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DUAL-TASK PERFORMANCE IN RIGHT- AND LEFT-HANDED ADULTS: A FINGER-TAPPING AND FOOT-TAPPING STUDY [1,2]

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Summary.—The dual-task paradigm has been used extensively to study laterality, with concurrent verbalization interfering with right finger-tapping in right handers. Only a few studies have used this paradigm to study interference patterns in left handers and have found inconsistent results. The dual-task paradigm has not been used to study interference effects with concurrent verbalization and foot-tapping. The objective of this study was to use this paradigm to assess whether verbal interference produces different effects on finger- and foot-tapping rate for right handers as compared to left handers. 12 right-handed and 12 left-handed men were studied, each with uncrossed hand and foot dominance, i.e., all individuals were either right handed and right footed or left handed and left footed. Subjects performed finger- and foot-tapping tasks with and without verbal interference. A significant relationship was found between handedness and finger- and foot-tapping rate; individuals with a stronger right-hand preference tended to tap at a higher rate on the right side and vice-versa. Analogous relationships were not found when participants were tapping and speaking concurrently. With verbal interference, both right and left handers had a significant asymmetric effect with a decremental response in right finger-tapping rate and a facilitative effect on left finger-tapping rate. In contrast, there was a bilateral decremental response in foot-tapping with verbal interference in both right and left handers. The implications of these findings are discussed with reference to cerebral laterality of language systems and to the differential organization and integration of the motor representations of the hand and the foot.

The dual-task paradigm has been used to investigate lateralized effects of verbal and nonverbal interference on unimanual tasks such as dowel balancing (Kinsbourne & Cook, 1971) and finger-tapping (Dalen & Hugdahl, 1986; Hiscock & Chipuer, 1986; Carlier, Dumont, & Beau, 1993; Dalen, 1993). In general, concurrent verbalization interferes with right-hand finger-tapping in right handers, and in some cases improves performance in the

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nondominant left hand. Kinsbourne and Hicks (1978) proposed a "functional cerebral space" model in which inhibitory interference results from the competition of two activities (manual motor and speech motor) that require access to shared functional units within the left cerebral hemisphere that may be anatomically close or overlapping. Others have suggested that "competition for resources" (Kee, Bathurst, & Hellige, 1984), "hemisphere overload" (Dalby, 1980), or "interhemispheric integration" (Hiscock, Kinsbourne, & Green, 1990; Murphy & Peters, 1994) may contribute to the decreased right finger-tapping with the left hemisphere-activating tasks. It remains unclear as to whether one neural system is associated with interference in manual performance more than another when performing concurrent verbal-motor tasks. Multiple neural systems are involved in producing these behaviors, including motor speech, language, primary and supplementary motor, praxis, and attention.

Although this paradigm has been used extensively to study lateralized behaviors in right handers, left handers have only been included in a few studies and inconsistent results have been reported (for review, Hiscock, *et al.*, 1990). Whereas van Strien and Bouma (1988) found that concurrent verbalization interfered with finger-tapping in the dominant hand in both right and left handers, van Hoof and van Strien (1997) found that only consistent left handers showed this interference effect. Others have found a decremental response in right finger-tapping in right and left handers (Murphy & Peters, 1994). Thus, specific handedness subgroups with different patterns of cerebral laterality for speech, language, and motor systems may have different responses to verbal-manual interference.

Given these variable effects of verbal interference in right versus left handers, it is necessary to define handedness groups precisely. Traditionally, individuals are classified into handedness groups based on one measure, i.e., writing hand, or a combination of measures including writing-hand preference, scores from handedness inventories, and hand-performance measures. In addition to handedness, most individuals prefer one foot for various activities (Porac & Coren, 1981), and there is some evidence that motor systems in individuals with uncrossed hand and foot dominance, i.e., right handed and right footed or left handed and left footed (Elias, Bryden, & Bulman-Fleming, 1998), may be more lateralized than individuals with crossed hand and foot dominance, i.e., right handed and left footed or vice versa (Elias & Bryden, 1997; Elias, *et al.*, 1998). There is also evidence that hand and foot dominance are predictive of ear advantage and speech/language lateralization (Searleman, 1980; Strauss & Wada, 1983; Strauss, 1986; Watson, Pusakulich, Hermann, Ward, & Wyler, 1993; Day & MacNeilage, 1996; Elias & Bryden, 1997), and some of these studies suggest that foot dominance is a better predictor of language lateralization than hand dominance (Searleman, 1980; Strauss, 1986; Watson, *et al.*, 1993; Elias & Bryden, 1997). However, less than 6% of right handers are left footed, whereas 20 to 40% of left handers are right footed (Augustyn & Peters, 1985; Kauranen & Vanharanta, 1996; Elias, *et al.*, 1998). Thus, foot dominance may be more important in language lateralization for left than right handers. To our knowledge, the dual-task interference paradigm has not been used to study interference in both finger- and foot-tapping and to investigate differences between right and left handers in finger- and foot-tapping.

