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COMPUTERIZED MEASURES OF FINGER TAPPING: EFFECTS OF HAND DOMINANCE, AGE, AND SEX[1, 2]

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Summary.—Computerized measures of digit tapping rate were obtained over 3 successive, 10-sec. periods in the right and left index fingers, from a community sample of 1,519 participants (ages 18 to 65 years; 607 men, 912 women). Differences between the dominant and non-dominant hands were found for tapping rate, movement initiation, and button down times, and the decline in tapping rate over the successive, 10-sec. periods. Declines were found in tapping rate in older participants in association with increased intertap variability. Men had higher tapping rates than women in all age ranges. The computerized finger tapping test is an efficient and precise measure of tapping speed and kinetics of potential utility in research and clinical studies of motor performance.

Finger tapping is a widely used test of motor function (Ashendorf, Vanderslice-Barr, & McCaffrey, 2009). The Finger Tapping Test (also called the Finger Oscillation Test) was included as part of the original Halstead Battery (1947), with typical participants showing tapping rates of 4–6 taps/sec. It has been related to cerebral lesion lateralization (Reitan & Wolfson, 1994; Prigatano & Wong, 1997) and severity of traumatic brain injury (Murelius & Haglund, 1991; Dikmen, Machamer, Winn, & Temkin, 1995;

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Prigatano & Borgaro, 2003). Tapping rate has also been used to predict functional outcome following stroke (de Groot-Driessen & van Heugten, 2006), Parkinson's disease (Crossley & Hiscock, 1992; Haaxma, Bloem, Overeem, Borm, & Horstink, 2010; Jiménez-Jiménez, Rubio, Alonso-Navarro, Calleja, Pilo-de-la-Fuente, Plaza-Nieto, *et al.*, 2010; Lee, Lyoo, Lee, Sim, Cho, & Choi, 2010), Huntington's disease (Hinton, Paulsen, Hoffmann, Reynolds, Zimbelman, & Rao, 2007), developmental disorders (Zelaznik & Goffman, 2010), and exposure to environmental toxins (Foo, Lwin, Chia, & Jeyaratnam, 1994).

Classical studies of finger tapping typically tallied the number of taps over 10-sec. intervals from the dominant and non-dominant index fingers using a mechanical counter, timed by the examiner with a stopwatch (Reitan & Wolfson, 1985). More recently, computerized finger-tapping tests involve special tapping devices (Western Psychological Services, 1998), or tapping with a standard mouse and/or keyboard directly connected to a computer (Tanner & Bowles, 1995; Christianson & Leathem, 2004; Gualtieri & Johnson, 2006). In addition to examining the mean tapping rate of each hand, tapping tests have also measured the shortest intertap interval (Turgeon, Wing, & Taylor, 2011), intertap variability (Schmidt, Oliveira, Krahe, & Filgueiras, 2000), hand asymmetry (Schmidt, *et al.*, 2000), tap initiation time (Cousins, Corrow, Finn, & Salamone, 1998), tap downtime (Todor & Smiley-Oyen, 1987), and the occurrence of abnormal finger movements (Prigatano & Borgaro, 2003). In addition, Todor and Smiley-Oyen (1987) defined "Failed Key Openings and Closures" in a study that measured the force of tapping movements. They noted instances where either the up or down movement was not completed so that the tap did not register on their computer-connected telegraph key. Todor and Smiley-Oyen (1987) reported that at least one tap failure occurred in 77.4% of all trials. Given the different methods for assessing finger tapping, including manual and computerized tasks, and how specialized equipment can affect the measurements in subtle ways, it is necessary to assess their validity and reliability. This includes evaluating how additional measures, made possible by computer-based quantification, might help explain differences in motor performance, assist in the differential diagnosis of neurological disorders, and improve symptom validity assessment of tapping rate performance.

The results of computerized finger tapping tests have also been compared to the results of traditional Halstead-Reitan tapping measures using a tapping board (Tanner & Bowles, 1995; Christianson & Leathem, 2004). Tanner and Bowles (1995) utilized a computer mouse with a 2 mm key depression height and tested participants over a continuous 2-min. period. They found high correlations between the average tapping rates of the first and last 40 sec. and the results of the traditional Reitan finger-tapping test, with tapping rates 3% faster overall with the mouse than the Reitan tapping board. Similarly, Christianson and Leathem (2004) used a 10-sec. tapping interval and found high correlations with Halstead-Reitan measures for the dominant and non-dominant hands, and similar overall mean tapping rates on the two tests.

Tapping rates generally decline over the tapping period, particularly when its duration exceeds 10 sec. For example, in his initial studies of finger tapping using a telegraph key, Wells (1908) noted that tapping rate declined by about 16% over 30-sec. intervals, with greater fatigue found in the non-dominant than in the dominant hand. Peters (1980), using a 13 mm tapping apparatus and 10-sec. trials, found increased intertap interval (ITI) durations for the final taps within each interval. With their 2-min. computerized tapping test, Tanner and Bowles (1995) detected slowing in both hands when they compared the first and last 40 sec. of their tapping period. They also observed that the dominant hand showed less deceleration in tapping rate than the non-dominant hand. Changes in tapping rate over time, possibly due to fatigue or other factors, may have diagnostic utility (e.g. Ling, Massey, Lees, Brown, & Day, 2012) and normative patterns of slowing could also be utilized for malingering detection.

Hand dominance is another important factor affecting tapping rate. Tapping rate is approximately 10% faster in the dominant hand than non-dominant hand (Reitan & Wolfson, 1985; Jarvis & Barth, 1994; Tanner & Bowles, 1995; Ashendorf, *et al.*, 2009). Differences between hands have also been observed in tap rate regularity (greater in the dominant hand), tapping downtime (reduced in the dominant hand), and applied force (smaller variance in applied up and down force in the dominant hand; Todor & Smiley-Oyen, 1987). Hervé, Mazoyer, Crivello, Perchey, and Tzourio-Mazoyer (2005) suggested that these differences reflected left-hemisphere dominance for speeded repetitive motor movements, with more asymmetric right and left hemisphere contributions seen in right-hand dominant individuals. This may also account for the finding that while tapping rates are similar for left and right-handers (Ruff & Parker, 1993), intermanual differences tend to be smaller for left-handers (Schmidt, *et al.*, 2000; Hervé, *et al.*, 2005).

Age-related slowing of tapping has been found in many studies (Shimoyama, Ninchoji, & Uemura, 1990; Elias, Robbins, Walter, & Schultz, 1993; Ashendorf, *et al.*, 2009; Aoki & Fukuoka, 2010; Bartzokis, Lu, Tingus, Mendez, Ricahrd, Peters, *et al.*, 2010; Godefroy, Roussel, Despretz, Quaglino, & Boucart, 2010), but the nature of age-related effects remains poorly understood. For example, age-related slowing might reflect an increased number of occasional, slowed, or incomplete taps. There is some evidence that ageing is associated with slowed movement initiation time, the time between button release and the next button depression (Cousins, *et al*., 1998). In addition, some investigators have found different age-related changes in the dominant and non-dominant hands (Ashendorf, *et al*., 2009). Finally, the population distribution of slowing is also of interest, as age-related differences could reflect age-related slowing in a subset of older adults, e.g., those with early symptoms of Parkinson's disease (Camicioli, Wieler, de Frias, & Martin, 2008; Haaxma, *et al*., 2010).

Sex differences are consistently found in tapping tasks with men tapping faster than women (Yeudall, Reddon, Gill, & Stefanyk, 1987; Elias, *et al*., 1993; Schmidt, *et al*., 2000; Dorfberger, Adi-Japha, & Karni, 2009; Roivainen, 2011). There is also some evidence that men have more regular tapping rates (lower intertap variability; Schmidt, *et al*., 2000). In addition, sex differences could reflect different age effects. Ruff and Parker (1993) reported a greater age-related decrease in tapping rate in women than men. Again, the response patterns underlying sex differences remain poorly understood. For example, it is unknown whether men show faster movement initiation, reduced down time, differences in tapping rate deceleration, or simply less frequent failures to complete taps in tapping performance.

