Journal of Clinical and Experimental Neuropsychology, 2013
Vol. 35, No. 7, 745–758, http://dx.doi.org/10.1080/13803395.2013.824070

Computerized measures of finger tapping: Reliability, malingering and traumatic brain injury

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We analyzed computerized finger tapping metrics in four experiments. Experiment 1 showed tapping-rate differences associated with hand dominance, digits, sex, and fatigue that replicated those seen in a previous, large-scale community sample. Experiment 2 revealed test–retest correlations ($r = .91$) that exceeded those reported in previous tapping studies. Experiment 3 investigated subjects simulating symptoms of traumatic brain injury (TBI); 62% of malingering subjects produced abnormally slow tapping rates. A tapping-rate malingering index, based on rate-independent tapping patterns, provided confirmatory evidence of malingering in 48% of the subjects with abnormal tapping rates. Experiment 4 compared tapping in 24 patients with mild TBI (mTBI) and a matched control group; mTBI patients showed slowed tapping without evidence of malingering. Computerized finger tapping measures are reliable measures of motor speed, useful in detecting subjects performing with suboptimal effort, and are sensitive to motor abnormalities following mTBI.

Keywords: Finger oscillation; Symptom validity; Traumatic brain injury; Tapping rate; Motor speed; Tap failure; Index finger; Effort; Test–retest.

The Finger Tapping Test (or Finger Oscillation Test) was developed as part of the Halstead Battery (Halstead, 1947) to evaluate performance speed on a simple motor task (Reitan & Wolfson, 1994; Strauss, Sherman, & Spreen, 2006). The traditional version of the task requires subjects to tap as fast as they can for 10 s with their dominant and nondominant index fingers on a tapping board. Typical tapping rates are 4–6 taps s^{-1} (Reitan & Wolfson, 1985), with 5 to 10 data sets acquired from each hand. Motor changes related to illness and disability have been examined using tapping-rate measures in patients with Parkinson's disease (Crossley & Hiscock, 1992; Haaxma, Bloem, Overeem, Borm, & Horstink, 2010; Jiménez-Jiménez et al., 2010; Lee et al., 2010), Huntington's disease (Hinton et al., 2007), developmental disorders (Zelaznik & Goffman, 2010), and exposure to environmental toxins (Foo, Lwin, Chia, & Jeyaratnam, 1994). Finger tapping has also been used to identify the lateralization of cerebral lesions (Prigatano & Wong, 1997; Reitan & Wolfson, 1994), predict recovery from stroke (de Groot-Driessen & van Heugten, 2006), and classify the severity of traumatic brain injury (Dikmen, Machamer, Winn, & Temkin, 1995; Murelius & Haglund, 1991; Prigatano & Borgaro, 2003). Tapping-rate measures are particularly important in computerized tests where measures of higher level cognitive processing often require button press responses (Gualtieri & Johnson, 2006).

Four experiments are presented to (a) describe tapping kinetics in the index and middle fingers of the dominant and nondominant hand; (b) evaluate the test–retest reliability of different tapping measures; (c) develop rate-independent metrics of

This research was supported by the VA Research Service Grant 6119R to D.L.W. The content is solely the responsibility of the authors and does not necessarily represent the official views of the agencies.

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intertap variability and interdigit differences to identifying malingering; and (d) determine whether differences in finger tapping rate are found in a group of patients with mild traumatic brain injury (mTBI) in comparison with a demographically matched control group.

Fatigue

Although traditionally tapping rate was assessed using 10-s trials, with breaks taken at set intervals to avoid fatigue (Reitan & Wolfson, 1985), slowing has been noted over the brief trial period (Peters, 1980). Others have used longer tapping trials, such as the 30-s trial in an early study by Wells (1908), who found an average decline in tapping rate of approximately 16% over the tapping interval and noted greater fatigue in the nondominant hand. Tanner and Bowles (1995) detected slowing using a 2-min computerized tapping test, with the nondominant hand demonstrating greater fatigue than the dominant hand. Fatigue effects were also detected in our community-based study of tapping rate with greater fatigue effects seen in the nondominant hand (Hubel, Reed, Yund, Herron, & Woods, 2013).

Finger and hand dominance

Tapping performance has been used as an indicator of hand dominance (Barnsley & Rabinovitch, 1970; Palmer, 1974), with the dominant index finger typically producing about 10% more taps than the nondominant index finger (Ashendorf, Vanderslice-Barr, & McCaffrey, 2009; Jarvis & Barth, 1994; Reitan & Wolfson, 1985; Tanner & Bowles, 1995). In our community-based sample (Hubel et al., 2013), significant differences between the hands were found for median tapping rate and tap kinetics (the relative time that the button is closed was reduced in the dominant hand), as well as tapping-rate variability and occurrence of slowed taps (both increased in the nondominant hand). Others have also noted that variability in tapping rate can differ by hand, as does the relative time spent in the button-closed position (Todor & Smiley-Oyen, 1987).

Although the differences between fingers have been less well studied, small differences have been reported between the index finger and middle fingers (Aoki, Francis, & Kinoshita, 2003; Koeneke, Battista, Jancke, & Peters, 2009), with more marked slowing seen for the ring and little fingers (Koeneke et al., 2009).

Sex

Male tapping rate reliably exceeds that of females (Christianson & Leathem, 2004; Peters & Campagnaro, 1996; Ruff & Parker, 1993; Schmidt, Oliveira, Krahe, & Filgueiras, 2000). In our large community sample, sex differences were independent of aging, fatigue effects, and movement kinetics (Hubel et al., 2013).

The results of four experiments using computerized analysis of finger tapping are reported below. Experiment 1 describes the characteristics of index and middle finger tapping in a control sample. Experiment 2 evaluates the test–retest reliability of different tapping measures. Experiment 3 describes tapping results in subjects who are instructed to malinger. Experiment 4 describes tapping responses in subjects with a history of mild TBI.

