PREDICTING HAND PREFERENCE WITH PERFORMANCE ON MOTOR TASKS

W.J. Triggs[1], **R. Calvanio**[2], **M. Levine**[2], **R.K. Heaton**[3] **and K.M. Heilman**[1]

(From the [1]Department of Neurology, University of Florida, Gainesville, the [2]Department of Neuropsychology, Spaulding Rehabilitation Hospital, Boston, and the [3]Department of Psychiatry, University of California, San Diego, USA)

Abstract

Handedness may be defined as preference or hand-differences in task performance. The strength and significance of the relationship between hand preference and hand performance asymmetries have been contested. To evaluate this relationship, we administered the Edinburgh Handedness Inventory and measured asymmetries in finger tapping, Purdue Pegboard, and grip strength in 30 subjects who prefer their right hand and 30 subjects who prefer their left hand. Hand asymmetries in finger tapping, Purdue Pegboard, and grip strength each predicted hand preference scores. However, a multiple regression equation best predicted hand preference by using performance of each task. Hand asymmetries in finger tapping correlated strongly with asymmetries in Purdue Pegboard performance, but neither of these asymmetries correlated strongly with asymmetries in grip strength. These findings indicate that hand preference and asymmetries in motor proficiency are strongly related, but suggest that preference and proficiency for different aspects of motor performance may be independently lateralized.

Introduction

Handedness is the most obvious human behavioral asymmetry. The term handedness, however, may refer either to hand preference or to the asymmetrical performance of manual tasks (Woo and Pearson, 1927; Barnsley and Rabinovitch, 1970; Provins and Cunliffe, 1972; Kimura and Davidson, 1975; Annett, 1976; Peters and Durding, 1978; Johnstone, Galin and Herron, 1979; McManus, Kemp and Grant, 1986; Harrison and Pauly, 1990; Shimoyama, Ninchoji and Uemura, 1990; Steinmetz, Volkmann, Jancke et al., 1991; Provins and Magliaro, 1993). Whereas there is evidence that preference and relative manual proficiency are directly related, the relationship between these two measures of handedness remains controversial. When subjects are grouped according to the strength of hand preference, a strong correlation has been repeatedly demonstrated between hand preference classification and hand-differences in the performance of a peg-moving task (Annett, 1970b, 1976, 1985). A similar relationship exists between hand preference and relative proficiency in finger tapping (Peters and Durding, 1978, 1979). These associations, and the fact that the distributions of relative manual proficiency were found to be unchanged during childhood (Annett, 1970a; Peters and Durding, 1978), led Annett (1985) to propose that one hand may be preferred over the other because it is more adept. Annett (1992) has since verified the relationship between hand preference classification and peg moving asymmetry using a series of pen and paper tasks designed to resemble peg moving. Annett's position, however, has been challenged (Flowers, 1975; Todor and Doane, 1977; Johnstone et al., 1979; Borod, Caron and Koff, 1984; Porac and Coren, 1981; Provins and Magliaro, 1993; Bryden, Ardila and Ardila, 1993; Peters, 1995). Porac and Coren (1981) suggested that preference and asymmetrical task proficiency are fundamentally different entities. These authors based this position on two observations. First, they noted that correlations between hand preference and hand performance asymmetries are often of only modest size. Second, they emphasized that preference and proficiency have distinct population distributions. Whereas the population distribution of hand preference scores is best described by a bimodal J-shaped distribution (Annett, 1970b), relative manual proficiency is typically distributed normally with a mean shift towards superior performance of the right hand (Woo and Pearson, 1927; Annett, 1972). However, Annett (1972, 1985) has indicated that the J-shaped distribution of preference can be superimposed on the normal distribution of proficiency asymmetry when the distributions are accurately represented [compare Figure 2.1 of Porac and Coren (1981) and Figure 13.4 (a) of Annett (1985)].