In the current experiment, age and sex-related differences in tapping rate were measured, as well as tapping kinetics, in a community sample of 1,519 adults ranging in age from 18 to 65 years. A computerized tapping test was used to assess slowing over time, hand dominance, age, and sex on tapping rate (represented by the intertap interval, ITI), button closure time (movement initiation time), button release time (down time), variability of ITI, and failures to complete a tap. Interactions between these factors were also examined. Effects of hand dominance, age, and sex were expected on tapping rate similar to those previously reported in the literature:

Hypothesis 1. Participants would demonstrate faster tapping rates with their dominant hands along with reduced slowing and variability.

Hypothesis 2. Hand dominance would have equal effects on movement initiation time and down time.

Hypothesis 3. Older participants would have slower overall tapping rates and greater deceleration in tapping rates across the test period.

Hypothesis 4. Men would have faster tapping rates than women (including less time spent on movement initiation and down time) and reduced tapping rate variability, including fewer occurrences of failed tap completions.

Method

Participants

Community volunteers (N = 1,634) were recruited from a study in Rotorua, New Zealand investigating the health effects of exposure to naturally occurring hydrogen sulfide. Data were excluded from participants who were ambidextrous (n = 37), due to the small number of participants and decision to compare dominant vs non-dominant hands. Participants were also excluded if they did not complete the full 30-sec. tapping period with each hand (n = 14), reported disability involving either index finger (n = 63), or experienced technical errors in data collection (n = 1). Of the remaining 1,519 participants, 40.0% were men, 10.7% left-handed by self-report (based on writing hand), and all were between the ages of 18 and 65 years (men M age = 46.3, women M age = 45.4). Table 1 reports the number of participants in each age group by sex and handedness. Participants had an average U.S. equivalent of 12.6 yr. of education including 76.7% with a secondary school qualification, 35.2% of who had a qualification beyond secondary school such as a bachelor's degree (12.1%), master's degree (2.9%), doctorate (1.6%), or other trade, technical, or professional qualification (31.7%). Ethnically, the sample identified primarily as being of European background (80.0%) and New Zealand Maori (15.6%). The remaining 4.4% represented a variety of ethnicities, none representing more than 1% of the sample. Most of the sample (78.7%) was employed. All participants signed written consent forms approved by the IRBs in Rotorua, the VANCHCS in Martinez, and University of California, Davis.

Apparatus and Stimuli

Finger tapping was performed with the left and right index fingers at the beginning of a 30-min. cognitive assessment battery that included other computerized tests from the California Cognitive Assessment Battery (CCAB; Woods, Kishiyama, Yund, Herron, Edwards, Poliva, *et al.*,

TABLE 1
Number of Participants Classified by Age Group, Handedness, and Sex

	Left-handed		Right-handed	
Age Group	Men	Women	Men	Women
18–24	3	8	27	52
25–31	4	7	39	69
32–38	11	11	75	110
39–45	14	13	93	165
46–52	18	19	114	170
53–59	16	17	114	142
60–65	8	14	71	115

2011; Woods, Herron *et al.*, 2011). Testing was performed in a quiet testing room, using a standard PC controlled by Presentation software (Versions 13 and 14, NeuroBehavioral Systems, Albany, CA). Participants were instructed to keep the palm of their hand on the table top while depressing a button of a high-precision gaming mouse (Razer, Sidewinder model, Carlsbad, CA) with the index finger over a travel distance of 2.0 mm. Participants practiced for 10 sec. with each digit before testing began. Each trial began with a visual cue. Participants first tapped as rapidly as possible with the right index finger for 30 sec. The task was then repeated using the left index finger.

Scoring and Data Preparation

The timing of each button press and release was recorded by the computer with high temporal precision using continuous sampling of the Windows high-precision programmable clock (100 kHz) that was also sampled to provide additional measures of temporal uncertainty for each response event (typical range = 0.1–0.3 msec.). Figure 1 depicts the information recorded by the computer during a representative button press. The times of button depression and release were measured on each tap.[3] Button down time (DT) was the duration of button depression, i.e., the interval between button close and button release. Movement initiation time (MIT) was the interval from button release to the next button depression. Thus, the total intertap interval (ITI) on each press was the sum of the MIT and DT. As noted in Fig. 1, participants differed in the percentage of the ITI due to the initiation or down time. Median ITI values across each test period were used as an index of motor speed where shorter ITIs represent faster tapping rates.

In order to analyze changes in tapping rate over time, the 30-sec. testing period was divided into three intervals starting with the first tap (Reitan & Wolfson, 1993). Only full taps were included (i.e., with both depression and release). Means, medians, and within-tests, standard deviations were obtained for ITI, fraction of time spent on movement initiation (MIT/ITI), and the fastest and slowest consecutive 10 taps for the left and right index fingers in each of the three tapping intervals. The standard deviation of the ITI was used to assess variability.

As an illustration of the tapping metrics used in this study, Fig. 2 shows ITIs, down times, and movement initiation times over the 30-sec. period from a representative single participant. While the ITIs in this

[3]When the computer log files were reviewed for each participant, occasional ITIs that were less than 40 msec. were found, comprising 0.1% of all measured taps. 96.7% of tapping runs (30 sec.) had no such taps, 1.8% had only 1, and 0.8% had 2 to 4 such taps. As these tap durations were significantly below the fastest sustained taps observed in these participants (~130 msec.), all taps faster than 40 msec. were removed from the data and the time accounted for by these taps was allotted to the subsequent tap.

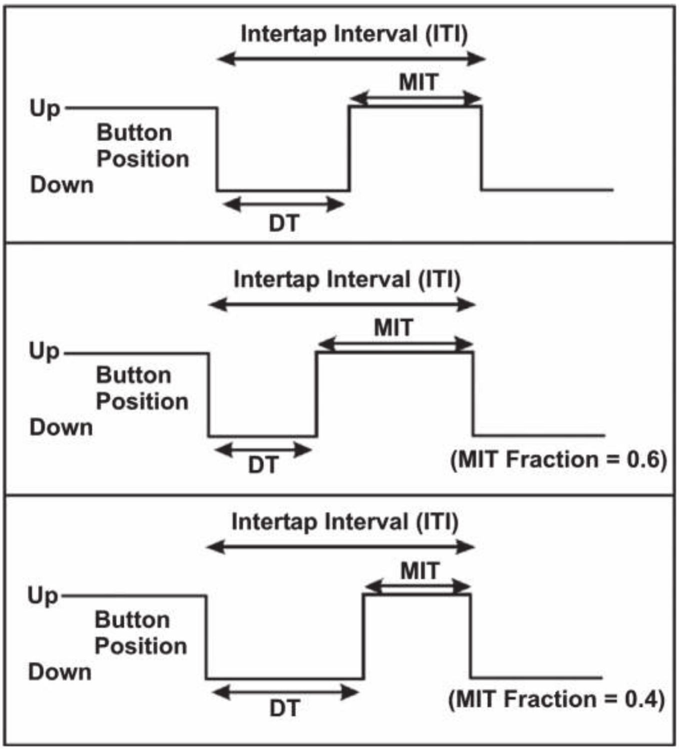

FIG. 1. Tapping measures assessed by the computer. Measurements include down time (DT), the time that the mouse button was depressed, and movement initiation time (MIT), the interval between button release and the next button press. The sum of DT and MIT defined the intertap interval (ITI) for each button press. The middle panel shows a tap with a longer MIT than DT (MIT Fraction = 0.6), whereas the bottom panel demonstrates a longer DT than MIT (MIT Fraction = 0.4).

participant averaged 165 msec. (tapping rate = 6.1 taps/sec.), three ITIs ("tap failures") exceeded 280 msec. The examination of the down and movement initiation times of these events showed that two of these "tap failures" reflected abnormally long down times (i.e., the button was not completely released) and one was due to an abnormally long movement initiation time (i.e., the button was not depressed).

Following Todor and Smiley-Oyen (1987), the authors defined tap failures as occurrences when the ITI was 67% longer than the best consecutive 10-tap ITI and the fraction of time spent on movement initiation was at least 0.1 less (failure to open) or greater (failure to close) than the mean fraction for each participant, as shown in Fig. 3.