EXPERIMENT 1

Method

Subjects

A total of 131 control subjects performed the finger tapping test. Subjects were recruited from advertisements on Craigslist. Subjects were required to meet the following inclusion criteria: (a) fluency in the English language; (b) no current or prior history of bipolar disorder, mania, or schizophrenia; (c) no current substance abuse; (d) no concurrent history of neurologic disease known to affect cognitive functioning; (e) on a stable dosage of any required medication; (f) auditory functioning sufficient to understanding normal conversational speech and visual acuity normal or corrected to 20/40 or better. Subjects were paid $25 per hour for their participation. Data were excluded from subjects who reported being ambidextrous ($n = 4$), who did not complete the full 30-s tapping period for at least one finger ($n = 1$), or who reported having a problem with either of their hands ($n = 3$). The remaining 123 subjects were 52.0% male, were 6.5% left-handed (by self-report), and had an average of 14.9 years of education. Subject ethnicities were 64% Caucasian, 12% African American, 14% Asian, 10% Hispanic/Latino, 2% Hawaiian/Pacific Islander, 2% American Indian/Alaskan Native, and 4% “other.” All subjects signed written consent forms approved by the institutional review boards (IRBs) at the Veterans Affairs Northern California Health Care System (VANCHCS) and University of California, Davis. Subjects ranged in age from

18 to 82 years (mean age = 32.2 years for men, 33.6 years for women). However, because the age distribution was not uniformly sampled (more than 80% of subjects were below 40 years of age), age effects were not examined.

Apparatus and stimuli

Finger tapping was performed at the beginning of the California Cognitive Assessment Battery (CCAB; Woods et al., 2010; Woods et al., 2011), a 2-hour computerized assessment battery. The CCAB includes 17 computerized tests and three adaptive questionnaires.[1] Testing was performed in a quiet testing room using a standard PC controlled by Presentation software (Versions 13 and 14, NeuroBehavioral Systems, Albany, CA, USA). Subjects 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, USA) over a travel distance of 2.0 mm. A picture on the computer screen indicated which finger and mouse button to use. Practice periods of 10 s were given for each finger prior to the 30-s test trial. Visual cues were used to initiate practice and test trials, with supervision by a test administrator. Subjects first tapped as fast as possible with the right index finger. The task was then repeated using the right middle finger, left index finger, and then left middle finger.

Scoring and data preparation

The times of each button press and release (as illustrated in Figure 1 (top)) were recorded with high temporal precision.[2] The total time to complete one tap, referred to as the intertap interval (ITI), included both the duration of button closure, or down time (DT), and the time from button release to the next button depression, referred to as motor initiation time (MIT).

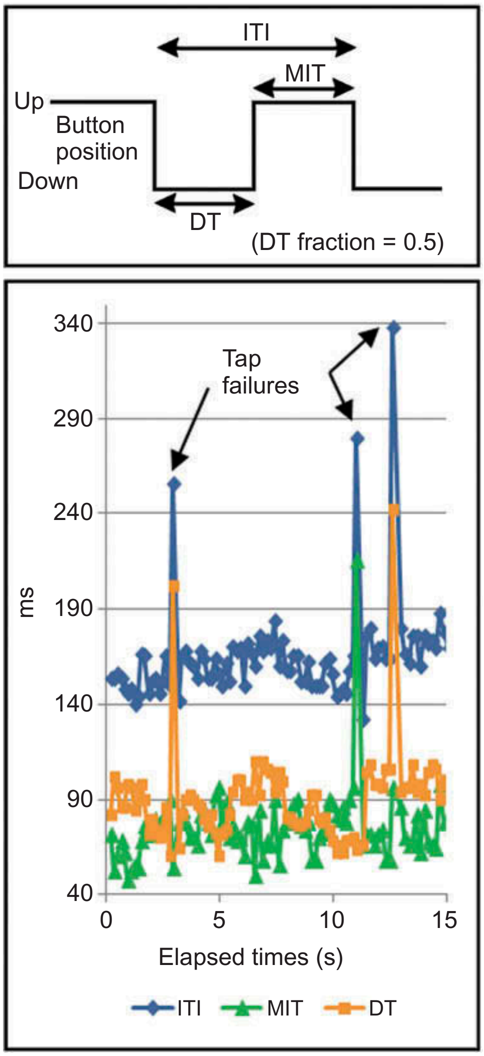

Figure 1. Top: Tapping measures assessed by the computer. Measurements include down time (DT), the time that the mouse button was depressed, and movement initiation time (MIT), the interval between button release and the next button press. The sum of DT and MIT defined the intertap interval (ITI) for each button press. Bottom: Example profile for a single subject tapping (only 15 s of the 30-s time period is shown). Dominant hand index finger performance is illustrated by ITI, MIT, and DT. Three tap failures are illustrated. To view a color version of this figure, please see the online issue of the Journal.

Figure 1 (bottom) illustrates a representative subject's 30-s dominant index finger test trial including ITI, DT, and MIT for each tap. The median ITI for this subject was 170 ms (tapping rate = 5.7 taps s^{-1}); however, they had three ITIs that exceeded 250 ms ("tap failures"), which were due to either abnormally long DTs (on two occasions the button was not completely released) or abnormally long MITs (on one occasion the button was not completely depressed).

[1]The CCAB includes the following computerized tests and questionnaires: finger tapping, simple reaction time, Stroop, digit span forward and backward, phonemic and semantic verbal fluency, verbal list learning, spatial span, trail making, vocabulary, design fluency, the Wechsler Test of Adult Reading (WTAR), visual feature conjunction, risk and loss avoidance, delay discounting, the Paced Auditory Serial Addition Task (PASAT), the Cognitive Failures Questionnaire (CFQ), the Posttraumatic Stress Disorder Checklist (PCL), and a traumatic brain injury (TBI) questionnaire.

[2]Presentation® software provides measures of timing precision for each event that averaged less than 0.5 ms for button depressions and releases. As in our previous study, we noted occasional ITIs that were less than 40 ms (0.1% of all measured taps). Because these extremely quick taps were much faster than fastest sustained observed tapping speed (~130 ms), all taps faster than 40 ms were removed from the data, and the time accounted for by these taps was allotted to the subsequent tap.

Timing of the 30-s testing period started with the first tap (Reitan & Wolfson, 1993). The full test trial was divided into three intervals in order to analyze fatigue. Only full taps (with both depression and release) were included in each interval. For each tapping interval, the median ITI, standard deviation of ITI, and DT fraction (DT/ITI) were obtained for the left and right index and middle fingers.