Bishop (1989) examined the relationship between preference and task proficiency with mathematical modeling. By assuming that hand preference is exponentially related to relative manual proficiency, Bishop developed a model that accounted for the modest size of correlations between preference and asymmetry in motor proficiency, as well as the differences in the distribution patterns of hand preference and asymmetrical proficiency noted by Porac and Coren (1981). Bishop (1989) concluded, however, that different aspects of motor proficiency (i.e. speed, strength, etc.) may have differential importance in determining hand preference for different manual tasks.

Hand preference has traditionally been measured using handedness inventories, quantifying hand preference for the performance of a variety of manual tasks. Since preferences for different types of manual tasks may be independently lateralized (Healey, Liederman and Geschwind, 1986; Steenhuis and Bryden, 1989), we posited that the correlation between hand preference and performance asymmetry would be increased by measuring asymmetries in multiple manual tasks. Therefore, we examined the strength of the correlation between hand preference and hand-differences in *multiple* manual tasks (finger tapping, pegboard dexterity and grip strength) using regression analysis.

To determine if performance asymmetries may be related to shared neural substrates, we also examined relationships between the performance of different manual tasks. For example, Lawrence and Kuypers (1968) demonstrated in monkeys that the corticospinal system is critical for performing independent finger movements. Finger tapping and picking up a peg require some degree of independent finger movement precision. Therefore, hand asymmetries associated with these two tasks may be related to asymmetries of the corticospinal system (Triggs, Calvanio and Levine, 1997). Because hand-differences in both of these tasks may be based in part on corticospinal asymmetries, we predicted that asymmetries in finger tapping speed would correlate more strongly with asymmetries in pegboard dexterity than they would with strength asymmetries.

Materials and Methods

Subjects

The subjects of this investigation were 60 healthy volunteers between 21 and 57 (mean 37 ± 9) years of age recruited according to preferred writing hand to include 30 right-handers without prior history of left-handedness and 30 left-handers. These subjects were used in a previous publication (Triggs et al., 1997). The two groups contained equal numbers of men and women and most subjects were recruited from hospital staff. None of these subjects had a history of brain injury or any medical condition (e.g. musculoskeletal injury, arthritis) expected to affect performance on the study tasks. All subjects had completed high school, and most had completed at least 4 years of college. Each subject participated after giving informed consent.

Tests and Procedure

Hand Preference

We quantified hand preference using the Annett Handedness Inventory, as modified by Briggs and Nebes (1975), and the Edinburgh Handedness Inventory (Oldfield, 1971). These inventories record self-reported hand preference for a series of motor tasks as ‘always right’, ‘usually right’, ‘either’, ‘usually left’, and ‘always left’. Scores on Briggs and Nebes (1975) version of Annett’s Handedness Inventory range from – 24 (all left) to + 24 (all right). Scores on the Edinburgh Handedness Inventory range from – 100 (all left) to + 100 (all right). In a previous report, Triggs et al. (1997) excluded from analysis the Edinburgh Inventory question regarding the hand held at the top of a broom while sweeping for purposes of classifying subjects as having consistent or nonconsistent hand preference. In the present report, we quantified hand preference using raw inventory scores. However, we verified that in no instance would removing the broom item have altered interpretation of the results.

Wrist-Finger Speed

We measured wrist-finger speed by asking subjects to use their index finger to tap the ‘7’ key of an IBM-compatible computer (Gateway 2000, North Sioux City, SD) running WordPerfect (WordPerfect Corporation, Orem, UT). Subjects were asked to tap as rapidly as possible during three 10 s trials with each hand. We derived right hand and left hand scores from the total number of ‘7’s’ tapped correctly with each hand over the three trials. Subjects were prevented from seeing the score of each hand on this task.

Finger Precision

We measured the precision of finger movements using the Purdue Pegboard (Tiffin, 1968). Subjects were asked to remove small metal pegs from a well and place them, one by one, into a vertically oriented row of holes. Subjects practiced the task with each hand prior to testing. Subjects were then asked to place as many pegs as possible during three 30 s trials with each hand. We derived right hand and left hand scores from the total number of pegs placed correctly with each hand over the three trials.

