat, &

Nebes, 1974; Veale, 2014). With respect to the original WHQ, Cavill and Bryden (2003) compared observed hand preference for a number of simple tasks (e.g., shaking a hammer, tossing a ball at a small target, lifting a door on a cabinet, etc.) to that reported via the WHQ for children and young adults aged 2–24 years. They found a small but significant positive correlation between reported and actual hand preference across all age groups. This suggests that, while questionnaire responses and behavioural test results are *generally* congruent, there is an important distinction between the cognitive aspect of hand preference (i.e., that reported via questionnaire) and the motor component of hand preference (i.e., that measured in performance-based tests). Similar problems have been highlighted with respect to the EHI, by researchers who report the presence of questions that may be redundant (e.g., questions on hand preferred for writing vs. drawing; Dragovic, 2004; Edlin et al., 2015) and/or uninformative [e.g., which hand do you use to swing a racket or bat? (Richardson, 1978), or which hand do you use to open a box lid? (Dragovic, 2004)]. One analysis of the EHI's validity recommended removing 6 of its 10 questions for reasons of high measurement error; the EHI—Short Form boasts simpler, less burdensome instructions for participants to follow, high reliability, and a more reasonable approximation of handedness categorization than the traditional EHI (Veale, 2014). Likewise, the WHQ has been revised a number of times, and versions of 20 items (Elias, Bryden, & Bulman-Fleming, 1998), 30 items (Judge & Stirling, 2003), 36 items (Benderlioglu & Nelson, 2004; Bryson, Grimshaw, & Wilson, 2009) are cited in the recent literature. In short, even among the most heavily-cited and broadly researched handedness questionnaires, there is considerable discussion both on which questions to ask participants, and on how best to interpret their answers.

In a similar vein, we wanted to assess the validity of the E-WHQ in terms of both its reliability and its usefulness in predicting hand use for a simple grasping task. This task, which asks participants to use building bricks to replicate simple 2D or 3D models, is appropriate for use in both child and adult populations. Given that hand preference for precision grasping predicts other forms of lateralization (Gonzalez & Goodale, 2009; Hinojosa, Sheu, & Michel, 2003; Rogers, 2009) and that preference for reaching and grasping is (by far) the most common method of inferring laterality in non-human primates (Papademetriou, Sheu, & Michel, 2005), determining whether handedness questionnaires accurately forecast hand use for grasping is imperative if we wish to use these questionaires in lieu of more time-intensive techniques. Our tests and subsequent analyses were designed to answer three primary questions regarding the E-WHQ. First, does overall handedness score correlate with hand preference on this simple grasping-preference test? Second, does the format of the handedness questionnaire contribute to the prevalence of unrealistic reports—that is, does the consistent, repetitive nature of the response key encourage participants to disregard the content of the questions themselves? And third, can the accuracy of participant responses be trusted—i.e., what is the test-retest reliability for individual questions, and the test as a whole?

We begin with a generic reliability assessment of the inventory items on the E-WHQ, to assess the internal consistency of item responses and their contribution to the ostensibly measured factor (i.e., "handedness"), before continuing with analyses designed to answer our three main questions. To answer our first question (whether handedness questionnaire responses predict behaviour), we performed a meta-analysis of data collected from 250 participants (approx. 20.9 ± 2.3 years old, ~70% female[1]) across seven studies performed in The Brain in Action lab at the University of Lethbridge between 2011 and 2017. Included studies shared the aforementioned block-building task designed to assess hand preference for grasping (Stone et al., 2013). This task required participants to reconstruct simple Lego models from an array spread out on a table before them, with an equal number of pieces on the left and right side of the table. Investigators tallied the number of grasps made with the right and left hands and divided those numbers by the total number of grasps (40–60 grasps, depending on the complexity of models used, which varied by experiment and age group). The resulting quotients represent an objective, direct-observation index of left and right hand preference for grasping small, manipulable objects located across left and right graspable space, as well as in near and far regions (i.e., peri- and extra-personal space; Gonzalez & Goodale, 2009; Gonzalez, Flindall, et al., 2014; Gonzalez, Mills, et al., 2014; Gonzalez et al., 2006, 2007). The proportion of right and left-handed grasps reported in these seven studies were then correlated with handedness score as determined via the E-WHQ. To answer our second and third questions, we presented a scrambled questionnaire to two undergraduate classes at the University of Lethbridge. For question 2 (whether the handedness questionnaire's repetitive structure influences participant responses), we compared the distribution of responses among self-reported right-handers between the scrambled digital tests and the consistent paper tests analyzed for question 1. To answer question 3 (whether handedness questionnaire responses are stable over time), we presented the scrambled test to the same classes, 2–4 weeks later. Students did not know they would be asked to complete the questionnaire a second time. Question responses were compared between T_1 and T_2 to assess the reliability of both individual questions and of the test scores as a whole.