Following our previous study (Hubel et al., 2013), and the findings of Todor and Smiley-Oyen (1987), we classified instances when a subject failed to move his or her finger far enough to either open or close the mouse key as "tap failures." Tap failures were defined as taps with ITIs 67% longer than the fastest consecutive 10-tap ITI and DT fraction at least 0.1 greater (failure to open) or less (failure to close) than the mean DT fraction for each subject. Overall, tap failures accounted for 3.9% of taps, with failures to open and close the mouse key occurring with a similar incidence (2.96 and 2.61 per 30 s, respectively). At least one tap failure occurred on 58% of trials. Approximately 88% of subjects had 4 or fewer tap failures per 10-s interval, and only 0.4% of subjects produced 12 or more. As noted in our previous study (Hubel et al., 2013), the distribution of combined total tap failures per subject was closely fit by a geometric distribution suggesting that tap failures are a separate Poisson-like noise process compared to normal taps. Tap failures were analyzed separately, and median values for ITI and DT fraction were used in order to eliminate the effects of tap failures on mean ITI, ITI variance, and DT fraction. Because median ITI values had standard deviations that were 7% smaller than mean values, median values were used to quantify performance. In addition, median values are more representative of a subject's consistent performance, such that the values are comparable to standardized tapping tests that include repeated trials.

Statistical analysis

Mixed analyses of variance (ANOVAs) were conducted with sex as a between-group factor and finger (index, middle), hand (dominant or nondominant), and interval (0–10 s, 10–20 s, 20–30 s) as within-subjects factors. Separate ANOVAs were performed for the following dependent variables: median ITI, ITI standard deviation with failures removed, and median DT fraction. ANOVAs were also conducted on the three time intervals to analyze fatigue as a function of finger, hand, and sex. *F*-ratios are reported for determining statistical significance, and effect sizes are reported as η^2_p values. Greenhouse–Geisser corrections of degrees of freedom were uniformly used in computing *p* values in order to correct for any nonspherical covariation or heterogeneity within factors or interactions.

Because the tap failures fit a geometric distribution, their analysis was conducted using negative binomial regression (Cameron & Trivedi, 1998; Gardner, Mulvey, & Shaw, 1995) with the logarithm of the total number of taps as a covariate. Wald χ^2 values were used to determine significance for negative binomial regression analyses. Finally, Pearson correlations were computed on selected pairs of variables. SPSS v.20 (www.ibm.com) was used for all analyses.

Results

Finger and hand dominance

Figure 2 illustrates the strong main effects of both hand and finger: The dominant fingers tapped faster than nondominant fingers overall (by 13.2%), and index fingers tapped faster than middle fingers (by 2.7%). In addition, the nondominant hand showed larger fatigue effects, producing a significant Hand × Interval interaction (Table 1). No significant differences in fatigue were found between the index and middle fingers. The ITI standard deviations were significantly higher in the nondominant hand (by 51.8%).

The correlation between MIT and DT was low, indicating that there were systematic differences in

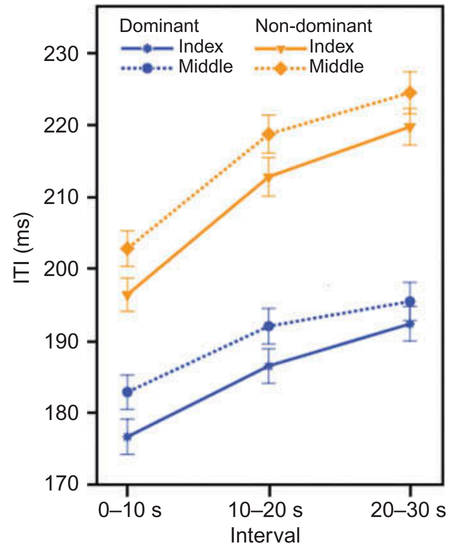

Figure 2. Intertap interval (ITI) for the dominant and nondominant index and middle fingers over the 30-s testing trial. To view a color version of this figure, please see the online issue of the Journal.

TABLE 1
Control group results of ANOVAs and negative binomial regression for intertap interval, movement initiation time fraction, standard deviation of ITI, and tap failures

	ITI			*MIT fraction*			*ITI SD*			*Tap failures*	
Factor/interaction	*F*	*df*	η^2_p	*F*	*df*	η^2_p	*F*	*df*	η^2_p	*Wald* χ^2	*df*
Interval	375.62***	2242	.76	0.45	2242	.00	0.49	2242	.00	0.65	2
Finger	33.30***	4121	.22	2.00	4121	.02	6.09*	4121	.05	0.01	1
Hand	240.40***	1121	.67	5.04*	1121	.04	107.38***	1121	.47	3.07	1
Gender	13.17**	1121	.10	0.78	1121	.01	0.02	1121	.00	65.66***	1
Finger × Interval	2.33	2242	.02	0.64	2242	.01	0.33	2242	.00	0.51	2
Hand × Interval	29.43***	2242	.20	0.27	2242	.00	1.56	2242	.01	2.25	2
Finger × Gender	0.06	1121	.00	0.61	1121	.01	0.10	1121	.00	0.08	1
Hand × Gender	0.47	1121	.00	0.16	1121	.00	5.91*	1121	.05	6.56*	1
Finger × Hand	0.21	1121	.00	0.01	1121	.00	0.20	1121	.00	1.26	1

Notes. ANOVA = analysis of variance; ITI = intertap interval; MIT = movement initiation time. Main effects of interval (0–10 s, 10–20 s, 20–30 s), finger (index, middle), hand (dominant or nondominant), and gender (male or female) and select interactions are listed.
*$p < .05$; **$p < .01$; ***$p < .0001$.

the time spent in button-open and button-closed positions in different subjects. Movement kinetics were significantly influenced by hand dominance, but not finger (Table 1). In both hands, more time was spent in the down position than on movement initiation; however, this difference was greater in the nondominant hand.

Sex

There were significant main effects of sex on ITI and tap failures (Table 1). Men tapped 8.0% faster than women and produced more tap failures. Men and women otherwise showed similar tap kinetics, with no significant sex difference seen in DT fraction.