Static Strength

We measured static strength with a hand-held dynamometer. Subjects were given three trials with each hand. We derived right hand and left hand scores from the mean peak grip force reached by each hand over the three trials.

Data Analyses

We transformed performance measures (finger tapping, pegboard, and grip strength scores) into hand-difference scores for each subject’s right and left hands. Hand-difference scores for motor performance are not necessarily independent of the overall level of performance. However, in no instance did correcting hand-difference scores to account for the overall level of performance alter interpretation of the results. We used linear multiple regression modeling to examine the relationships between hand-differences in manual performance and preference. We used Pearson-product moment correlation coefficients to examine the relationships among hand-differences in manual performance.

RESULTS

Hand Preference

In right-handed subjects, scores on the Annett Handedness Inventory ranged from + 10 to + 24 (mean + 20 ± SD 4) and scores on the Edinburgh Handedness Inventory ranged from + 50 to + 100 (mean + 90 ± SD 13) In left-handed subjects, scores on the Annett Handedness Inventory ranged from – 24 to + 20 (mean – 14 ± SD 11) and scores on the Edinburgh Handedness Inventory ranged from – 100 to + 60 (mean – 68 ± SD 38). Scores on the two hand preference inventories were strongly correlated ($r = 0.98$; $p < 0.0001$).

Analysis of Handedness Effects on Task Performance

The results of evaluation of handedness effects on task performance in these subjects has been reported previously (Triggs et al., 1997). In brief, analysis of variance for each task showed a highly significant two-way interaction between the hand tested and handedness, such that the right hand performed better than the left hand in right-handers and the left hand performed better than the right hand in left-handers ($p < 0.0001$ for each task). Details of the effects of handedness on task performance are provided in Table I.

TABLE I
Effects of Handedness on Task Performance

	Left-handers (n = 30)		Right-handers (n = 30)	
Motor task	Left hand	Right hand	Left hand	Right hand
Finger-tapping	197 ± 22	186 ± 20	191 ± 26	206 ± 23
Purdue Pegboard	50 ± 5	46 ± 5	47 ± 5	51 ± 4
Grip Strength	23 ± 6	22 ± 6	22 ± 6	23 ± 6

Note. This table contains Finger Tapping scores expressed as the sum of taps in three 10 second trials, Purdue Pegboard scores expressed as the sum of pegs placed in three 30 second trials, and Grip Strength scores expressed as mean peak force (kg) reached over three trials. All data are expressed as mean ± standard deviation.

To examine the relationship between hand preference and asymmetrical task performance, we computed the correlations which appear in Table II. The table is divided into two sections and illustrates the results using scores on both the Annett and Edinburgh Handedness Inventories as separate dependent variables. The first row of each section of the table shows the Pearson-product moment correlation coefficients for the relationships between hand preference and hand asymmetries in the performance of each of the three tasks, using handedness

TABLE II
Predicting Preference from Performance

	Predictors	Finger Tapping	Purdue Pegboard	Grip Strength	R
Annett Handedness Inventory (Briggs and Nebes, 1975)					
	r	0.69‡	0.69‡	0.60‡	—
	β	0.302*	0.314*	0.348†	0.80‡
Edinburgh Handedness Inventory (Oldfield, 1971)					
	r	0.70‡	0.73‡	0.58‡	—
	β	0.286*	0.377†	0.309†	0.81‡

Note. This analyses used each subject's scores on the Annett and Edinburgh Hand Preference Inventories as dependent variables. Independent variables included the difference in the performance of each subject's right and left hands in each manual task. The table shows the Pearson-product moment correlation coefficient (r) for the correlation of preference with asymmetry in the performance of each motor task. The table contrasts the results of simple regression analyses with the correlation coefficient (R) and standard coefficients (β) obtained with multiple regression analysis using asymmetries in all three motor tasks as independent variables.
* = p < 0.03; † = p < 0.005; ‡ = p < 0.0001.