[1]Information on age and gender were reported at each participant's own discretion; as such, gender information was available for 90% of participants, while age information was only available for 50% of participants. However, as all participants were recruited from the same pool of psychology, kinesiology, and neuroscience undergraduate students at the University of Lethbridge, the demographic information reported here is assumed to be representative of our overall sample.

Methods and results

Generic reliability assessment

To assess the degree of error with which "handedness" is estimated by the E-WHQ, we approximated generic reliability via Cronbach's Alpha using SPSS Statistics (v24). Because participant data from the paper tests analysed in question 1 included a disproportionately high number of left handers, data collected for question 2 (specifically, T_1 data) were analysed instead. Cronbach's Alpha for T1 data was high (.939), indicating high internal consistency between items. Table 1 shows the correlation between individual items and overall score, along with the change in alpha were that item to be removed from the questionnaire. Removal of two items would improve the Cronbach's alpha; specifically, items 19 ("use a broom (upper hand)") and 22 ("use a baseball bat (upper hand)"). That these items negatively affect Cronbach's alpha suggests they may be driven by a factor other than "handedness;" this is consistent with findings from previous studies (Dragovic, 2004).

Table 1. E-WHQ inter-item correlation coefficients and effect on Cronbach's α if item removed. Removal of two items would improve Cronbach's α for items on the E-WHQ; item 19 (*which hand would you use to hold a broom (upper hand)?*), and item 22 (*which hand would you use to swing a baseball bat (upper hand)?*).

Question	Corrected Item-Total Correlation	Squared Multiple Correlation	Cronbach's Alpha if Item Deleted
Q1: … spin a top?	0.622	0.484	0.937
Q2: … hold a paintbrush?	0.7	0.558	0.935
Q3: … pick up a cheerio?	0.503	0.383	0.938
Q4: … hold a spoon to eat soup?	0.756	0.636	0.934
Q5: … pick up a piece of paper?	0.567	0.512	0.937
Q6: … turn a key in a lock?	0.612	0.428	0.937
Q7: … insert a plug into an outlet?	0.601	0.474	0.937
Q8: … throw a ball?	0.642	0.519	0.936
Q9: … pick up a marble?	0.57	0.482	0.937
Q10: … use a hand saw?	0.757	0.754	0.934
Q11: … open a drawer?	0.539	0.449	0.938
Q12: … turn a doorknob?	0.528	0.436	0.938
Q13: … use a hammer?	0.82	0.817	0.933
Q14: … for writing?	0.824	0.923	0.933
Q15: … turn a combination dial?	0.598	0.468	0.937
Q16: … sign your name?	0.823	0.929	0.933
Q17: … use scissors?	0.769	0.696	0.934
Q18: … use a toothbrush?	0.743	0.617	0.934
Q19: … use a broom (upper hand)?	0.33	0.234	0.942
Q20: … strike a match?	0.787	0.674	0.934
Q21: … kick a ball?	0.478	0.369	0.938
Q22: … use a baseball bat (upper hand)?	0.279	0.196	0.944

Question 1: Can handedness questionnaire responses be used to predict hand preference for reach-to-grasp actions in a simple construction task?

First, to determine whether total score on the handedness questionnaire was correlated with hand-preference on the grasping task, a bivariate correlation was applied to these variables. A Kendall Tau- b correlation[2] was applied due to the strong positive skew of the handedness scores. Estimates of effect size are reported via r, calculated according to the formula $r = \sin(.5\pi^*\tau)$ (Gilpin, 1993; Walker, 2003). A significant positive correlation was obtained, $\tau = .245$, $p < .001$ (2-tailed), estimated $r = .375$, indicating that with increased reported right-hand preference on the handedness questionnaire ($M = 17.446$, SE = 1.103), participants are more likely to use their right-hands in the grasping task ($M = 59.8\%$, SE = 1.3%). This result is unsurprising, given the self-reported hand preference of our overall sample (71.2% right-handed ($n = 178$), 26.8% left-handed ($n = 67$), 2% ambidextrous ($n = 5$)).