Tap failures occurred on 71% of all 30-sec. trials and accounted for 4.1% of all taps, with failures to open and close occurring with a similar

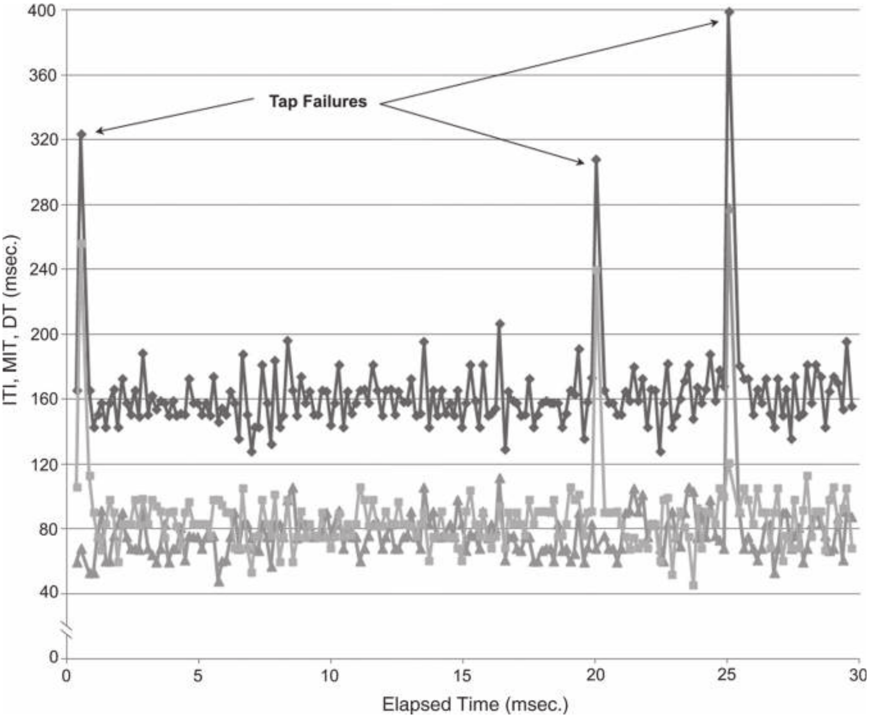

FIG. 2. Example profile for a single participant tapping over the 30-sec. time period. Dominant hand index finger performance is illustrated with the intertap interval (ITI, diamonds), movement initiation time (MIT, triangles), and down time (DT, squares). Three tap failures are illustrated. Approximately 65% of participants demonstrated at least one tap failure (open or closed) per interval, and about 10% of participants demonstrated more than five failures per interval.

incidence (3.28 and 3.02 per 30 sec., respectively). More than 85% of participants had four or fewer tap failures per 10-sec. interval, and only 0.6% of participants produced 12 or more. For participants with 12 or fewer total number of tap failures per interval (99.4% of participants), there was no statistically significant correlation between number of tap failures and ITI (Pearson $r = -.03$). The distribution of combined total tap failures per participant fit a geometric distribution: the Kolmogorov-Smirnov test (Conover, 1971) does not reject a null hypothesis that the total tap failures per participant is modelled by its best-fit geometric distribution ($p = .98$). This distribution on the number of tap failures suggests that tap failures are a separate Poisson-like noise process that occurs randomly within the mainly rhythmic tapping of participants (Fig. 2; Todor & Smiley-Oyen, 1987). The geometric distribution of the tap failure counts also implies

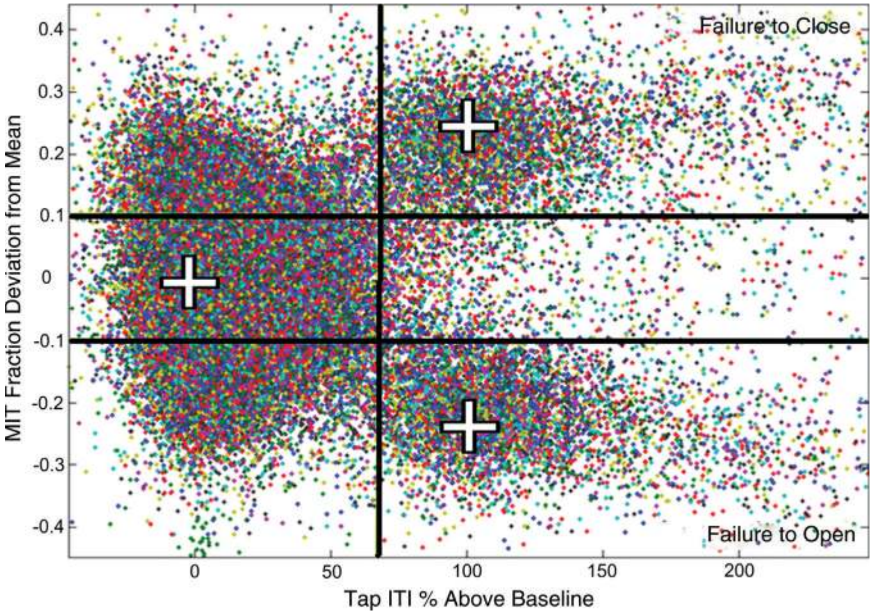

FIG. 3. A scatter plot showing the intertap intervals (ITIs) relative to the best consecutive 10 ITI from each participant trial on the abscissa and movement initiation time (MIT) fraction (percent of the ITI with the button raised) on the ordinate. Tap failures were defined as ITIs that were at least 67% above the best-10 ITI *and* with either MIT fractions 0.1 below the participant's mean MIT fraction (failure to open) or MIT fractions 0.1 above the participant's mean MIT fraction (failure to close). Tap failures occurred on 4.1% of all taps. Crosses indicate prototypical regular taps (left) and failures to open (right bottom) and close (right top). The prototypical tap failure contributes to a tap that is roughly 100% longer than a good tap with an MIT to down time ratio that approaches either 3:1 or 1:3 (i.e., 0.25 above or below the mean MIT fraction).

that one cannot analyze them using Gaussian statistics (see below). Therefore, the authors aimed to eliminate the effects of tap failures from most variables and analyze them separately. Thus, medians were used to quantify ITI, movement initiation time, and down time to prevent the tap failures from inflating ITI variance and altering ITI or its components. Using median ITI values is preferable also because they had a tighter distribution (7% smaller standard deviation) across participants than did mean ITI values (statistically significantly tighter using a Mood two-sided scale test: $Z = 7.3$, $p < .0001$; Conover, 1971) and better captured a participant's consistent performance, making the values more comparable to standardized tapping tests that include repeated trials.

Statistical Analysis

Participants were classified into one of seven different 7-year-wide age ranges (Table 1). Most results were first analyzed using a multifactor mixed analysis of variance (ANOVA), with Age-group, Sex, and Hand (dominant or non-dominant) as independent variables. Additional analyses were conducted with independent variables classifying participants by handedness (right or left) and tapping speed cohorts (fastest vs slowest 50%). Separate ANOVAs were performed for the following dependent variables: median intertap interval (ITI), ITI standard deviation with failures removed, and median fraction of time spent on movement initiation. ANOVAs were also conducted on the three time intervals (0–10 sec., 10–20 sec., and 20–30 sec.) to analyze tapping rate deceleration as a function of Hand, Age, and Sex. Effect sizes are reported as partial η^2 values. Greenhouse-Geisser corrections of degrees of freedom were uniformly used in computing p values to correct for any nonspherical covariation within factors or interactions. Because the tap failures are count data that fit a geometric distribution, their analysis was conducted using negative binomial regression (Gardner, Mulvey, & Shaw, 1995; Cameron & Trivedi, 1998). Wald χ^2 values were used to assess statistical significance for negative binomial regression analyses. Finally, Pearson correlations were computed on selected pairs of variables. A p value of .001 was set as the criterion of statistical significance to avoid Type I errors due to multiple measures obtained from each hand. SPSS Version 20 (www.ibm.com) was used for all analyses.