Discussion

Comparisons to previous results

Tapping rates in the current study sample replicated those in our previous study (Hubel et al., 2013) of a large community sample in New Zealand. The current sample averaged 5.3 and 4.5 taps s^{-1} for the dominant and nondominant index fingers, respectively, versus 5.5 and 4.8 taps s^{-1} in our previous study. The results were also similar to those reported in adult normative data using the manually administered Halstead–Reitan Finger Tapping Test (Heaton, Miller, Taylor, & Grant, 2004; Ruff & Parker, 1993) and other electronic (Western Psychological Services, 1998) and computerized (Christianson & Leathem, 2004; Gualtieri & Johnson, 2006; Tanner & Bowles, 1995) tapping measures, with all devices producing mean index finger tapping rates in adults ranging from 4.8 to 5.7 s^{-1}, and all showing clear hand dominance effects.

Finger and hand dominance

Results of this study replicated differences in ITI, movement kinetics, fatigue, variability, and tap failure rate between dominant and nondominant index fingers (Hervé, Mazoyer, Crivello, Perchey, & Tzourio-Mazoyer, 2005; Hubel et al., 2013; Peters, 1980; Schmidt et al., 2000; Teixeira, 2008; Todor & Smiley-Oyen, 1987). The fingers of the dominant hand tapped faster, showed less fatigue, were less variable, and had lower tap failure rates than the fingers of the nondominant hand. Movement initiation was also faster with the dominant index and middle fingers, and these fingers also spent relatively less time in the down position.

One novel aspect of this study was the comparison of tapping rates in the index and middle fingers (Figure 2). While significant differences were found between the two digits, interdigit differences in fatigue, movement kinetics, ITI variability, and tap failures were much smaller than hand dominance effects, consistent with previous reports (Aoki et al., 2003; Koeneke et al., 2009).

Sex effects

As in previous studies (Christianson & Leathem, 2004; Peters & Campagnaro, 1996; Ruff & Parker, 1993; Schmidt et al., 2000), men tapped faster than women. We did not find a significant interaction between sex and hand dominance, as reported by Nalçaci, Kalaycioğlu, Çiçek, and Genç (2001). There were, however, small effects of sex on tapping-rate variability and tap failures. Men demonstrated more tap failures overall, but women demonstrated a larger discrepancy in tap failures between hands.

Sex differences in tapping rate are likely specific for repetitive movements as sex differences are not found in reaction time tests (Commodari & Guarnera, 2008), and women generally outperform men in fine motor tasks such as the Grooved Peg Board (Peters & Campagnaro, 1996; Ruff & Parker, 1993). In addition, no sex differences are seen in motor evoked potentials (Tobimatsu, Sun, Fukui, & Kato, 1998), nerve conduction velocity (Robinson, Rubner, Wahl, Fujimoto, & Stolov, 1993), or relative area or thickness of motor cortex (Kang, Herron, Cate, Yund, & Woods, 2012). However, sex differences have been found in the cerebellum (Fan et al., 2010), which plays a central role in the control of rapid alternating movements.

EXPERIMENT 2: TEST–RETEST RELIABILITY OF FINGER TAPPING

In Experiment 2, the reliability of the tapping measures described in Experiment 1 was examined using tests performed on three different days. Previous studies of the test–retest correlations of tapping rate over repeated sessions have shown high test–retest correlations (Dikmen, Heaton, Grant, & Temkin, 1999; Gill, Reddon, Stefanyk, & Hans, 1986; Morrison, Gregory, & Paul, 1979; Ruff & Parker, 1993). For example, the computerized finger tapping test used in CNS Vital Signs is reported to have a test–retest reliability of .78 (Gualtieri & Johnson, 2006). Although tapping tests are generally considered to be stable over time, small but significant improvements in performance have been detected across testing sessions by some investigators (Dikmen et al., 1999; Gill et al., 1986). In addition, Gill et al. (1986) found higher reliability rates for men than women. Some reports have also indicated differences in reliability between the dominant and nondominant hands (Massman & Doody, 1996; Provins & Cunliffe, 1972), and Morrison et al. (1979) noted lower reliability for the ratio of the nondominant and dominant hands than for individual hand performance. In addition, tapping practice with the middle finger of one hand was reported to produce improvement in all other fingers of both hands (Koeneke et al., 2009). Little is known of the reliability of other tapping measures that were obtained in Experiment 1 including tap kinetics, tapping-rate variance, tap failures, and interdigit differences.

Method

Subjects

Fifty-five young, neurologically normal subjects from Experiment 1 were recruited for repeated testing (three replications and a fourth session involving simulating TBI symptoms). Other subjects, recruited before and after this cohort, were not asked to participate in the repeated testing protocol. More than 90% of the subjects recruited for repeated testing participated and completed all three test sessions. Inclusion/exclusion criteria and payment were the same as those in Experiment 1, and all subjects gave written informed consent following IRB regulations of the VANCHCS. The subjects included 28 men and 27 women between the ages of 18 and 46 years (mean age = 26.2 years). Most were right-handed (96.4%) students with an average of 14.9 years of education.

Apparatus and stimuli

In order to evaluate test–retest reliability, each subject underwent three CCAB test sessions at intervals ranging from 1 to 70 days (median time between sessions was seven days). Test procedures were similar to those described in Experiment 1.

Statistical analysis

Correlations for each session were averaged across fingers, intervals, or both. Additional test–retest correlations were conducted using median ITI to examine hand dominance differences for the index and middle finger, fatigue effects between the first and second and second and third intervals for each finger, and the ratio of the fastest 10 to slowest 10 taps. The average of the correlations between Sessions 1 and 2, 2 and 3, and 1 and 3 are reported. Average correlations across all fingers and intervals were also analyzed separately for male and female subjects and compared using Fisher *z*-tests.

Results

A preliminary mixed ANOVA demonstrated that the main effect of session (1, 2, or 3) on ITI only trended toward significance, $F(2, 106) = 3.20$, $p < .05$, $\eta^2_p = .06$, but without substantial learning effects: Subjects were slightly faster in the first session. This was due to small increases in DT across sessions, $F(2, 106) = 13.93$, $p < .0001$, $\eta^2_p = .21$.