To assess whether handedness score correlated with responses on the E-WHQ *aside* from the bias predicted by self-reported handedness, the data were split by self-reported handedness group (Left Handed, Right Handed, or Ambidextrous, as selected by the participant's response to question 23 on the E-WHQ) and the same Kendall Tau-b correlation was applied to all three groups. Note that while neither Left Handed nor Ambidextrous groups showed significant signs of skewness or kurtosis, the non-normal distribution of both the handedness scores and hand preference tallies in the Right Handed group necessitated the use of a non-parametric correlation statistic.

Handedness score did not correlate with right-hand preference in the block-building task in any of our self-report groups: neither the Left Handed (Score M=−15.15, SE = 2.02; RH Pref. $M = 46.3\%$, SE = 2.7%; $\tau = .004$, $p = .961$, estimated $r = .0065$), the Right Handed group (Score $M = 30.28$, SE = .52; RH Pref. $M = 65.3\%$, SE = 1.4%; $\tau = .042$, $p = .415$, estimated $r = .066$), nor the Ambidextrous participants (Score $M = -2.6$, SE = 8.5; RH Pref. $M = 45.0\%$, SE = 6.1%; $\tau = .400$, $p = .327$, estimated $r = .588$) showed a significant correlation between these two variables (Figure 1). These results indicate that within self-defined handedness groups, individual score on the E-WHQ is not useful in predicting right-hand preference in a simple grasping task.

We further investigated whether/which items on the E-WHQ were most useful in predicting hand-preference for a simple grasping task. We performed

[2]We are aware that past research has recommended polychoric correlation to assess the relationship between items on the EHI (Dragovic, 2004). In this case, however, our dependent variable (probability of right hand use in a grasping task) is measured on a continuous scale, and our independent variable (E-WHQ score) is reported on an 88-point ordinal scale (which may safely be treated as continuous; see Rhemtulla, Brosseau-Liard, & Savalei, 2012); for these reasons (and again, because our data fails the test of normality), we have instead used Kendall's tau to estimate rank correlation.

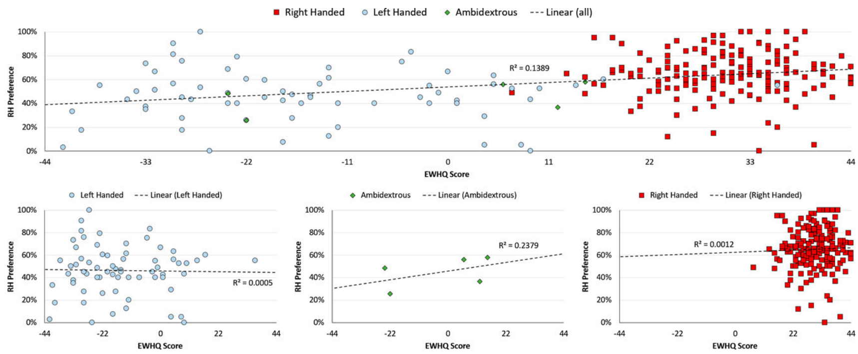

Figure 1. Relationship between Handedness Questionnaire Score (range: [−44, +44]) and right-hand preference for grasping during the block-building task (range: [0%, 100%]). When treated as a single group, there is a significant positive correlation between handedness score and RH preference for grasping ($p < .001$; top panel). However, if divided into subgroups based on self-reported handedness, no significant correlation exists between HQ score and RH preference among any group [left handed ($p = .961$), ambidextrous ($p = .327$), or right handed ($p = .415$); bottom panel.]

a multiple regression analysis with percent right hand use in the block-building task as the dependent variable and individual question response (22 questions total), total handedness score, and handedness self-report (left-handed, right-handed, ambidextrous) from the paper test as independent variables. Entry of independent variables was forward stepwise, with handedness self-report dummy coded. Nearly all independent variables showed positive skewness due to the nature of the questionnaire and the expected number of right-handed respondents; however, because multiple regression analysis makes no assumption regarding the distribution of independent variables, this skewness was ignored. No multivariate outliers were observed (all $\chi^2 < 2.5$).

Table 2 displays the unstandardized (B) and standardized (β) regression coefficients for the five variables that contributed significantly to the prediction of right-hand use in the block-building task. In order of step entered, these variables were questions 14 (*Which hand would you use to write?*), 16

Table 2. Regression coefficients for the five most relevant variables for the prediction of right-hand use in the block-building task.