inventory (Annett or Edinburgh) scores as the dependent variable and performance asymmetries in Finger Tapping, Purdue Pegboard, and Grip Strength as independent variables. For each of the two handedness inventories, each of the three correlations is significant and all are of about the same magnitude. The second row of each section of the table shows the multiple regression equation in which the dependent variable, Handedness Inventory (Annett or Edinburgh) scores, is related to hand asymmetries in Finger Tapping, Purdue Pegboard, and Grip strength as simultaneously entered independent variables. The standardized coefficients (β) for all three proficiency asymmetry measures proved to be significant and of approximately the same magnitude. The resulting multiple regression equation accounted for R^2 = 64% (Annett Inventory) and 66% (Edinburgh Inventory) of the variance in hand preference for all subjects combined. When this regression equation was used to predict scores on the Annett Handedness Inventory, 26 of 30 (87%) left-handers and 27 of 30 (90%) right-handers (88% of all subjects) were classified correctly. For the Edinburgh Handedness Inventory, 27 of 30 (90%) left-handers and 28 of 30 (93%) right-handers (92% of all subjects) were classified correctly.

To examine the relationship between asymmetries of task performance, we computed the correlations which appear in Table III. Figure 1 illustrates these Pearson-product-moment correlations among hand asymmetries in manual

TABLE III
Correlations of Hand-Differences in Manual Performance

All subjects (n = 60)			Right-handers (n = 30)			Left-handers (n = 30)		
	Tap	Peg		Tap	Peg		Tap	Peg
Peg	0.78‡	—	Peg	0.57†	—	Peg	0.50†	—
Grip	0.41†	0.42†	Grip	0.40*	0.29	Grip	– 0.18	– 0.09

Note. This table shows levels of correlation (r) among right and left hand differences in Finger Tapping speed (Tap), Purdue Pegboard performance (Peg) and Grip Strength (Grip).
* = p < 0.03; † = p < 0.005; ‡ = p < 0.0001.