Correlations for median ITI, ITI standard deviation, DT fraction, taps per interval, combined

TABLE 2
Test–retest correlations for the median ITI, taps, taps plus tap failures, failures to open, failures to close, standard deviation of ITI, and median fraction of time spent on button depression

Pearson correlation (2-tailed)	*Median ITI*	*Taps*	*Taps + all failures*	*Failures to open*	*Failures to close*	*ITI* SD	*DT fraction*
Across all intervals and fingers	.91**	.88**	.91**	.71**	.73**	.78**	.56**
Males only	.90**	.87**	.89**	.69**	.78**	.85**	.48[c]
Females only	.91**	.89**	.92**	.73**	.68**	.67*	.68**
Across all intervals							
Dominant index	.86**	.82**	.86**	.45*[a]	.60**	.49**	.30[d]
Dominant middle	.88**	.83**	.86**	.45*[b]	.38**	.41*[b]	.52**
Nondominant index	.82**	.81**	.82**	.50**	.49**	.68**	.53**
Nondominant middle	.87**	.83**	.86**	.52**	.51**	.66**	.45*[b]
Across all fingers							
Interval 1	.89**	.85**	.89**	.58**	.67**	.61**	.59**
Interval 2	.89**	.86**	.90**	.62**	.48**	.67**	.50**
Interval 3	.90**	.86**	.90**	.51**	.64**	.61**	.46**

Notes. ITI = intertap interval; DT = down time (button depression). Correlations are averaged across Session 1 versus 2, 2 versus 3, and 1 versus 3.
[a]Correlation for Sessions 1 and 2, $p < .05$; for remaining sessions, $p < .01$. [b]Correlation for Sessions 1 and 3, $p < .05$; for remaining sessions, $p < .01$. [c]Correlation for Sessions 1 and 3 was not significant; for remaining sessions, $p < .01$. [d]Correlation for Sessions 1 and 3 was not significant; Sessions 1 and 2, $p < .05$, Sessions 2 and 3, $p < .01$.
*$p < .05$; **$p < .01$.

taps and tap failures per interval, failures to close, and failures to open (averaged across either fingers, intervals, or both) are shown in Table 2. Median ITI averaged over all fingers and intervals showed the highest correlation ($r = .91$), both overall and in each 10-s interval (minimum $r = .89$). Measures of tapping variability, including the ITI standard deviation (after excluding tap failures) and failures to open and close, showed smaller, but still highly significant, test–retest correlations. In addition, the ratio of the fastest 10 to slowest 10 taps was reliable across testing sessions ($r = .65$, $p < .0001$). DT fraction was the least reliable dependent measure but still showed significant test–retest reliability.

The reliability of hand dominance effects and fatigue (slowing across the 30-s trial) was also analyzed. Hand differences (dominant faster than nondominant hand) averaged across intervals were reliable across sessions for the index and middle fingers ($r = .55$, $p < .005$ and $r = .75$, $p < .0001$, respectively). However, fatigue effects did not show significant correlations over the three test sessions.

Discussion

Tapping characteristics in individual subjects were highly stable over time. In general, CCAB test–retest correlations of tapping rate were higher than those previously reported in traditional (Dikmen et al., 1999; Gill et al., 1986; Morrison et al., 1979; Ruff & Parker, 1993) or previous computerized (Gualtieri & Johnson, 2006) tapping tests. The increased reliability may have reflected the use of median ITI values and the exclusion of tap failures. Median tapping rate and the combination of taps and failures (failure to open and failure to close) were the most reliable measures. More subtle features of performance, including the DT fraction, ITI standard deviation, failures to open, failures to close, hand differences (for index and middle fingers), and the ratio of fastest to slowest taps, also showed significant test–retest reliability. This suggests that the manner in which a subject taps, as well as the rate, is highly consistent across test sessions.

EXPERIMENT 3: THE EFFECTS OF MALINGERING ON FINGER TAPPING

Previous studies have found that subjects instructed to malinger show abnormally low tapping rates (Arnold et al., 2005; Greiffenstein & Baker, 2008; Heaton, Smith, Lehman, & Vogt, 1978; Larrabee, 2003; Mittenberg, Rotholc, Russell, & Heilbronner, 1996; Tanner, Bowles, & Tanner, 2003). For example, Larrabee (2003) found that 40% of patients with "malingered neurocognitive dysfunction" produced abnormally low tapping rates, while Heaton et al. (1978) and Mittenberg et al. (1996) found that 50% of injury simulators showed similar abnormalities. Arnold et al. (2005) argued that cutoff scores for detecting noncredible performance should be specific for sex and differential diagnosis. Using a computerized tapping test (the T3), Tanner et al. (2003) found that subjects simulating head injury slowed their tapping by an average of nearly 50% compared to best effort conditions. The authors also noted that slowing diminished across a 2-min trial in the malingering condition and found that malingering subjects demonstrated smaller hand differences in tapping rate and reduced tapping-rate variability.

Experiment 3 was designed to evaluate tapping rate in a condition where subjects simulated self-selected symptoms of traumatic brain injury (TBI). Subjects who decided to simulate impaired performance on the finger tapping tests were expected to show slowed tapping. However, the critical question was whether these TBI simulators (i.e., subjects with abnormal ITIs) would be able to maintain normal tapping characteristics (e.g., fatigue, interhand differences, and intertap variance) when malingering. The goal of Experiment 3 was to construct a tapping-rate malingering index (TRMI), independent of mean tapping rate, which would provide an additional assessment of malingering that would be independent of overall tapping rate.

Method

Subjects

Forty-nine of the 55 subjects from Experiment 2 participated in Experiment 3. Data from two subjects were not included in the analyses due to subjects not completing the full 30-s tapping period. Inclusion/exclusion criteria and payment were the same as those in Experiment 1, and all subjects gave written informed consent following IRB regulations of the VANCHCS. The subjects included 25 men and 22 women between the ages of 18 and 39 years (mean age = 26.2 years). As in Experiment 2, most were right-handed (97.9%) students with an average of 14.9 years of education.