Results

Hand Dominance

Figure 4 shows ITIs for the dominant and non-dominant hand over the three 10-sec. intervals. Mean ITIs were 15% shorter in the dominant hand, producing a statistically significant main effect of Hand ($F_{1,1505}$ = 1467.91, $p < .0001$, partial $\eta^2 = 0.49$). ITIs also increased progressively over the three tapping intervals, producing a statistically significant main effect of Interval ($F_{2,3010} = 940.24$, $p < .0001$, partial $\eta^2 = 0.39$). Slowing effects were more than twice as large in the non-dominant as in the dominant hand, producing a significant Hand x Interval interaction ($F_{2,3010}$ = 97.08, $p < .0001$, partial $\eta^2 = 0.06$). ITI variance was 42% higher in the non-dominant hand ($F_{1,1505} = 415.97$, $p < .0001$, partial $\eta^2 = 0.22$). ITI variance also decreased over the three intervals ($F_{2,\,3010} = 75.12$, $p < .0001$, partial $\eta^2 = 0.05$) and was accompanied by a decreased incidence of tap failures [Wald χ^2 (1) = 15.90, $p < .0001$].

Figure 5 shows movement initiation time (MIT) and down time (DT) over the three 10-sec. tapping intervals for the dominant and non-dominant hands. Movement kinetics were influenced by hand dominance and slowing across intervals. Not surprisingly, movement initiation and down time were both statistically significantly correlated with ITI (Pearson $r = .65$, $p < .001$ and Pearson $r = .81$, $p < .0001$, respectively). However, the correlation between

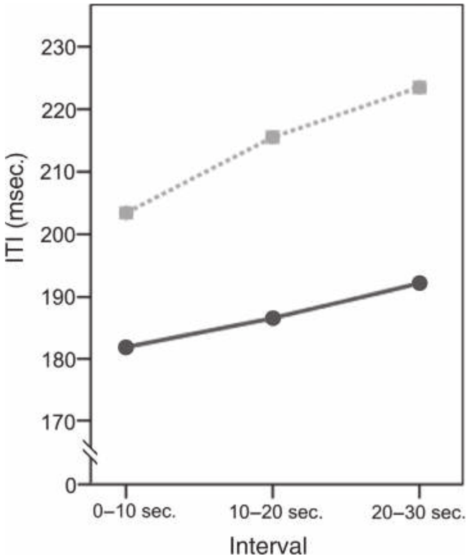

FIG. 4. Mean intertap interval (ITI) for the dominant (circles) and non-dominant (squares) hands over successive measurement periods. Error bars show SEM.

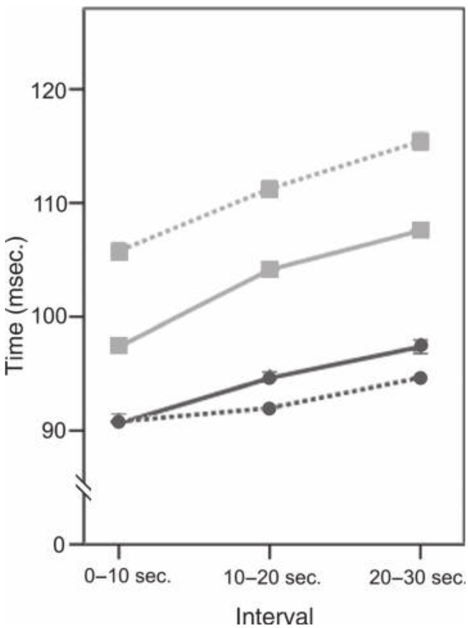

FIG. 5. Movement initiation time (MIT, solid lines) and down time (DT, dotted lines) for the dominant (circles) and non-dominant (squares) hands across the three intervals. Error bars show SEM.

TABLE 2
DIFFERENCE BETWEEN DOMINANT AND NON-DOMINANT HAND TAPPING RATES
BASED ON MEDIAN INTERTAP INTERVALS

		Left-handed		Right-handed	
		% Difference	*n*	% Difference	*n*
Sex	Men	8.7	74	14.9	533
	Women	8.2	89	15.8	823
Age Group	18–24	–0.1	11	18.3	79
	25–31	3.1	11	18.1	108
	32–38	9.2	22	16.8	185
	39–45	12.6	27	16.6	258
	46–52	6.4	37	14.5	284
	53–59	9.5	33	15.1	256
	60–65	11.8	22	12.3	186

Note.—Percentages indicate extent to which the dominant hand was faster.

movement initiation and down time was low (Pearson $r = .08$, $p < .0001$). This indicates that different participants had systematic differences in the relative time spent in button-open and button-closed positions.

Although the fraction of time spent on movement initiation (MIT) was strongly correlated between the dominant and non-dominant hands of participants (Pearson $r = .63$, $p < .0001$), significant hand dominance differences were also observed. The dominant hand had greater MIT than down time (DT) whereas the non-dominant hand had a larger DT than MIT. This resulted in a significant main effect of Hand on MIT fraction ($F_{1,1505} = 124.23$, $p < .0001$, partial $\eta^2 = 0.08$). Decreases in tapping rate were also associated with changes in tapping kinetics: the MIT fraction increased over the three tapping intervals ($F_{2,3010} = 25.87$, $p < .0001$, partial $\eta^2 = 0.02$).

Comparisons of right- and left-handed participants showed no statistically significant main effects of Handedness on ITI, fraction of time spent on movement initiation, ITI standard deviation, or tap failures. There was, however, a Handedness (left or right) x Hand (dominant or non-dominant) interaction for ITI ($F_{1,1491} = 44.89$, $p < .0001$, partial $\eta^2 = 0.03$), movement initiation time fraction ($F_{1,1491} = 19.83$, $p < .0001$, partial $\eta^2 = 0.01$), and ITI standard deviation ($F_{1,1491} = 22.86$, $p < .0001$, partial $\eta^2 = 0.02$). Consistent with previous reports, tapping rates for left-handers were slower than for right-handers and left-handers had more variability in rate when using their dominant hand. Left-handers also had smaller differences than right-handers between the dominant and non-dominant hand in terms of tapping rate, tapping kinetics, and ITI variance. Table 2 lists dominant vs non-dominant hand differences in tapping rate for right- and left-handers, broken down by sex and age group. Although left-handers tended to show somewhat greater differences between their dominant and non-dominant hands compared to right-handers, the Hand x Handedness x Age three-way interaction was not statistically significant ($F_{6,1491} = 2.91$, $p = .008$, partial $\eta^2 = 0.01$].

Age

Figure 6 shows ITI, movement initiation time (MIT), and down time (DT) for participants in the different age groups. ITIs lengthened in participants over 38 yrs of age: tapping was slowed by 14% in participants in the oldest age group sampled (60–65), compared to those less than 45 years of age. This resulted in a significant main effect of age on ITI ($F_{6,1505} = 32.78$, $p < .0001$, partial $\eta^2 = 0.12$). Tap kinetics were also affected by age: the MIT fraction increased with age starting in the 30s ($F_{6,1505} = 4.13$, $p < .0001$, partial $\eta^2 = 0.02$). There was also a significant main effect for age on ITI variance ($F_{6,1505} = 6.03$, $p < .0001$, partial $\eta^2 = 0.02$), with older participants having larger tap variability.

Figure 7 shows the effects of age on movement initiation (MIT) and down time (DT) measures separately for the dominant and non-dominant hand. These measures did not statistically significantly differ for the dominant vs non-dominant hand either in median ITI or in movement kinetics across age. However, there was a small, age-related change in tapping rate over time ($F_{12,3010} = 2.93$, $p < .0001$, partial $\eta^2 = 0.01$): tapping rates for younger participants (in particular the 18- to 24-year-olds) showed greater declines over the three 10-sec. intervals.