Question: Which hand would you use to …	Regression Coefficients (*B*)	Standardized Regression Coefficients (β)	Adjusted R^2	Step
… write?	.091	.778	.177	1
… sign your name?	−.049**	−.361	.186	2
… hold a broom?	.018*	.122	.193	3
… turn a dial?	.027*	.162	.198	4
… use a toothbrush?	−.029	−.219	.207	5
Constant	.558**			

$R = .472$**; adjusted $R^2 = .207$; **$p < .001$, *$p < .05$.

(*Which hand would you use to sign your name?*), 19 (*Which hand would you use to hold a broom (upper hand)?*), 15 (*Which hand would you use to turn the dial on a combination lock?*), and 18 (*Which hand would you use to hold a toothbrush to brush your teeth?*). The adjusted R^2 at each step is also reported in Table 2. *R* was significantly different from zero, $F(5, 243) = 13.958$, $p < .001$. Altogether, only 21% of the variance in right-hand use was predicted using the responses on these five questions.

Question 2: Does the repetitive organization of the handedness questionnaire responses contribute to the prevalence of artificially-high (or artificially-low, in the case of left-handers) handedness scores?

To assess whether self-reported preference for various tasks (as assessed by E-WHQ) is influenced by questionnaire design, a digital version of the E-WHQ was presented to students in two introductory neuroscience courses at the University of Lethbridge (Spring semester, 2017). These students reported their hand preference for the same 22 inventory items on the traditional paper-based test via the A-E response buttons on an iClicker response pad (© *Macmillian Learning, New York, USA*). However, unlike the paper-based questionnaire, responses on the digital test were scrambled. The five possible response choices on the digital test (A-E) were identical to the paper test (always/usually left, equal, usually/always right), however these responses were scrambled within- and between-questions, such that no two questions used the same letter + response pairing or order (see Figure 2).

Digital responses were collected at the beginning of class in two separate sessions separated by a minimum of two weeks. Unique responses were collected from 267 students, of whom 218 both a) provided responses to all 22 inventory items in the first session, and b) self-identified as right-handed. Note that because many of the studies included in our paper-based E-WHQ tally specifically recruited left-handed participants, there was a significant disparity in number of respondents identifying as left-handed between our paper-based tests (67 left handers) and digital respondents (22 left handers); we therefore limited analysis in this section to right-handed respondents only, as these two groups were comparable in size. First-session handedness scores collected from "digital right-handers" were compared to the scores from 178 "paper right-handers" (right-handed respondents on the traditional paper test) via independent samples t-test. This analysis revealed that scores were indeed different between the two groups, $t(394) = -3.172$, $p = .002$. As expected, average scores on the digital/scrambled test ($M = 29.12$, SE = .43) were significantly lower than scores on the traditional paper test ($M = 31.17$, SE = .48), representing a drop of 4.7%. Scrambled vs. Traditional distribution is presented in Figure 3.

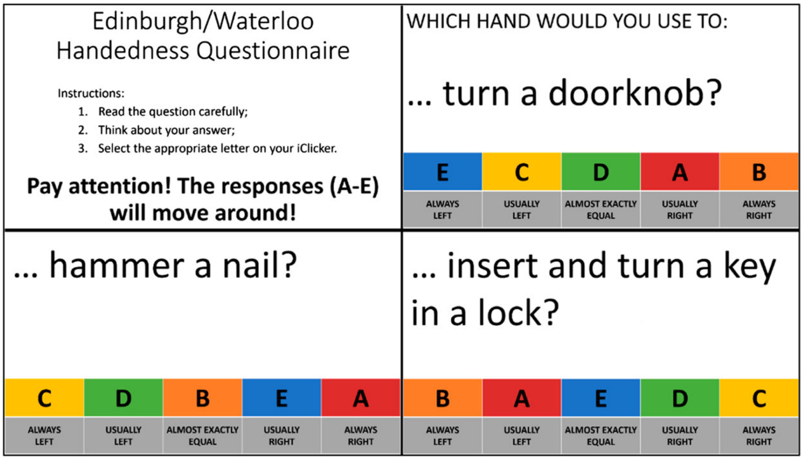

Figure 2. Instructions and sample questions from the digital handedness questionnaire. Twenty-two questions were presented via Microsoft PowerPoint to a class of approximately 250 students. Questions were advanced after thirty seconds, or when all participants had submitted their response electronically, whichever came first. Note that letter + response pairings are shuffled between questions; no two questions, consecutive or otherwise, shared the exact same letter + response pairings. Question order (and letter + response pairings) were shuffled between T_1 and T_2 (see Methods, Question 3).