Apparatus and stimuli

As described in relation to the CCAB digit span test (Woods et al., 2011), after their third CCAB session, subjects were given a description of TBI symptoms emphasizing deficits in memory and executive function deficits. Subjects were instructed to simulate TBI symptoms on the CCAB tests on their next testing session so that their pattern of results would be similar to that of a patient who had suffered a mild TBI (mTBI). Because the mTBI deficits were described as greater for memory and executive function, we anticipated that some subjects might choose not to malinger on the finger tapping task. However, we did not query subjects about their strategy on each test so the actual portion of subjects who purposely simulated impaired performance on the tapping test was unknown. The modal interval between the third (Experiment 2) and fourth (Experiment 3) sessions was 7 days, with five subjects undergoing the simulation session more than 30 days after the previous session. Test procedures were otherwise the same as those in Experiments 1 and 2.

Statistical analysis

A tapping-rate malingering index (TRMI), independent of median tapping rate, was created first by extracting performance distribution measures from an independent data set of 1600 subjects previously analyzed (Hubel et al., 2013). Three distributions were used: (a) hand dominance; 83.4% of subjects showed faster tapping in the dominant hand; (b) fatigue; 85.3% of subjects showed slowing over successive response intervals; (c) consistency; 78.5% of subjects had a ratio of 10-slowest to 10-fastest consecutive taps that exceeded .75. For each subject, we extracted p values from each of the three distributions and combined them into the TRMI using Fisher's method (Brown, 1975) for aggregating the results of multiple, single-sided tests. This combination involved converting p values to χ^2 values, summing, and converting back to a p value after correcting for between-measure correlations (all had pairwise Pearson correlations below $r = .2$). A small p value of the TRMI thus indicated statistically unusual patterns of tapping. For example, a malingering subject might begin a tapping trial with a very slow tapping rate but gradually accelerate to a more natural tapping rate over the 30-s period.

Data from the TBI simulation condition were analyzed in isolation and were compared with the results from the first full effort control session (Experiment 1). Mixed ANOVAs were conducted using the same procedures and variables as those in Experiment 1 with the addition of a condition (simulation or control) factor. TRMI p values were converted to z score values and analyzed in normal and simulated TBI conditions, as well as all control subjects (Experiment 1) and for mTBI subjects whose results are reported in Experiment 4. A cutoff of $z = 1.28$ was selected based on a false-positive rate of 10% to identify probable malingering. As age and sex have been shown to impact tapping speed, median ITIs were adjusted using the following formula derived from 1600 subjects who participated in our community-based study (Hubel et al., 2013):

$$\text{Adjusted ITI} = \text{ITI} - [1.0079 \times (\text{age} - 46)] - [0.0311 \times (\text{age} - 46)^2] - [\text{sex} \times 15.7904]$$

In the formula, ITI refers to the median ITI for the left and right index fingers over the 30-s tapping periods, and sex is coded as 0 for male and 1 for female. Index fingers were only used for TRMI analysis, as middle fingers were not assessed in the community-based study. Abnormal tapping rate was defined as adjusted median ITIs more than two standard deviations above the average control condition adjusted ITI.

Results

As shown in Table 3, the median ITI in malingering conditions averaged 304 ms, an increase of 52% relative to full-effort performance, $F(1, 45) = 26.30$, $p < .0001$, $\eta^2_p = .37$. Overall, 62% of simulation subjects produced abnormal adjusted median ITIs relative to controls. In comparison, 3% of subjects in the control condition demonstrated abnormal adjusted ITIs. There was also a Condition × Finger interaction, $F(1, 45) = 8.21$, $p = .006$, $\eta^2_p = .15$, that reflected greater slowing in the right than left index finger during malingering.

Typical hand dominance and digit effects were absent in the malingering condition. Comparisons of malingering and control conditions also revealed increases in ITI standard deviations, $F(1, 45) = 20.00$, $p < .0001$, $\eta^2_p = .31$, tap failures (Wald $\chi^2 = 4.42$, $p < .05$), and DT fraction, $F(1, 45) = 13.55$, $p = .0006$, $\eta^2_p = .23$, during malingering. However, malingering subjects produced normal slowing over the 30-s interval, $F(2, 90) = 6.86$, $p < .0001$, $\eta^2_p = .13$.

We operationally assumed that subjects who had decided to simulate TBI symptoms on the finger tapping test would show abnormal ITIs. TRMI *z* scores are shown in Figure 3 for these abnormally slow tappers. Of TBI simulation subjects with abnormal tapping rates, 48% exceeded the TRMI cutoff. Overall, 31% of malingering subjects exceeded both the TRMI and ITI criteria. In the standard control condition, no subject exceeded both the TRMI and ITI criteria.

Discussion

Overall, 62% of subjects in the simulation condition tapped at abnormally slow rates. They also demonstrated changes in movement kinetics, variability, and tap failures and lacked normal finger and hand dominance effects.

Malingering subjects perform a dual task: They must perform the primary task and at the same time monitor their responses to maintain consistently slowed tapping. Malingering effects are often enhanced when the primary task is easier (Greiffenstein & Baker, 2008), as in the current study where malingering effects were largest for the dominant index finger. The TRMI, based on hand dominance differences, fatigue effects, and the ratio of fastest to slowest ITIs, was abnormal in 48% of simulation subjects with slowed tapping rates. This suggests that ancillary performance characteristics (i.e., adjusting tapping rates appropriately

TABLE 3
Simulated malingering and control conditions

	Malingering (n = 47)		*Control (Session 1, n = 123)*	
Factor	*Mean (SD)*	*%*	*Mean (SD)*	*%*
Median ITI	304.58 (147.18)		190.76 (24.79)	
Impaired (>2 *SD*s) ITI		61.7		3.3
Anti-fatigue effect				
Dominant index		27.7		6.5
Dominant middle		36.2		12.2
Nondominant index		23.4		5.7
Nondominant middle		21.3		6.5
TRMI for abnormal tappers				
z score	0.65 (1.32)		−0.31 (0.97)	
$z > 1.28$		48.3		0.0

Note. ITI = intertap interval; TRMI = tapping-rate malingering index. Conditions: Median index finger ITI; percentage with adjusted ITIs more than two standard deviations greater than the average control adjusted ITI across 30 s; Anti-fatigue effect: percentage with faster tapping rates in the last interval than in the first; TRMI *z* score and TRMI *z* scores greater than 1.28 ($p = .10$) for tappers with impaired ITI.