The present study was undertaken to investigate lateralized effects of concurrent verbal interference on right and left finger- and foot-tapping in right and left handers with uncrossed hand and foot dominance. The major goal of this study was to use the dual-task interference paradigm to evaluate effects of hand and foot preference on lateralized tapping rate and to assess possible differences between right and left handers. We predicted that hand preference would be related to asymmetries in tapping speed, with right handers producing more taps with the right than with the left hand and left handers producing more taps with the left than with the right hand, within a given measurement period. If language is lateralized to the left cerebral hemisphere in both right and left handers, then the left hemisphere will be selectively activated in both groups with verbalization, and the number of taps with the right hand will be reduced by verbal interference in both right and left handers. On the other hand, if right handers have language lateralized to the left whereas left handers have language bilaterally or inconsistently lateralized, then verbal interference effects will differ across handedness groups, with right handers having a decremental response with right finger-tapping and the left handers being less consistently influenced by verbal interference. Similar effects may be predicted with foot-tapping and verbal interference, although it may be that neither group has a decremental response with either foot, as the motor representation of the foot is more medially placed along the length of the primary motor cortex than the motor representation of the hand, which is more laterally placed and anatomically closer to motor speech areas. Conversely, given the more medial location of the foot representation, it may also be hypothesized that foot-tapping may activate either contralateral or ipsilateral motor cortex. If this is the case, then decremental responses in both right and left foot-tapping may be observed with verbal interference in both right and left handers.

Method

Subjects

Twenty-four subjects, 12 right-handed and 12 left-handed men, were recruited via word of mouth and advertisements posted in and around Tulane University School of Medicine. As sex differences have been found in manual dexterity, the sample was limited to males to reduce variance within the hand-preference groups (Kauranen & Vanharanta, 1996). The subjects ranged in age from 21 to 52 years old ($M = 28.3$ yr., $SD = 6.3$), and mean education was 17.3 yr. ($SD = 1.4$). There was no significant difference in age or education between left and right handers. All participants were screened to exclude subjects with a history of neurologic or psychiatric disorders, motor deficits, substance abuse, or developmental disabilities.

Materials and Procedure

Handedness and footedness.—Handedness was established using the Edinburgh Handedness Inventory (Oldfield, 1971). All individuals with positive scores on the Inventory were assigned to the Right Handed group and vice versa. Footedness was measured by asking subjects which foot would be used to kick a ball and which foot would move first when initiating gait. Behavioral measures of hand and foot preferences were also obtained to confirm correct group assignment. Specifically, subjects were observed while writing, throwing a ball, kicking a ball, and initiating gait. If for any subject hand or foot used for these behaviors did not match the hand or foot preferences obtained via survey items, the subject was excluded. Uncrossed lateral preferences (right handed and right footed or left handed and left footed) were required for inclusion in the study. Subjects who had crossed lateral preference, e.g., a subject who was right handed and left footed, were excluded.

Finger-tapping and foot-tapping tasks.—The finger-tapping test was administered in three steps: instruction and demonstration of the test, a 10-sec. practice trial for each hand to become familiar with the equipment, and administration of the test. The finger-tapping device consisted of two fixed push-button counters spaced 10 in. apart on a board. The subject was instructed to "place your index fingers on the levers, resting the base of your palm and your other fingers on the board at all times. To count for a full tap iteration, you must push the lever all the way down and release it all the way up for it to change your counter number." If the finger tap included wrist movement instead of finger movement only, the correct motion was demonstrated.

Under two conditions, Baseline (without interference) and Verbal Interference, finger-tapping tasks were performed with the right and left hands separately, with three 15-sec. trials per condition. To establish Baseline performance, each subject tapped with the right and left hand, without interference. For the Verbal Interference tasks, each subject tapped with the right or left hand while repeating the words "wolf, butterfly, duck" aloud throughout the 15-sec. trial. The subject attempted to tap as many times as possible within the timed interval. The subject was given a 15-sec. rest interval between trials to prevent fatigue. Task order was randomized across subjects.