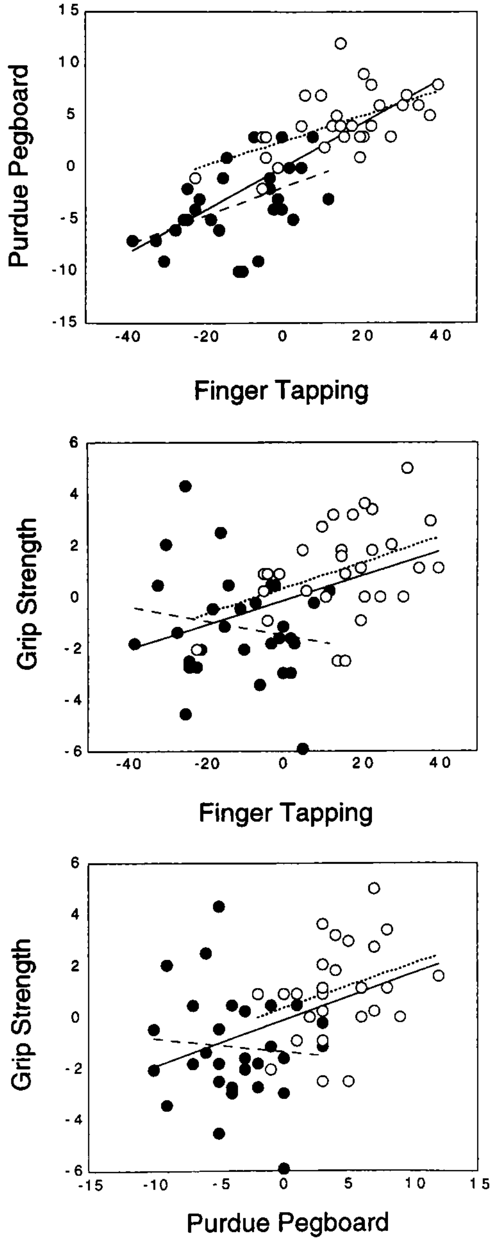

Fig. 1 – *Correlations between hand-differences (right hand – left hand) in Finger Tapping, Purdue Pegboard and Grip Strength in 30 left-handed (●) and 30 right-handed (○) subjects. Each scatterplot shows regression lines for all subjects (solid line), as well as separate regression lines for left-handed (dashed line) and right-handed (dotted line) subjects. See Table III for correlation coefficients and significance levels.*

performance. Both the table and figure show these correlations for all subjects, as well as for right-handers and left-handers analyzed separately. These data illustrate three main findings. First, the data show highly significant correlations between finger tapping and Purdue pegboard asymmetries scores in all subject classifications. This association between finger tapping and peg moving asymmetry is greater than between either of these asymmetries and asymmetry of grip strength. Second, the data show that grip strength asymmetry is positively related to finger tapping asymmetry in right-handers. Third, the data show that grip strength asymmetry is unrelated to finger tapping or peg moving asymmetry in left-handers.

Discussion

Porac and Coren (1981) reviewed correlations between hand preference and relative manual proficiency of the size recorded in the top row of Table I – i.e. correlations around 0.60 – and concluded that preference is at best only marginally related to proficiency. The variance in hand preference accounted for by the correlations in the present study ranges from $(0.6)^2$ = 36 to $(0.7)^2$ = 49%. These authors assumed, however, that hand preference is relatively constant across different tasks. In contrast, an individual's preference for performing different types of manual tasks may vary according to the type of task (Healey et al., 1986; Steenhuis and Bryden, 1989; Peters and Pang, 1992). In our analysis, we questioned the assumption that hand preference is unidimensional. Using a multiple regression model that included hand-differences in three tasks, we were able to account for almost two thirds of the variance in hand preference inventory scores. This is a substantial proportion of the variance in hand preference to be accounted for by asymmetries in the performance of only three tasks. Furthermore, this multiple regression model used asymmetrical task performance to correctly classified dichotomized hand preference in nearly 90% of our subjects. The results of this analysis are inconsistent with the view of Porac and Coren (1981) that preference and proficiency may be orthogonal dimensions of handedness. Instead, our results suggest that preference is strongly related to hand asymmetries in task performance. However, hand asymmetries in finger tapping, peg moving, and grip strength tasks *each* contributed *independently* to predicting preference inventory scores, suggesting that hand preference may be related to asymmetries in multiple neural substrates. These results are consistent with a modification of the hypothesis of Annett (1985), namely that asymmetries in multiple dimensions of manual proficiency may contribute to the development of hand preference (Bishop, 1989). Performance of simple tasks such as finger tapping and peg-placing improves during childhood (Annett, 1970a; Peters and Durding, 1978; Curt, Maccario and Dellatolas, 1992; Carlier, Dumont, Beau et al., 1993) and with prolonged practice (Annett, Hudson and Turner, 1974; Peters, 1981), but the relative performance asymmetry between the two hands remains unchanged, consistent with this hypothesis.

We found that asymmetries of finger tapping and peg moving were highly correlated. These results appear to be inconsistent with Peters (1995) interpretation of the relationship between preference and skill. Peters (1995) hypothesized that preference induces asymmetry in skill as a result of increased use of the preferred hand. Peters (1995) suggested that the experience relevant to the development of skill asymmetry is task-dependent, and therefore predicted a poor correlation between asymmetries in finger tapping and peg moving. In contrast to Peters' prediction, we found that hand asymmetries in finger tapping and peg-placing were highly correlated. Although this finding may suggest that hand preference results from, rather than determines, skill asymmetry, it remains possible that experience is shared across seemingly independent tasks (e.g. finger tapping and peg moving).