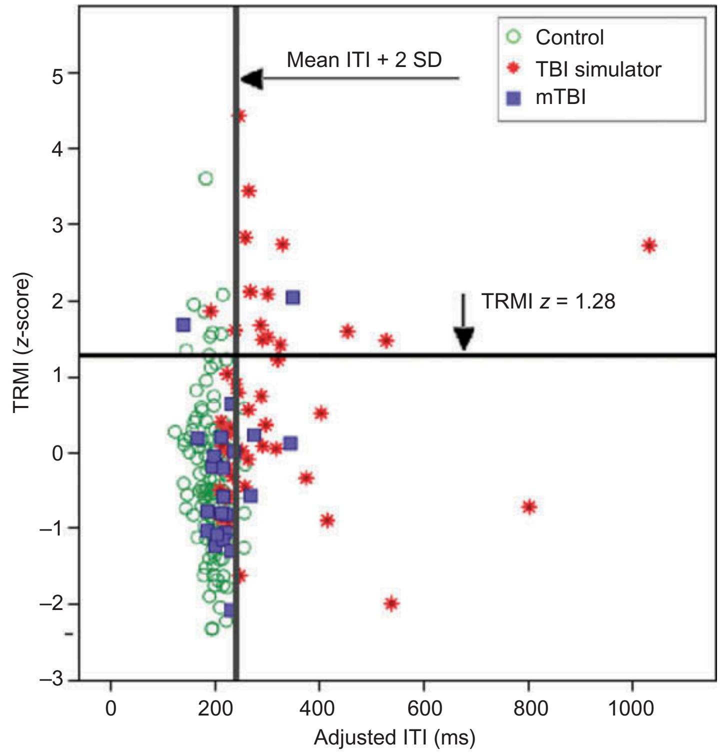

Figure 3. Tapping-rate malingering index (TRMI) *z* scores compared to adjusted median intertap interval (ITI) for control subjects in standard ($n = 123$) and traumatic brain injury (TBI) simulation ($n = 47$) conditions and subjects with a history of mild TBI (mTBI, $n = 24$). Higher *z* scores indicate increased likelihood of malingering. Lines illustrating malingering index *z* scores of 1.28 ($p = .10$; horizontal) and adjusted ITIs more than 2 standard deviations above the adjusted control mean ITI (vertical) are shown. To view a color version of this figure, please see the online issue of the Journal.

for the two hands and maintaining consistent performance), may be hard to maintain under "dual task" (i.e. malingering) conditions, even in a task as simple as finger tapping.

EXPERIMENT 4: EFFECTS OF TBI ON FINGER TAPPING

Finger tapping abnormalities in TBI increase with TBI severity (Dikmen et al., 1995). However, patients with mild TBI (mTBI) show subtle abnormalities when tested acutely (De Monte et al., 2005) and in the chronic recovery phase following impact trauma (Haaland, Temkin, Randahl, & Dikmen, 1994) and sports concussions (Murelius & Haglund, 1991). For example, a recent study of 102 young mTBI patients one year after injury found that the average number of taps produced by mTBI patients was approximately 3.5/sec (Tsushima, Lum, & Geling, 2009), roughly 70% of the number of taps normally produced by control subjects (Ruff & Parker, 1993). In the current experiment we examined the effects of TBI on our computerized measure of finger tapping in 24 veterans who had suffered mTBI, due primarily to blast trauma.

Method

Subjects

Subjects included 24 right-handed male veterans with a history of mTBI and 31 male controls matched in age, education, and handedness with the patients. mTBI patients (ages 20 to 61) were right-handed (95.7%) and had an average education level of 13.7 years. All subjects gave written informed consent following IRB regulations of the VANCHCS. All TBI events occurred at least 9 months prior to testing (range 9 months to 25 years). Some evidence of posttraumatic stress disorder (PTSD) was also evident in 77% of the TBI sample. Additional demographic information for TBI subjects is presented in Table 4 including the PTSD Checklist (PCL; Weathers, Litz, Herman, Huska, & Keane, 1993) scores and PTSD diagnosis based on the PCL (Blanchard, Jones-Alexander, Buckley, & Forneris, 1996; Lang, Laffaye, Satz, Dresselhaus, & Stein, 2003). The mTBI patients

TABLE 4
TBI patient characteristics

ID	*Age*	*EDU*	*Etiology*	*PCL*	*Median taps* s^{-1}
P28[b,c]	24	12	Blast	54	4.7
P27[b,c]	28	12	Blast	66[d]	4.9
P25[b,c]	43	14	Blast[a]	80[d]	2.9[e,f]
P22	30	14	MVA	—	4.8
P21[b]	52	14	MVA	27	4.5
P20[b,c]	41	14	Blast[a]	45[d]	5.5
P19	20	14	Blast[a]	41[d]	7.6[f]
P17[c]	25	15	Fall	—	5.2
P16	28	13	Blast	47[d]	5
P15[c]	25	12	Blast	57[d]	3.8[e]
P14	29	12	Blast	54[d]	4.5
P13[b,c]	47	14	Blast[a]	52	2.9[e]
P12	28	14	Fall	43[d]	6.4
P11[b]	29	13	Blast	27	5.4
P10[c]	61	18	MVA[a]	52[d]	4.5
P09[b,c]	27	15	Blast	72[d]	4.9
P08[b,c]	48	13	Blast	59[d]	5.4
P07[b,c]	50	20	MVA	62[d]	3.7[e]
P06[b]	49	12	Fall	47[d]	4.3
P05[b]	28	14	Fall	68[d]	4.4
P04[b,c]	39	13	MVA	64[d]	5.2
P03[b,c]	25	12	Blast[a]	72[d]	4.5
P02[b,c]	45	14	MVA	60[d]	4.7
P01[b,c]	23	14	Fall	67[d]	5.1

Notes. TBI = traumatic brain injury; PCL = PTSD Checklist; PTSD = posttraumatic stress disorder; EDU = years of education; MVA = moving vehicle accident. Age in years. Median taps per second are averaged across all fingers and intervals.
[a]Multiple TBIs. [b]Chronic pain. [c]Sleep problems. [d]Meet DSM–IV (Diagnostic and Statistical Manual of Mental Disorders–Fourth Edition) criteria for PTSD based on PCL. [e]Average intertap interval (ITI) is 2 standard deviations greater than control ITI. [f]Tapping-rate malingering index (TRMI) z score is greater than 1.28 ($p = .10$).

had already completed compensation and pension evaluations and had volunteered for research studies. They were informed that their experimental data would be encrypted and used exclusively for research purposes and that participation would have no impact on their clinical care or pension benefits.