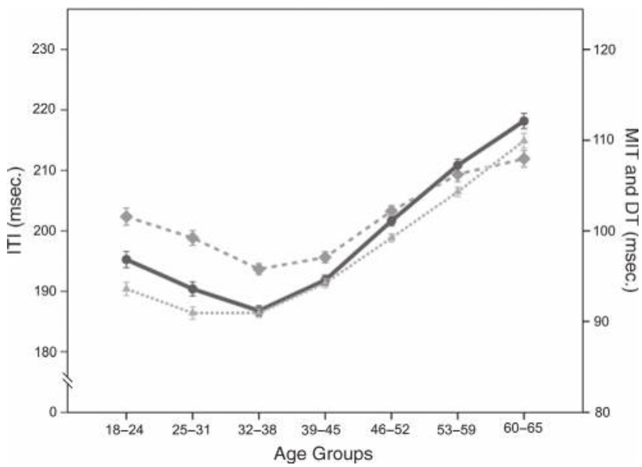

FIG. 6. Plot of mean tap duration (ITI, solid line) and time spent in movement initiation (MIT, dotted line) and down time (DT, dashed line) by age group. Error bars show SEM.

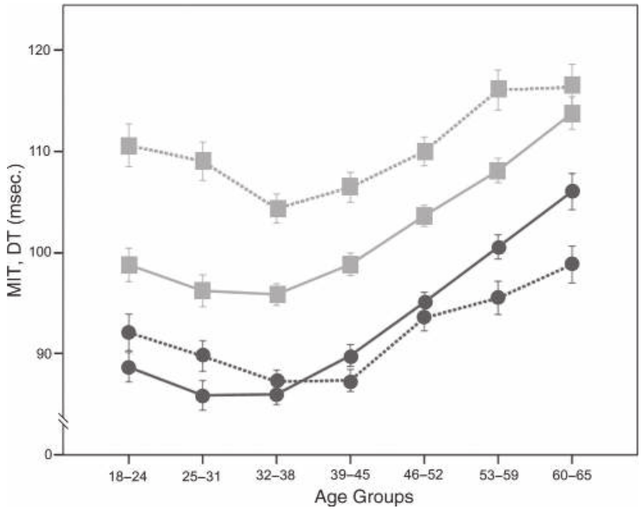

FIG. 7. Movement initiation time (MIT, solid lines) and down time (DT, dotted lines) for the dominant (circles) and non-dominant (squares) hands by age group. Error bars show SEM.

To assess if age effects were associated with increased slowing of a subset of older participants, further analyses were performed on participants in each age cohort with ITIs above and below the group median. Age effects remained statistically significant when analyzed in the fast-cohort group ($F_{6,1491} = 61.12$, $p < .0001$, partial $\eta^2 = 0.20$). However, there was also a statistically significant Age x Speed-cohort interaction ($F_{6,1491} = 4.90$, $p < .0001$, partial $\eta^2 = 0.02$), reflecting the fact that tappers in the slower cohort showed larger age-related changes than tappers in the faster cohort. Slower tappers also showed larger differences between the dominant and non-dominant hands ($F_{1,1491} = 26.99$, $p < .0001$, partial $\eta^2 = 0.02$), smaller movement initiation time fractions ($F_{1,1491} = 19.91$, $p < .0001$, partial $\eta^2 = 0.01$), and increased ITI variance ($F_{1,1491} = 59.08$, $p < .0001$, partial $\eta^2 = 0.04$). However, faster tappers showed more tap failures [Wald $\chi^2 = 190.97$, $p < .0001$].

Sex Differences

There was a statistically significant main effect of Sex as shown in Fig. 8: ITIs were 8% faster in men than women ($F_{1,1505} = 92.43$, $p < .0001$, partial $\eta^2 = 0.06$). The Sex x Hand interaction was not significant ($F_{1,1505} = 2.97$, ns). Men had a higher number of tap failures than women [Wald χ^2 (1) = 131.14, $p < .0001$], but there were no statistically significant differences in overall ITI variance ($F_{1,1505} = 7.27$, ns). Men and women otherwise showed similar tap kinetics, with no significant sex difference in movement initiation time fraction ($F_{1,1505} = 3.14$, ns). Sex also did not significantly influence

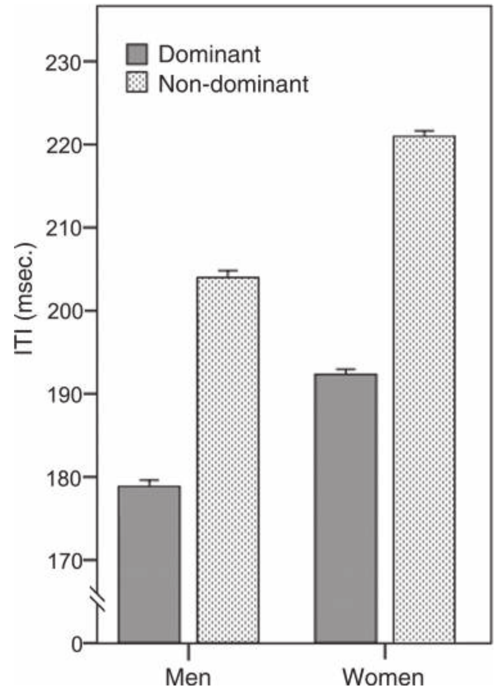

FIG. 8. Intertap interval (ITI) time for men and women. Error bars show SEM.

tapping rate deceleration ($F_{2,3010}$ = 2.63, ns), and did not interact with age ($F_{6,1505}$ = 1.00, ns).

DISCUSSION

Comparisons with Other Finger Tapping Tests

In the current study, we used a novel test of finger tapping from the California Cognitive Assessment Battery (CCAB) with microsecond precision and supplementary measures of tapping performance. Table 3 compares the results of the current study with adult normative data collected by Ruff and Parker (1993) and Heaton, Miller, Taylor, and Grant (2004) using the manually administered Halstead Retain Finger Tapping Test, measures from the Computerized Finger Tapping Test (Christianson & Leathem, 2004), T3 computer-assisted finger tapping task (Tanner & Bowles, 1995), the WPS Electronic Tapping Test (Western Psychological Services, 1998; Christianson & Leathem, 2004), and CNS Vital Signs (Gualtieri & Johnson, 2006). Despite the minor differences in procedures and response devices, all tests show similar results, with mean tapping rates that range from 4.8 to 5.7/sec. and clear hand dominance effects.

TABLE 3

COMPARISON OF CALIFORNIA COGNITIVE ASSESSMENT BATTERY (CCAB) FT TAPS PER 10-SEC. INTERVAL TO OTHER TAPPING TEST DATA

Device and Source of Data	Age Range	Education, yr. (*SD*)	Participants		Dominant Hand		Non-dominant Hand	
			% Men	*n*	*M*	*SD*	*M*	*SD*
Halstead-Reitan, Ruff, & Parker (1993)	16–70	7–22	50	358	50.6	6.3	46	5.9
Halstead-Reitan (1947); Heaton (2004)	46.6 (18.1)	13.6 (2.8)	56.8	1,212	49.2	8.7	44.8	7.8
Computer Finger Tapping Test, Christianson & Leathem (2004)	16–70		50	86	56	7.1	49.6	5.4
T3 computer-assisted finger tapping task, Tanner & Bowles (1995), 1950s version	12–70	16.9 (2.8)	50	40	50.8		45.3	
WPS Electronic Tapping Test, Western Psychological Services (1998); Christianson & Leathem (2004)	16–60†		61.7	298	54	11.2	51.9	12.7
CNS Vital Signs, Gualtieri & Johnson (2006)	15–90		37.4	932	56.5*	11.1*	54.7*	9.8*
CCAB FT (based on 30-sec. average)	18–65	12.6 (3.4)	40	1,519	54.9	9.2	48.1	8.1
CCAB FT (based on 1st 10-sec. average)	18–65	12.6 (3.4)	40	1,519	56.3	9.6	50.4	8.5

†Some information not provided. *Reported data for right and left hand, 91% of sample was right-handed.