Question 3: Are handedness scores stable over time? i.e., does the handedness questionnaire demonstrate high within-participant test-retest reliability?

To determine whether handedness inventory responses are stable over time, classroom participants were asked to repeat the E-WHQ 2–4 weeks after their initial completion. To avoid potential response bias, participants were not informed in the first session that they would be asked to repeat the questionnaire several weeks later. Both the order of questions and their letter + response pairings were shuffled anew for the second testing session (T_2).

Consistency of responses per question was determined by analysing correlation coefficients of responses between T_1 and T_2. Polychoric correlation analyses were conducted in R (v3.5), however all but two questions (15 and 16) failed the chi square test for bivariate normality (all $p < .05$), again necessitating the use of a non-parametric correlation statistic. The Kendall Tau coefficients for each question are reported in Table 2. While all correlations were strongly significant, no correlation coefficients were larger than .8, with the large majority being smaller than .6 (Mean $\tau = .525$). On average, 34% of participants changed their response on any given question between T_1 and T_2. Only two questions remained consistent for more than 80% of respondents between first and second sessions; 94.3% of respondents provided a consistent answer to question 16 (*Which hand would you use to sign your name?*) and

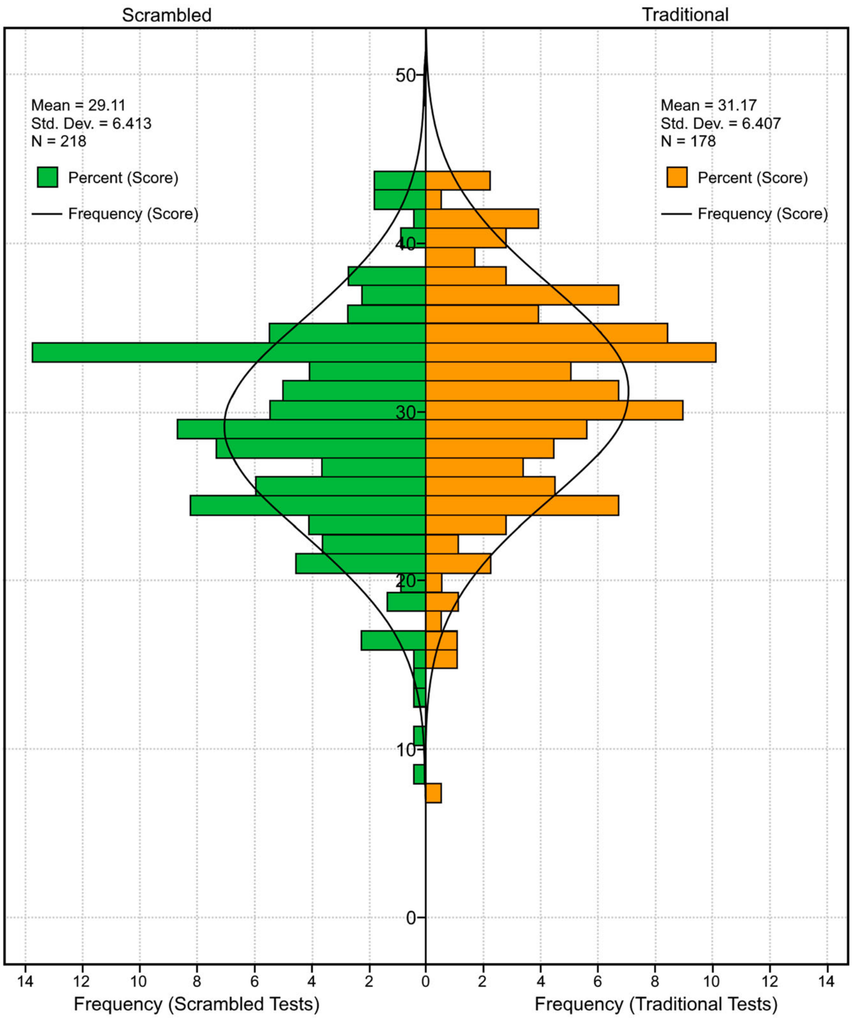

Figure 3. Frequency (%) distribution of scores on scrambled (left, green) and traditional (right, orange) E-WHQs (right-handed respondents only). Average score on traditional paper-based inventory is significantly higher than average score on scrambled inventory.