Apparatus and stimuli

The same procedures as those described in Experiment 1 were used in this experiment. Additional CCAB measures utilized in this study were the PCL and questionnaires gathering information about reported head injuries, psychiatric history, chronic pain, sleep patterns, and so on.

Statistical analysis

The same procedures for data preparation and analysis as those described in Experiment 1 were used in Experiment 4, with the exceptions noted below. Analyses were conducted comparing mTBI patients with the matched control sample. One mTBI subject was excluded from the latter analyses due to questionable effort that was observed across the entire CCAB test battery. Pearson correlations were also analyzed for select variables. A TRMI score was computed for all subjects. A univariate ANOVA was conducted with TRMI scores as the dependent variable and group (mTBI or matched control) as the independent variable. Age was not included in the analyses due to the skewed age distribution of subjects.

Results

Figure 4 shows median adjusted ITIs from the mTBI patients who demonstrated significantly slower median tapping rates than matched controls, $F(1, 52) = 4.45$, $p = .04$, $\eta^2_p = .08$. There was no significant Group × Hand or Group × Finger interaction. PCL scores of mTBI subjects did not significantly correlate with tapping rate, $r(21) = .21$, *ns*, or tap failures, $r(21) = -.28$, *ns*.

Two TBI patients exhibited abnormal TRMI scores, one of whom demonstrated extremely slow tapping rates (ITI greater than 2 standard deviations above the mean of the control group, see Figure 3). One was the aforementioned patient who displayed questionable effort on other tests in the CCAB battery and was excluded from the mTBI analyses described above. Overall, the remaining TBI patients and matched controls performing with full effort conditions did not significantly differ in

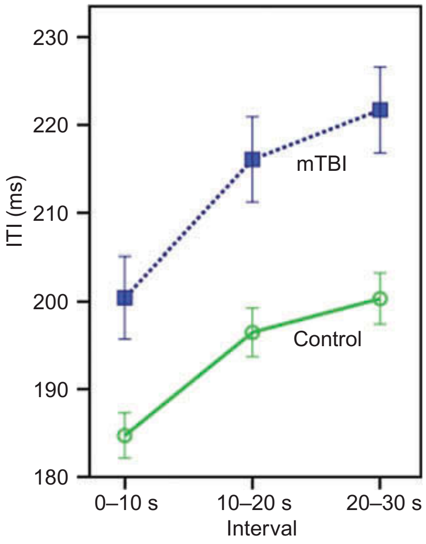

Figure 4. Intertap interval (ITI) over the 30-s testing trial of control ($n = 31$) and mild traumatic brain injury (mTBI; $n = 23$) subjects. To view a color version of this figure, please see the online issue of the Journal.

TRMI scores, $F(1, 56) = .03$, *ns*. However, the TRMI scores of control subjects in malingering conditions (Experiment 3) were significantly greater than those of the TBI patients, $F(1, 75) = 6.43$, $p < .02$, $\eta^2_p = .14$.

Discussion

Consistent with previous studies of mTBI (De Monte et al., 2005; Murelius & Haglund, 1991; Tsushima et al., 2009), we found that mTBI patients had slower tapping rates than matched controls. The TRMI appears to have utility in the mTBI population, identifying one subject who had been flagged as having questionable effort. The fact that most mTBI patients showed normal TRMI scores indicates that while their finger tapping was slowed, they maintained relatively consistent tapping rates throughout the test, showed normal fatigue, and produced normal differences in tapping rates between the dominant and nondominant hand.

Limitations

These four experiments on the CCAB finger tapping test were conducted as part of a larger study to evaluate the reliability and patterns of performance on CCAB tasks by control subjects, TBI simulators, and mTBI patients. As such, there were limitations in data collection due to time restraints. For example, we did not query the malingering subjects to determine whether they malingered on each test (i.e., the finger tapping test): We merely assumed that control subjects with significantly slowed tapping rates were malingering. In addition, although mTBI patients showed the expected low incidence of malingering on the TRMI measure, we did not test them on other standardized malingering/symptom-validity measures. In addition, the mTBI sample was relatively small and heterogenous. A larger sample would strengthen these suggestive findings.

CONCLUSION

Four experiments were conducted using the CCAB finger tapping test: a time-efficient, computerized measure of motor speed. In Experiment 1, control subjects' tapping rates, fatigue, hand dominance, and tapping kinetics replicated the findings from our previous large-scale population sample (Hubel et al., 2013). In addition, middle finger tapping was found to be slightly slower than that of index fingers for each hand. In Experiment 2, the reliability of CCAB finger tapping measures was evaluated over three testing sessions. Use of median ITI measures of tapping rate and the combination of taps plus tap failures resulted in the highest test–retest reliability, which exceeded the test–retest reliability reported for traditional measures of finger tapping in previous tapping studies. Differences due to hand dominance and the ratio of subject's 10 fastest to 10 slowest taps were also highly reliable. Experiment 3 examined finger tapping in subjects instructed to simulate symptoms of TBI. A tapping-rate malingering index (TRMI), independent of tapping rate, was developed based on the 10 fastest versus 10 slowest taps as well as fatigue and hand dominance effects. Of the subjects who demonstrated abnormally slow tapping rates, 48% had abnormal TRMIs—that is, tapping patterns suggestive of malingering. In Experiment 4, tapping-rate differences were found between a group of 24 mTBI patients and matched controls. One mTBI patient was excluded from analysis because he showed signs of reduced effort on other CCAB tests and also produced abnormal TRMI scores. Additional studies with larger samples of combat-TBI patients will be required to further elucidate the motor deficits following mTBI in combat veterans.

Original manuscript received 9 May 2012
Revised manuscript accepted 8 July 2013
First published online 12 August 2013

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