While the mean tapping rate of the CCAB tapping test is similar to that of the classic Halstead-Reitan (HR), the CCAB tapping test has several procedural advantages: (1) the CCAB finger tapping test only takes about two minutes to administer and gathers median tap interval values from each finger over 30-sec. periods, whereas typical finger tapping administration requires five consistent 10-sec. trials, which can require up to 10 minutes of testing when rest breaks are included (Camara, Nathan, & Puente, 2000; Strauss, Sherman, & Spreen, 2006); (2) the CCAB utilizes a low-cost computer mouse, precluding the need for a specific tapping board; and (3) the CCAB quantifies a large number of motor kinetic variables including tapping variance, slowing over time, tap failures, and tap kinetics (i.e., movement initiation and down time) in addition to mean and median tapping rate. These variables may have utility in both research and clinical use. For example, differences in tapping variability, tapping rate, and changes in tapping rate over time have been found between individuals with Parkinson's disease, progressive supranuclear palsy, and controls (Ling, *et al.*, 2012).

Hand Dominance

There were large differences between the dominant and the non-dominant hands, consistent with many previous reports (Peters, 1980; Todor & Smiley-Oyen, 1987; Schmidt, *et al.*, 2000; Hervé, *et al.*, 2005; Teixeira, 2008). These differences were due to three factors: (1) participants initiated movements faster in the dominant than non-dominant hand (i.e., movement initiation time was reduced); (2) the dominant hand was faster to execute movements (i.e., down time was reduced); and (3) the dominant hand showed less decrease in rate over the 30-sec. period, possibly indicating less fatigue, slowing by 5.6% vs 9.9% in the non-dominant hand over the three 10-sec. intervals. The greater slowing in the non-dominant hand is consistent with the findings of Tanner and Bowles (1995), who tested participants over a 2-min. period. As suggested by Wells (1908), "the preferred hand has greater immunity to fatigue." Electrophysiological studies show that motor evoked potential (MEP) amplitudes decline following repetitive finger tapping as well as with imaginary hand movements, suggesting that fatigue effects can arise at cortical levels (Kluger, Palmer, Shattuck, & Triggs, 2012).

There were also significant hand differences in tapping kinetics: down time (DT) increased more than movement initiation time (MIT) in the non-dominant vs dominant hand comparisons. Peters (1980) reported a similar result. In a smaller sample, Todor and Smiley-Oyen (1987) also found a statistically significant difference in "dwell" time (DT) between hands, but not in "slack" time (MIT). They noted that the difference between the hands was not simply due to uniform slowing but reflected difficulty with movement termination and applying appropriate amounts of force. The dominant hand executed movements more precisely (i.e., there were fewer tap failures) and with reduced ITI variability, particularly after excluding the tap failures. Peters and Durding (1979) and Todor and Smiley-Oyen (1987) also noted a smaller percentage of failed taps and reduced tap variability in the dominant hand.

Consistent with Schmidt, *et al.* (2000) and Hervé, *et al.* (2005), we found reduced hand asymmetries in left-handed individuals. This is consistent with many observations that left-handed individuals show a more mixed pattern of cerebral dominance (Rasmussen & Milner, 1977; Taylor, Falconer, & Flor-Henry, 2010). It could also be related to the finding that left-handers tend to have a more symmetrical hand size, whereas right-handers have larger dominant hands (Purves, White, & Andrews, 1994). Data regarding degree of handedness/hand dominance, hand size, or hand strength were not obtained as a part of this study, but would be useful in further evaluation of this topic.

Cerebral structural correlates of hand dominance have proven elusive. For example, there are no clear differences in the relative sizes of left- and right-hand motor regions in left- and right-handed participants (Hervé, *et al.*, 2005), nor are consistent asymmetries observed in the volume of the corticospinal tracts (Westerhausen, Huster, Kreuder, Wittling, & Schweiger, 2007) or in pyramidal decussations (Kertesz & Geschwind, 1971). However, using magnetic resonance imaging, right-handed participants showed anatomical, interhemispheric asymmetries in the amount of cortical surface area of the pre- and post-central gyrus (Kang, Herron, & Woods, 2011a) and interhemispheric differences in pericortical tissue measures of fiber tract coherence and myelination (Kang, Herron, & Woods, 2011b), while left handers showed less consistent asymmetries (Foundas, Hong, Leonard, & Heilman, 1998). Electrophysiological studies have also established that MEP thresholds are lower over the dominant hemisphere (Triggs, Calvanio, & Levine, 1997), suggesting more effective connections between the dominant motor cortex and the contralateral hand muscles.

Age Effects

Consistent with previous reports (Shimoyama, *et al.*, 1990; Elias, *et al.*, 1993; Ruff & Parker, 1993; Ashendorf, *et al.*, 2009; Aoki & Fukuoka, 2010; Bartzokis, *et al.*, 2010; Godefroy, *et al.*, 2010; Turgeon, *et al.*, 2011), finger tapping slowed and ITI variance increased with age (de Frias, Dixon, Fisher, & Camicioli, 2007; Camicioli, *et al.*, 2008). As reported by Bartzokis, *et al.* (2010), statistically significant ITI increases begin after the mid-30s with responses slowed by about 14% by age 65 yrs. Age-related changes in tapping speed correlate with changes in the myelination of fiber tracts in the frontal lobe (Bartzokis, *et al.*, 2010). MEP thresholds also increase with age (Rossini, Desiato, & Caramia, 1992). As in previous studies (Cousins, *et al.*, 1998), there were small but statistically significant age-related changes in movement kinetics: movement initiation time increased more than down time.

Surprisingly, older participants did not show greater decelerations in tapping rates over time: younger participants showed greater increases in both ITI and MIT over the 30-sec. tapping period. This could be due to younger individuals' faster tapping rates, causing them to tire more quickly; or, older participants tending to begin with tapping rates closer to their optimum speed. Others have noted paradoxical reductions of hand muscle fatigue with increasing age (Chan, Raja, Strohschein, & Lechelt, 2000). Finally, despite observations that ageing can result in greater deterioration in right hemisphere function in some tasks (Greenwald & Jerger, 2001), there was no interaction of age and hand in finger tapping (Teixeira, 2008). However, one limitation of this study was that the upper age limit was 65 years.

Sex Differences

As in previous studies (Ruff & Parker, 1993; Peters & Campagnaro, 1996; Schmidt, *et al*., 2000; Christianson & Leathem, 2004), there were longer ITIs in women. Unlike previous reports (Nalçaci, Kalaycioğlu, Ciçek, & Genç, 2001), there were no significant interactions between hand dominance and sex. Sex differences in the current study were also independent of other factors that influenced tapping rate, including both age and slowing over time. There are reports in the literature of men having less tapping variability than women (Schmidt, *et al*., 2000) and the reverse (Todor & Smiley-Oyen, 1987). In the current sample, no significant sex differences were found for ITI variance; however, men had more tap failures.

Sex differences in tapping rate appear to be specific for repetitive movements, rather than generalized sex-related slowing of all motor responses. For example, sex-related differences are not found in simple visual reaction time tasks (Der & Deary, 2006; Commodari & Guarnera, 2008). In addition, the Grooved Peg Board Test, a test of fine motor task performance, tends to be superior in women (Ruff & Parker, 1993; Peters & Campagnaro, 1996). Studies of *motor evoked potentials* (MEPs; Tobimatsu, Sun, Fukui, & Kato, 1998) and nerve conduction velocity (Robinson, Rubner, Wahl, Fujimoto, & Stolov, 1993) also fail to show sex differences. Nor are sex differences found in the relative area or thickness of motor cortex (Kang, *et al*., 2011a). However, differences have been found in the structure of the cerebellum (Fan, Tang, Sun, Gong, Chen, Lin, *et al*., 2010), a brain region that is known to play a central role in the generation of rapid alternating movements.

Conclusion

Computerized measures of finger tapping in a large community sample showed significant effects of slowing over a 30-sec. interval and revealed large effects of hand dominance (faster tapping in the dominant hand), sex (faster tapping in men), and age (slower tapping after the mid-30s). Both increasing age and the use of the non-dominant hand increased intertap variability and caused larger increases in down time than in movement initiation time. Computerized tapping tests can accurately assess sources of slowing during finger tapping tests and can reveal aspects of tapping performance that may have potential diagnostic utility.

REFERENCES

Aoki, T., & Fukuoka, Y. (2010) Finger tapping ability in healthy elderly and young adults. *Medicine and Science in Sports and Exercise,* 42(3), 449-455.