There is no a priori reason to expect that hand asymmetries in finger tapping would be related to hand asymmetries in pegboard dexterity, and these two types of manual tasks have been identified through factor analysis of individual differences as independent dimensions of manual proficiency (Fleishman and Hempel, 1954). Whereas a high correlation between hand asymmetries in finger tapping and pegboard performance would not be anticipated, the high correlation we observed suggests that both tasks may depend in part on a common neural substrate. Finger tapping of one key and peg moving may depend upon independent finger movements and precision of finger movement, respectively. Since the corticospinal tract is a critical substrate for independent finger movement (Lawrence and Kuypers, 1968) and for precision grip (Muir and Lemon, 1983), we speculate that asymmetries in finger tapping and pegboard dexterity are related, at least in part, to asymmetry in the corticospinal system. Support for this postulate comes from the observation that in these same subjects, Triggs et al. (1997) found a high correlation between hand asymmetries in both finger tapping and peg moving tasks with hand asymmetries in the threshold for corticospinal activation with transcranial magnetic stimulation.

Although lateralized asymmetries in finger tapping, pegboard dexterity and grip strength *each* correlated significantly with preference inventory scores, grip strength, in contrast to finger tapping and peg-placing tasks, does not require independent or precise control of the fingers. Thus, the corticospinal system is probably not an important substrate for synergistic flexion of the fingers in a power grip. For example, Lawrence and Kuypers (1968) reported that monkeys lost the ability to make independent finger movements after pyramidotomy, but could still flex the digits together strongly in a power grip. Furthermore, large cortical motoneurones may be active during application of low levels of finely controlled force (e.g. during a precision grip), but may become paradoxically inactive during a power grip (Muir and Lemon, 1983) or at high force levels (Fetz and Cheney, 1987). We speculate that hand asymmetries in grip strength were less strongly correlated with hand asymmetries in either finger tapping speed or finger precision because hand asymmetries in grip strength are independent of asymmetry in the corticospinal system.

Annett (1985) has proposed that the normally distributed continuous differences in the strength and skill of the right and left hands are the result of numerous small accidental influences on the development of the two sides of the body (e.g. larger muscles, more efficient neuromuscular coordination). Annett has hypothesized that superimposed on this distribution of manual differences is an underlying genetic influence producing a systematic bias towards increased strength and skill on the right side of the body (the Right Shift). In contrast, Annett has hypothesized that there exists no such systematic bias favoring the development of strength and skill on the left side. The present results appear consistent with Annett's hypotheses. We have suggested that finger tapping and peg moving asymmetries are strongly associated because they depend in part on corticospinal asymmetry as a common neural substrate. However, we found that grip strength asymmetry was still significantly associated with finger tapping asymmetry in right-handers, but was unrelated to finger tapping asymmetry in left-handers. To the extent that asymmetries of strength and finger tapping reflect functional asymmetries in distinct neural substrates (Lawrence and Kuypers, 1968), the present findings provide support for the existence of an underlying bias favoring the development of the right hand in right-handers and the absence of such a bias favoring the left hand in left-handers.

The idea that performance asymmetry may influence the development of hand preference does not reduce the possibility that hand preference is multifactorial in origin. Our finding that behavioral asymmetries strongly correlate with preference does not preclude other factors from being important in the development of hand preference. For example, Liederman (1983) suggested that "[handedness in the infant] is due to the conjoint influence of many factors that themselves can operate relatively independently, rather than a single mechanism that reveals itself over time." We postulate that relatively lower-order structures may provide the substrates of asymmetries in simple manual abilities (Triggs, Calvanio, Macdonell et al., 1994). In contrast, mechanisms residing in higher-order structures undoubtedly contribute to the development of asymmetries in more complicated tasks or skills: activities which entail the synthesis of elementary manual abilities through practice and learning (Schmidt, 1988). Activity in such higher-order substrates may be particularly likely during the acquisition of new skills (Pascual-Leone, Grafman and Hallett, 1994).