92.4% of respondents provided a consistent answer to question 14 (*Which hand would you use for writing?*). Somewhat surprisingly (or perhaps not surprisingly, given the results of our analysis in question 1), E-WHQ questions 3 (*Which hand would you use to pick up a cheerio?*) and 5 (*which hand would you use to pick up a piece of paper?*) were the least stable, with τ correlations of .338 and .307, respectively. That is, the questions eliciting the smallest correlation between testing times T_1 and T_2 were the only two questions to directly reference simple unimanual grasps. Also of interest is the fact that in the two week period between sessions, eight participants changed their

Table 3. Changes in inventory item scores from "digital" respondents ($n = 264$).

Question (Which hand would you use to …)	Response Pairs Analyzed ($N = 264$)	T_1:T_2 Correlation [Kendall's τ (estimated r)]	Avg. Response Change (absolute)	% Responses Changed
Q1: … spin a top?	253	.470 (.673)	+0.0079	37.2%
Q2: … hold a paintbrush?	257	.519 (.728)	−0.0545	40.9%
Q3: … pick up a cheerio?	248	.338 (.506)	+0.0927	54.0%
Q4: … hold a spoon to eat soup?	259	.544 (.754)	−0.1583	31.3%
Q5: … pick up a piece of paper?	261	.307 (.464)	+0.0421	45.6%
Q6: … turn a key in a lock?	260	.478 (.682)	−0.0346	40.8%
Q7: … insert a plug into an outlet?	260	.432 (.628)	−0.0500	47.3%
Q8: … throw a ball?	260	.490 (.696)	−0.1654	34.6%
Q9: … pick up a marble?	263	.425 (.619)	−0.0418	44.5%
Q10: … use a hand saw?	262	.615 (.823)	−0.0420	22.5%
Q11: … open a drawer?	261	.432 (.628)	+0.1264	47.5%
Q12: … turn a doorknob?	260	.475 (.679)	−0.0577	41.9%
Q13: … use a hammer?	265	.534 (.744)	−0.1472	22.3%
Q14: … for writing?	264	.786 (.944)	−0.0568	7.6%
Q15: … turn a combination dial?	265	.505 (.713)	−0.0792	35.5%
Q16: … sign your name?	265	.784 (.943)	−0.0868	5.7%
Q17: … use scissors?	263	.505 (.713)	−0.0608	30.8%
Q18: … use a toothbrush?	263	.626 (.832)	−0.0152	31.6%
Q19: … use a broom (upper hand)?	257	.560 (.771)	+0.1868	46.3%
Q20: … strike a match?	259	.529 (.739)	−0.0811	31.7%
Q21: … kick a ball?	262	.588 (.798)	−0.0992	34.0%
Q22: … use a baseball bat (upper hand)?	259	.599 (.808)	−0.0232	23.9%

reported handedness (i.e., responses to the question *Do you consider yourself Left Handed, Right Handed, or Ambidextrous?* were inconsistent between T_1 and T_2). Kendall Tau-b coefficients (and estimated r values), average response change, and percentage of changed responses per question are reported in Table 3. A visual representation of changed responses is presented in Figure 4.

Discussion

The current experiment and analyses were designed to answer three primary questions. First, do handedness inventory responses correlate with actual hand-preference for prehension? Second, does the format of the handedness questionnaire artificially influence the participants' responses, inflating the reported degree of right-handedness? Third, are responses on the handedness inventory stable over time (i.e., how reliable are participant responses)? To answer these questions, a variety of behavioural and statistical tools were employed. First, analysis of handedness inventory responses versus hand preference in a simple block building task indicates that the E-WHQ is of little use for predicting *actual* hand preference for grasping. Second, when question responses are scrambled, average handedness score among self-identified right-handers drops by nearly 5%, suggesting that scores are significantly higher (i.e., more skewed toward absolute right-hand preference)

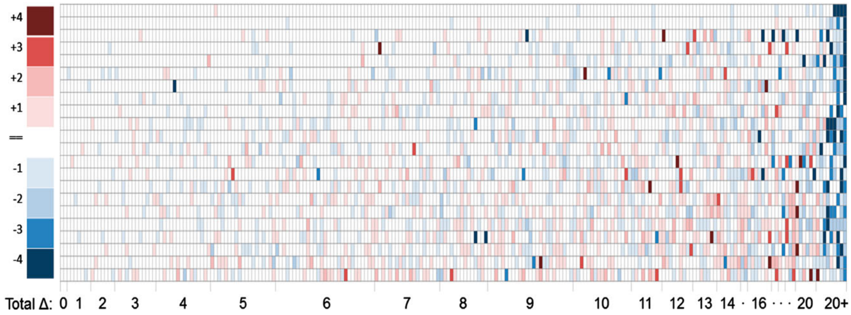

Figure 4. Response changes per participant (columns; $n = 230$) per question (rows), arranged with respect to stability, from most (top, left) to least (bottom, right) stable. Only participants who responded to every inventory item in both test sessions are included in this figure. Only two participants (left-most columns) had perfectly consistent responses on all inventory items; both of these participants answered "always right" (+2) to every single question, indicating that, for these 22 tasks at least, they *never* use their left hands.