Ashendorf, L., Vanderslice-Barr, J. L., & McCaffrey, R. J. (2009) Motor tests and cognition in healthy older adults. *Applied Neuropsychology,* 16(3), 171-176.

Bäckman, L., Nyberg, L., Lindenberger, U., Li, S-C., & Farde, L. (2006) The correlative triad among aging, dopamine, and cognition: current status and future prospects. *Neuroscience and Biobehavioral Reviews,* 30(6), 791-807.

Bartzokis, G., Lu, P. H., Tingus, K., Mendez, M. F., Richard, A., Peters, D. G., Oluwadara, B., Barral, K. A., Finn, J. P., Villablanca, P., Thompson, P. M., & Mintz, J. (2010) Lifespan trajectory of myelin integrity and maximum motor speed. *Neurobiology of Aging,* 31(9), 1554-1562.

Camara, W. J., Nathan, J. S., & Puente, A. E. (2000) Psychological test usage: implications in professional psychology. *Professional Psychology: Research and Practice,* 31(2), 141-154.

Cameron, A. C., & Trivedi, P. K. (1998) *Regression analysis of count data*. Cambridge, UK: Cambridge University Press.

Camicioli, R. M., Wieler, M., de Frias, C. M., & Martin, W. R. W. (2008) Early, untreated Parkinson's disease patients show reaction time variability. *Neuroscience Letters,* 441(1), 77-80.

Chan, K. M., Raja, A. J., Strohschein, F. J., & Lechelt, K. (2000) Age-related changes in muscle fatigue resistance in humans. *The Canadian Journal of Neurological Sciences,* 27(3), 220-228.

Christianson, M. K., & Leathem, J. M. (2004) Development and standardisation of the computerised finger tapping test: comparison with other finger tapping instruments. *New Zealand Journal of Psychology,* 33(2), 44-49.

Commodari, E., & Guarnera, M. (2008) Attention and aging. *Aging: Clinical and Experimental Research,* 20(6), 578-584.

Conover, W. J. (1971) *Practical nonparametric statistics*. New York: John Wiley & Sons.

Cousins, M. S., Corrow, C., Finn, M., & Salamone, J. D. (1998) Temporal measures of human finger tapping: effects of age. *Pharmacology Biochemistry and Behavior,* 59(2), 445-449.

Crossley, M., & Hiscock, M. (1992) Age-related differences in concurrent-task performance of normal adults: evidence for a decline in processing resources. *Psychology and Aging,* 7(4), 499-506.

de Frias, C. M., Dixon, R. A., Fisher, N., & Camicioli, R. (2007) Intraindividual variability in neurocognitive speed: a comparison of Parkinson's disease and normal older adults. *Neuropsychologia,* 45(11), 2499-2507.

de Groot-Driessen, D., & van Heugten, C. (2006) Speed of finger tapping as a predictor of functional outcome after unilateral stroke. *Archives of Physical Medicine and Rehabilitation*, 87(1), 40-44.

Der, G., & Deary, I. J. (2006) Age and sex differences in reaction time in adulthood: results from the United Kingdom Health and Lifestyle Survey. *Psychology and Aging,* 21(1), 62-73.

Dikmen, S. S., Machamer, J. E., Winn, H. R., & Temkin, N. R. (1995) Neuropsychological outcome at 1-year post head injury. *Neuropsychology,* 9(1), 80-90.

Dorfberger, S., Adi-Japha, E., & Karni, A. (2009) Sex differences in motor performance and motor learning in children and adolescents: an increasing male advantage in motor learning and consolidation phase gains. *Behavioural Brain Research,* 198(1), 165-171.

Elias, M. F., Robbins, M. A., Walter, L. J., & Schultz, N. R. (1993) The influence of gender and age on Halstead-Reitan Neuropsychological Test performance. *Journals of Gerontology,* 48(6), 278-281.

Fan, L., Tang, Y., Sun, B., Gong, G., Chen, Z. J., Lin, X., Yu, T., Li, Z., Evans, A. C., & Liu, S. (2010) Sexual dimorphism and asymmetry in human cerebellum: an MRI-based morphometric study. *Brain Research,* 1353, 60-73.

Foo, S. C., Lwin, S., Chia, S. E., & Jeyaratnam, J. (1994) Chronic neurobehavioural effects in paint formulators exposed to solvents and noise. *Annals of the Academy of Medicine, Singapore,* 23(5), 650-654.

Foundas, A. L., Hong, K., Leonard, C. M., & Heilman, K. M. (1998) Hand preference and magnetic resonance imaging asymmetries of the central sulcus. *Neuropsychiatry, Neuropsychology, and Behavioral Neurology*, 11(2), 65-71.

Gardner, W., Mulvey, E. P., & Shaw, E. C. (1995) Regression analyses of counts and rates: poisson, overdispersed poisson, and negative binomial models. *Psychological Bulletin,* 118(3), 392-404.

Godefroy, O., Roussel, M., Despretz, P., Quaglino, V., & Boucart, M. (2010) Age-related slowing: perceptuomotor, decision, or attention decline? *Experimental Aging Research,* 36(2), 169-189.

Greenwald, R. R., & Jerger, J. (2001) Aging affects hemispheric asymmetry on a competing speech task. *Journal of the American Academy of Audiology,* 12(4), 167-173.

Gualtieri, C. T., & Johnson, L. G. (2006) Reliability and validity of a computerized neurocognitive test battery, CNS Vital Signs. *Archives of Clinical Neuropsychology,* 21(7), 623-643.

Haaxma, C. A., Bloem, B. R., Borm, G. F., & Horstink, M. W. (2008) Comparison of a timed motor test battery to the Unified Parkinson's Disease Rating Scale–III in Parkinson's disease. *Movement Disorders,* 23(12), 1707-1717.

Haaxma, C. A., Bloem, B. R., Overeem, S., Borm, G. F., & Horstink, M. W. (2010) Timed motor tests can detect subtle motor dysfunction in early Parkinson's disease. *Movement Disorders,* 25(9), 1150-1156.

Halstead, W. C. (1947) *Brain and intelligence*. Chicago: University of Chicago Press.

Heaton, R. K., Miller, S. W., Taylor, M. J., & Grant, I. (2004) *Revised comprehensive norms for an expanded Halstead-Reitan battery: demographically adjusted neuropsychological norms for African American and Caucasian adults.* Lutz, FL: Psychological Assessment Resources.

Hervé, P-Y., Mazoyer, B., Crivello, F., Perchey, G., & Tzourio-Mazoyer, N. (2005) Finger tapping, handedness and grey matter amount in the Rolando's genu area. *NeuroImage,* 25(4), 1133-1145.

Hinton, S. C., Paulsen, J. S., Hoffmann, R. G., Reynolds, N. C., Zimbelman, J. L., & Rao, S. M. (2007) Motor timing variability increases in preclinical Huntington's disease patients as estimated onset of motor symptoms approaches. *Journal of the International Neuropsychological Society,* 13(3), 539-543.

Jarvis, P. E., & Barth, J. T. (1994) *The Halstead-Reitan Neuropsychological Battery: a guide to interpretation and clinical applications.* (2nd ed.) Odessa, FL: Psychological Assessment Resources.

Jiménez-Jiménez, F. J., Rubio, L., Alonso-Navarro, H., Calleja, M., Pilo-de-la-Fuente, B., Plaza-Nieto, J. F., Venito-León, J., García-Ruiz, P. J., & Agúndez, J. A. G. (2010) Impairment of rapid repetitive finger movements and visual reaction time in patients with essential tremor. *European Journal of Neurology,* 17(1), 152-159.

Kang, X., Herron, T. J., & Woods, D. L. (2011a) Characteristics of brain anatomy on projection maps of the cortical surface. *Proceedings of the 17th Annual Meeting of the Organization for Human Brain Mapping (OHBM).* Québec City, Canada, June 2011.

Kang, X., Herron, T. J., & Woods, D. L. (2011b) Regional variation, hemispheric asymmetries and gender differences in pericortical white matter. *NeuroImage,* 56(4), 2011-2023.