References

ANNETT, M. The growth of manual preference and speed. *British Journal of Psychology, 61:* 545-558, 1970a.

ANNETT, M. A classification of hand preference by association analysis. *British Journal of Psychology, 61:* 303-321, 1970b.

ANNETT, M. The distribution of manual asymmetry. *British Journal of Psychology, 63:* 343-358, 1972.

ANNETT, M. A coordination of hand preference and skill replicated. *British Journal of Psychology, 67:* 587-592, 1976.

ANNETT, M. *Left, Right, Hand and Brain: The Right Shift Theory*. London: Lawrence Erlbaum Associates, 1985

ANNETT, M. Five tests of hand skill. *Cortex, 28:* 583-600, 1992.

ANNETT, M., HUDSON, P.T., and TURNER, A. The reliability of differences between the hands in motor skill. *Neuropsychologia, 12:* 527-531, 1974.

BARNSLEY, R.H., and RABINOVITCH, M.S. Handedness: Proficiency versus stated preference. *Perceptual and Motor Skills, 30:* 343-362, 1970.

BISHOP, D.V.M. Does hand proficiency determine hand preference? *British Journal of Psychology, 80:* 191-199, 1989.

BOROD, J.C., CARON, H.S., and KOFF, E. Left-handers and right-handers compared on performance and preference measures of lateral dominance. *British Journal of Psychology, 75:* 177-186, 1984.

BRIGGS, G.G., and NEBES, R.D. Patterns of hand preference in a student population. *Cortex, 11:* 230-238, 1975.