when inventory responses are repetitive. Finally, responses to inventory items are not especially stable; more than 99% of participants will change their stated hand preference for at least one inventory item when asked only a couple weeks later, suggesting that the accuracy of a *single* handedness determination (via E-WHQ) may be questionable; at worst, E-WHQ handedness score may be irrelevant when it comes to predicting hand preference for grasping.

Do questionnaire responses correlate with hand preference for grasping? Perhaps, but only in a general sense. If you ignore self-classification (i.e., "I consider myself [left, right] handed/ambidextrous,") then yes, there is a correlation between absolute score on the E-WHQ and hand preference for grasping. However, if a researcher is looking to use the E-WHQ for predictive power *within* groups of left and/or right handers (as we have, previously), then the questionnaire is not especially useful. In the current study, actual hand preference for grasping was not predicted within any given subgroup of participants (left handers, right handers, ambidextrous); the correlation between handedness score and right-hand preference for grasping was simply too low. In our stepwise multiple regression analysis, we identified five questions that contribute the *most* to hand-preference in our grasping task, however only two of these questions are shown to be stable in our test-retest analysis. Curiously, one of these predictive questions (*which hand would you use to hold a broom (upper hand)?*) has been flagged by previous research as having an unacceptably low factor loading on handedness; that is to say, responses on this particular question are probably driven by a factor other than "handedness" per se (Dragovic, 2004). This possibility is supported by the current study, as our analysis of generic reliability shows that removal of this question would improve the overall consistency of the E-WHQ. In addition, as shown by the particularly high predictive value this question has for right hand use for grasping, we may speculate that responses to this particular question may be driven by "hand preference for grasping" rather than "handedness." Based on these somewhat unintuitive results, we suggest that hand preference for grasping and hand dominance overall may be discrete, as they so rarely correlate (Flindall et al., 2015; Gonzalez, Flindall, et al., 2014; Gonzalez et al., 2006, 2007). Further supporting this dichotomy are studies which show no difference between left and right-hand kinematics for reach-to-grasp actions (Flindall & Gonzalez, 2013; Flindall et al., 2015; Grosskopf & Kuhtz-Buschbeck, 2006; Tretriluxana, Gordon, & Winstein, 2008), another unexpected result, considering both the lateralized preference for grasping (Gonzalez et al., 2007) and the robust kinematic asymmetries between left and right-handed *reaching* movements (for a brief review, see Grouios, 2006). These studies imply that overall hand dominance does not affect the execution of simple reach-to-grasp actions and, further, that the lateralized preference for such actions may be similarly unaffected. It is possible that hand preference for grasping may be predicted by a new handedness inventory, one using items that correlate with our behavioural measure. Ongoing research in our lab aims to develop such a questionnaire. Regardless, even *if* some questions are of more predictive value than others, their usefulness may *still* be severely limited, considering we may not be able to trust the responses themselves.

Does the format of the questionnaire bias responses? Perhaps; we show here that by changing the format of the responses from a consistent Likert scale to a scrambled one, we can shift the average handedness score by 2 points (approximately 5%). However, it is also possible that this slight leftward shift of scrambled responses may be due to the nature of the testing environments. In the lab (paper tests, traditional setup), handedness questionnaires are normally presented at the end of data collection so as not to bias the participant's behaviour during the experimental task. This design of course leaves us (as researchers) open to the possibility that the experimental task itself (in this case, a block-building task) may be biasing responses on the E-WHQ. Also, it is worth noting that abnormal prevalence spikes exist at + 22 and + 44 in both versions of the test; this suggests that, despite the scrambling of the test, some participants may still answer "usually right" or "always right", consistently, to all questions.