KLUGER, B., PALMER, C., SHATTUCK, J., & TRIGGS, W. (2012) Motor evoked potential depression following repetitive central motor initiation. *Experimental Brain Research,* 216(4), 585-590.

LEE, M. S., LYOO, C. H., LEE, M. J., SIM, J., CHO, H., & CHOI, Y. H. (2010) Impaired finger dexterity in patients with Parkinson's disease correlates with discriminative cutaneous sensory dysfunction. *Movement Disorders,* 25(15), 2531-2535.

LING, H., MASSEY, L. A., LEES, A. J., BROWN, P., & DAY, B. L. (2012) Hypokinesia without decrement distinguishes progressive supranuclear palsy from Parkinson's disease. *Brain: a Journal of Neurology*, 135(Part 4), 1141-1153.

MURELIUS, O., & HAGLUND, Y. (1991) Does Swedish amateur boxing lead to chronic brain damage? 4. A retrospective neuropsychological study. *Acta Neurologica Scandinavica,* 83(1), 9-13.

NALÇACI, E., KALAYCIOĞLU, C., CIÇEK, M., & GENÇ, Y. (2001) The relationship between handedness and fine motor performance. *Cortex: A Journal Devoted to the Study of the Nervous System and Behavior,* 37(4), 493-500.

PETERS, M. (1980) Why the preferred hand taps more quickly than the non-preferred hand: three experiments on handedness. *Canadian Journal of Psychology,* 34(1), 62-71.

PETERS, M., & CAMPAGNARO, P. (1996) Do women really excel over men in manual dexterity? *Journal of Experimental Psychology: Human Perception and Performance,* 22(5), 1107-1112.

PETERS, M., & DURDING, B. (1979) Left-handers and right-handers compared on a motor task. *Journal of Motor Behavior,* 11(2), 103-111.

PRIGATANO, G. P., & BORGARO, S. R. (2003) Qualitative features of finger movement during the Halstead finger oscillation test following traumatic brain injury. *Journal of the International Neuropsychological Society,* 9(1), 128-133.

PRIGATANO, G. P., & WONG, J. L. (1997) Speed of finger tapping and goal attainment after unilateral cerebral vascular accident. *Archives of Physical Medicine and Rehabilitation,* 78(8), 847-852.

PURVES, D., WHITE, L. E., & ANDREWS, T. J. (1994) Manual asymmetry and handedness. *Proceedings of the National Academy of Sciences of the United States of America*, 91(11), 5030-5032.

RASMUSSEN, T., & MILNER, B. (1977) The role of early left-brain injury in determining lateralization of cerebral speech functions. *Annals of the New York Academy of Sciences,* 299, 355-369.

REITAN, R. M., & WOLFSON, D. (1985) *The Halstead-Reitan Neuropsychological Test Battery: theory and clinical interpretation*. Tucson, AZ: Neuropsychology Press.

REITAN, R. M., & WOLFSON, D. (1993) *The Halstead-Reitan Neuropsychological Test Battery: theory and clinical interpretation*. (2nd ed.) Tucson, AZ: Neuropsychology Press.

REITAN, R. M., & WOLFSON, D. (1994) Dissociation of motor impairment and higher-level brain deficits in strokes and cerebral neoplasms. *Clinical Neuropsychologist,* 8(2), 193-208.

ROBINSON, L. R., RUBNER, D. E., WAHL, P. W., FUJIMOTO, W. Y., & STOLOV, W. C. (1993) Influences of height and gender on normal nerve conduction studies. *Archives of Physical Medicine and Rehabilitation,* 74(11), 1134-1138.

ROIVAINEN, E. (2011) Gender differences in processing speed: a review of recent research. *Learning & Individual Differences,* 21(2), 145-149.

ROSSINI, P. M., DESIATO, M. T., & CARAMIA, M. D. (1992) Age-related changes of motor evoked potentials in healthy humans: non-invasive evaluation of central and peripheral motor tracts excitability and conductivity. *Brain Research,* 593(1), 14-19.

RUFF, R. M., & PARKER, S. B. (1993) Gender- and age-specific changes in motor speed and eye-hand coordination in adults: normative values for the Finger Tapping and Grooved Pegboard Tests. *Perceptual & Motor Skills,* 76(3, Part 2), 1219-1230.

SCHMIDT, S. L., OLIVEIRA, R. M., KRAHE, T. E., & FILGUEIRAS, C. C. (2000) The effects of hand preference and gender on finger tapping performance asymmetry by the use of an infra-red light measurement device. *Neuropsychologia,* 38(5), 529-534.

SHIMOYAMA, I., NINCHOJI, T., & UEMURA, K. (1990) The finger-tapping test: a quantitative analysis. *Archives of Neurology,* 47(6), 681-684.

STRAUSS, E., SHERMAN, E. M., & SPREEN, O. (2006) *A compendium of neuropsychological tests: administration, norms, and commentary.* (3rd ed.) New York: Oxford University Press.

TANNER, B. A., & BOWLES, R. L. (1995) Preliminary data on a computerized test of finger speed and endurance. *Behavior Research Methods, Instruments and Computers,* 27(2), 160-161.

TAYLOR, D. C., FALCONER, M. A., & FLOR-HENRY, P. (2010) Some evidence of bilateral speech representation in sinistrals. *Clinical EEG and Neuroscience: Official Journal of the EEG and Clinical Neuroscience Society (ENCS),* 41(4), 214-218.

TEIXEIRA, L. A. (2008) Categories of manual asymmetry and their variation with advancing age. *Cortex: a Journal Devoted to the Study of the Nervous System and Behavior,* 44(6), 707-716.

TOBIMATSU, S., SUN, S. J., FUKUI, R., & KATO, M. (1998) Effects of sex, height and age on motor evoked potentials with magnetic stimulation. *Journal of Neurology,* 245(5), 256-261.

TODOR, J. I., & SMILEY-OYEN, A. L. (1987) Force modulation as a source of hand differences in rapid finger tapping. *Acta Psychologica,* 65(1), 65-73.

TRIGGS, W. J., CALVANIO, R., & LEVINE, M. (1997) Transcranial magnetic stimulation reveals a hemispheric asymmetry correlate of intermanual differences in motor performance. *Neuropsychologia,* 35(10), 1355-1363.

TURGEON, M., WING, A. M., & TAYLOR, L. W. (2011) Timing and aging: slowing of fastest regular tapping rate with preserved timing error detection and correction. *Psychology and Aging,* 26(1), 150-161.

WELLS, F. L. (1908) Normal performance in the tapping test: before and during practice, with special reference to fatigue phenomenon. *The American Journal of Psychology,* 19(4), 437-483.

WESTERHAUSEN, R., HUSTER, R. J., KREUDER, F., WITTLING, W., & SCHWEIGER, E. (2007) Corticospinal tract asymmetries at the level of the internal capsule: is there an association with handedness? *NeuroImage,* 37(2), 379-386.

WESTERN PSYCHOLOGICAL SERVICES. (1998) *WPS Electronic Tapping Test manual*. Los Angeles: Western Psychological Services.

WOODS, D. L., HERRON, T. J., YUND, E. W., HINK, R. F., KISHIYAMA, M. M., & REED, B. (2011) Computerized analysis of error patterns in digit span recall. *Journal of Clinical and Experimental Neuropsychology,* 33(7), 721-734.

WOODS, D. L., KISHIYAMA, M. M., YUND, E. W., HERRON, T. J., EDWARDS, B., POLIVA, O., HINK, R. F., & REED, B. (2011) Improving digit span assessment of short-term verbal memory. *Journal of Clinical and Experimental Neuropsychology,* 33(1), 101-111.

YEUDALL, L. T., REDDON, J. R., GILL, D. M., & STEFANYK, W. O. (1987) Normative data for the Halstead-Reitan Neuropsychological Tests stratified by age and sex. *Journal of Clinical Psychology*, 43(3), 346-367.

ZELAZNIK, H. N., & GOFFMAN, L. (2010) Generalized motor abilities and timing behavior in children with specific language impairment. *Journal of Speech, Language, and Hearing Research*, 53(2), 383-393.

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