BRYDEN, M.P., ARDILA, A., and ARDILA, O. Handedness in native Amazonians. *Neuropsychologia, 31:* 301-308, 1993.
CARLIER, M., DUMONT, A.M., BEAU, J., and MICHEL, F. Hand performance of French children on a finger-tapping test in relation to handedness, sex, and age. *Perceptual and Motor Skills, 76:* 931-940, 1993.
CURT, F., MACCARIO, J., and DELLATOLAS, G. Distributions of hand preference and hand skill asymmetry in preschool children: Theoretical implications. *Neuropsychologia, 30:* 27-34, 1992.
FETZ, E.E., and CHENEY, P.D. Functional relations between primate motor cortex cells and muscles: Fixed and flexible. In G. Bock, M. O'Conner and J. Marsh (Ed.), *Motor Areas of the Cerebral Cortex. Ciba Foundation Symposium, vol. 132*. Chichester, Sussex, UK: John Wiley and Sons, 1987, pp. 98-117.
FLEISHMAN, E.A., and HEMPEL, W.E. A factor analysis of dexterity tests. *Personnel Psychology, 7:* 15-32, 1954.
FLOWERS, K. Handedness and controlled movement. *British Journal of Psychology, 66:* 39-52, 1975.
HARRISON, D.W., and PAULY, R.S. Manual dexterity, strength, fatigue, and perseveration: An initial test of asymmetry in cerebral activation. *Perceptual and Motor Skills, 70:* 739-744, 1990.
HEALEY, J.M., LIEDERMAN, J., and GESCHWIND, N. Handedness is not a unidimensional trait. *Cortex, 22:* 33-53, 1986.
JOHNSTONE, J., GALIN, D., and HERRON, J. Choice of handedness measures in studies of hemispheric specialization. *International Journal of Neuroscience, 9:* 71-80, 1979.
KIMURA, D., and DAVIDSON, W. Right arm superiority for tapping with distal and proximal joints. *Journal of Human Movement Studies, 1:* 199-202, 1975.
LAWRENCE, D.G., and KUYPERS, H.G. The functional organization of the motor system in the monkey. I. The effects of bilateral pyramidal lesions. *Brain, 91:* 1-14, 1968.
LIEDERMAN, J. Mechanisms underlying instability in the development of hand preference. In G. Young, S.J. Segalowitz, C.M. Corter and S.E. Trehub (Ed.), *Manual Specialization and the Developing Brain*. New York: Academic Press, 89, 1983.
MCMANUS, I.C., KEMP, R.I., and GRANT, J. Differences between fingers and hands in tapping ability: dissociation between speed and regularity. *Cortex, 22:* 461-473, 1986.
MUIR, R.B., and LEMON, R.N. Corticospinal neurons with a special role in precision grip. *Brain Research, 261:* 312-316, 1983.
OLDFIELD, R.C. The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9:* 97-113, 1971.
PASCUAL-LEONE, A., GRAFMAN, J., and HALLETT, M. Modulation of cortical motor output maps during development of implicit and explicit knowledge. *Science, 263:* 1287-1289, 1994.
PETERS, M. Handedness: effect of prolonged practice on between hand performance differences. *Neuropsychologia, 19:* 587-590, 1981.
PETERS, M. Handedness and its relation to other indices of cerebral lateralization. In R.J. Davidson and K. Hugdahl (Ed.), *Brain Asymmetry*. Cambridge: MIT Press, 183-214, 1995.
PETERS, M., and DURDING, B.M. Handedness measured by finger tapping: A continuous variable. *Canadian Journal of Psychology, 32:* 257-261, 1978.
PETERS, M., and DURDING, B.M. Left-handers and right-handers compared on a motor task. *Journal of Motor Behavior, 11:* 103-111, 1979.
PETERS, M., and PANG, J. Do "right-armed" lefthanders have different lateralization of motor control for the proximal and distal musculature? *Cortex, 28:* 391-399, 1992.
PORAC, C., and COREN, S. *Lateral Preferences and Human Behavior*. New York: Springer-Verlag, 1981, pp. 1-11.
PROVINS, K.A., and CUNLIFFE, P. The reliability of some motor performance tests of handedness. *Neuropsychologia, 10:* 199-206, 1972.
PROVINS, K.A., and MAGLIARO, J. The measurement of handedness by preference and performance tests. *Brain and Cognition, 22:* 171-181, 1993.
SCHMIDT, R.A. *Motor Control and Learning*. Champaign, Illinois: Human Kinetics Publishers. 1988
SHIMOYAMA, I., NINCHOJI, T., and UEMURA, K. The finger-tapping test. A quantitative analysis. *Archives of Neurology, 47:* 681-684, 1990.
STEENHUIS, R.E., and BRYDEN, M.P. Different dimensions of hand preference that relate to skilled and unskilled activities. *Cortex, 25:* 289-304, 1989.
STEINMETZ, H., VOLKMANN, J., JANCKE, L., and FREUND, H.J. Anatomical left-right asymmetry of language-related temporal cortex is different in left- and right-handers. *Annals of Neurology, 29:* 315-319, 1991.
TIFFIN, J. *Purdue Pegboard Examiner Manual*. Chicago: Science Research Associates, Inc., 1968, pp. 1-15.
TODOR, J.I., and DOANE, T. Handedness classification: Preference versus proficiency. *Perceptual and Motor Skills, 45:* 1041-1042, 1977.
TRIGGS, W.J., CALVANIO, R., and LEVINE, M. Transcranial magnetic stimulation reveals a hemispheric

asymmetry correlate of intermanual differences in motor performance. *Neuropsychologia, 35:* 1355-1363, 1997.
TRIGGS, W.J., CALVANIO, R., MACDONELL, R.A., CROS, D., and CHIAPPA, K.H. Physiological motor asymmetry in human handedness: Evidence from transcranial magnetic stimulation. *Brain Research, 636:* 270-276, 1994.
WOO, T.L., and PEARSON, K. Dextrality and sinistrality of hand and eye. *Biometrika, 19:* 165-199, 1927.

William J. Triggs, MD, Department of Neurology, Box 100236 UFHSC, Gainesville, FL 32610-0236, USA.
E-mail: triggswj@medmac.ufl.edu

(*Received 22 October 1999; accepted 24 March 2000*)