How does the E-WHQ fare in terms of test-retest reliability? Poorly. 99% of respondents changed their response on at least one question, with 8 being the median number of responses changed. Interestingly, some questions are far more stable than others; questions that reference bimanual tasks that use the non-preferred hand for stabilization (e.g., signing your name, writing, or using hand tools) are far more likely to produce stable responses than are questions referencing a context-dependent action (holding a broom, or turning a doorknob), or, interestingly, questions that specifically reference a unimanual grasping action (picking up a cheerio, or picking up a piece of paper). Of particular note are these last two questions; the fact that the *only* two questions that specifically reference hand preference for grasping are the *least* stable questions in the current study lends credibility to our hypothesis that "hand dominance" and "hand preference for grasping" are not directly equivalent. Furthermore, if we judge responses solely on their retest consistency, some participants seem to be answering randomly; 24% of respondents changed their answers by an absolute value of 12 or more points. While the majority of these responses ended up cancelling each other out (that is, a large number of shifts ultimately results in only a small change in overall E-WHQ score), fully 10% of respondents had a score shift of 10 points or more in their handedness assessment. This is of course problematic, for a number of reasons. First, not all questions are equal: because of the ordinal measure of the Likert scale used, the difference of a single point on a single question may represent a large difference in analysis of behaviour. For example, 21% of our left-handed respondents in the paper questionnaires reported scores that would place them in the weakly- to moderately-right-hand dominant population. Nevertheless, they identify as left-handed, presumably owing to their left-hand preference for writing and signing their name. The importance we bestow on "key" types of behaviours, like writing, make it difficult to classify left- and right-handedness by score alone, let alone determine the strength of that dominance. Second, we do not validate individual questionnaire responses in the lab: whatever participants fill out on their visit is treated as gospel. The results of this analysis reveal that responses on average questions vary by an average of .37 points; on a 5-point scale, that represents a $\pm$ 10% range of variability *per question*. If by chance that variability stacks rather than cancelling itself out, it represents an enormous shift in score for an individual participant. From the researcher's perspective, we cannot know if the first test response is more valuable than the second; and, since we usually only have the first (single) response, we cannot say for sure whether it is more useful than any other additional response. Third, 3% of digital-respondents provided questionnaire responses that are self-contradictory and, in all likelihood, fabrications. These are the people who identified as right-handed at T_1 but left-handed or ambidextrous at T_2 (or vice versa), or had strongly negative scores on day 1 and strongly positive scores on day 2 (or vice versa). It is unlikely that these participants simply misunderstood the instructions, or were answering randomly; the consistency of their responses, in spite of the scrambled response keys, suggests they understood the responses perfectly fine. Instead, it is possible that these participants represent those "mischievous responders" who *explicitly choose* not to respond honestly when presented with questionnaires (Fish & Russell, 2017; Robinson-Cimpian, 2014). In experiments like this one, where we have large sets of data with which to compare their responses, they are relatively easy to identify and may be safely discarded. But in other situations, when group size is small and testing is limited to a single session, they may be far more insidious and difficult to identify. How many of our paper-test participants belonged to this group? How many, of the hundreds of participants who have contributed to our studies over the years responded randomly or pseudo-randomly on the questionnaire? Normally, such respondents may be filtered from the sample by cross-referencing multiple low-response items, or responses with low or inverse correlations (Robinson-Cimpian, 2014); however, the E-WHQ has no low-response items, nor do the questionnaires from which it was constructed. It may be wise to include a catch-question on handedness questionnaires going forward; perhaps asking participants to report which hand they are likely to use for a supporting task, e.g., *which hand would you use to stabilize a nail,* or *which hand would you use to hold a jar when opening it?* Though unlikely, it is possible that mischievous responders are responsible for the handedness questionnaire's failure to correlate significantly with behavioural measures in previous studies; after all, it is far easier to err on subjective responses than it is to fake behaviour. We must be open to this possibility in future studies.

In conclusion, the current study finds that Handedness inventory data collected by self-report are problematic at best. If the goal is to classify participants in one handedness group or another to estimate hand preference for grasping, the same relevant information may be collected via a single question: *which hand do you use to sign your name?* or, even simpler, *do you consider yourself right handed, left handed, or ambidextrous?* If instead the ultimate goal is to determine hand preference, then the best course of action would be to actually assess hand preference through a battery of physical tests of behaviour (for review, see Scharoun & Bryden, 2014). Self-report is notoriously spurious (whether forgery is motivated by mischievousness, malice, or apathy is ultimately irrelevant), but behaviour is far more difficult to successfully mimic. As the saying goes, the proof of the pudding is in the eating.

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