The foot-tapping dexterity test was performed analogously to the finger-tapping test. The subject was instructed to sit in a chair, resting the ball of the foot on the ground with the feet shoulder width apart. The subject was instructed to raise the ball of the foot as much as possible while keeping the heel on the floor and then to place the foot flush to the floor for a complete foot-tapping cycle. The subject was given a 10-sec. interval for each foot in which to practice this motion and, if the motion was performed incorrectly, was stopped and instructed on the correct motion. The subject performed this task under the same conditions as done for finger-tapping: Right and Left foot-tapping for both Baseline (without interference) and Verbal Interference (while saying "wolf, butterfly, duck") conditions. The experimenter counted foot taps as they occurred; no counting apparatus was used for measuring foot taps.

Scoring.—The variables of interest were Interference, Hand Preference, Finger-tapping Rate for both hands, Foot-tapping Rate for both feet, and Laterality Quotients for both hands and feet. Interference was a dichotomous variable with Baseline and Verbal Interference. Hand preference was scored both along a continuum using the score obtained from the Edinburgh Handedness Inventory (Oldfield, 1971) and as a grouping variable with two levels, Left Handed and Right Handed. The number of finger or foot taps from the three 15-sec. trials per performance task were averaged to yield the final scores for the two tasks: Finger-tapping Rate and Foot-tapping Rate. Laterality Quotients were calculated for each condition using the formula $100 \cdot \left(\frac{\text{Right} - \text{Left}}{\text{Right} + \text{Left}}\right)$, where "Right" and "Left" referred to a participant's right- and left-side tapping speeds, respectively.

Results

The hypotheses of interest were that (1) Tapping Rates were predicted to be directly related to hand preference, with preference and performance advantages tending to be lateralized in the same direction, i.e., leftward or rightward, within an individual and (2) For the Right-handed group, right-side Tapping Rates were predicted to be lower for the Verbal Interference condition than for the Baseline condition, and this difference was expected to be greater than the analogous difference for left-side Tapping Rates. Competing hypotheses were proposed for the left-handed group. If language is lateralized to the left in Left Handers then, as was predicted for Right Handers, right-side Tapping Rates will be lower with Verbal Interference than for Baseline. However, if language is lateralized to the right or bilaterally represented in Left Handers, then Verbal Interference effects will be expected to vary across Hand-Preference groups.

Both questions were first addressed by examining the intercorrelations between Edinburgh Handedness Inventory scores and Laterality Quotients. As can be seen in Table 1, both the Finger-tapping and Foot-tapping Laterality Quotients were significantly correlated with Edinburgh Handedness Inventory scores ($r = .48$, $p < .05$ and $r = .41$, $p < .05$, respectively). In other words, individuals with high Edinburgh Handedness Inventory scores (indicating right-hand preference) tended to have high laterality quotients (indicating Right-Hand Finger-tapping Rates were higher than Left-Hand Finger-tapping Rates), and vice-versa. However, analogous relationships were not found when participants were tapping and speaking concurrently. For the Verbal Interference condition, no significant relationships between Edinburgh Handedness Inventory and Tapping Laterality Quotients were found.

TABLE 1
INTERCORRELATIONS AMONG HAND PREFERENCE AS ASSESSED VIA THE EDINBURGH HANDEDNESS INVENTORY AND FINGER- AND FOOT-TAPPING LATERALITY QUOTIENTS BY INTERFERENCE VARIABLE, BASELINE, AND VERBAL INTERFERENCE

Edinburgh Score (Laterality Quotient)	Edinburgh Handedness	Laterality Quotients			
		No Interference		Verbal Interference	
		Finger	Foot	Finger	Foot
Finger-tapping, Baseline	.48*				
Foot-tapping, Baseline	.41*	.23			
Finger-tapping, Verbal Interference	.38	.82†	−.02		
Foot-tapping, Verbal Interference	.16	−.28	.25	−.32	

*$.01 \le p < .05$. †$p < .01$.

In the following analyses, Finger-tapping Rates and Foot-tapping Rates were examined to assess whether Left Tapping Rates, Right Tapping Rates, or both varied across levels of the Interference variable. Tapping Rate data were analyzed via two three-way mixed analyses of variance with Interference (with levels Baseline and Verbal Interference) and Tapping Side (with levels Left and Right) as repeated-measures factors and Hand Preference (with levels Left Handed and Right Handed) as a grouping factor. Separate analyses were conducted for dependent variables Foot-tapping Rate and Finger-tapping Rate. Means and standard deviations for Finger-tapping Rate and Foot-tapping Rate are shown for all conditions in Table 2. Performance laterality and Verbal Interference effects are shown using mean Laterality Quotients and mean change in Tapping Rates associated with Verbal Interference. However, all analyses were conducted on raw Tapping Rates (averaged across three 15-sec. trials).

The Finger-tapping Rate analyses are discussed first. There was no significant main effect of Hand Preference on Finger-tapping Rate, and this variable did not participate in any significant interactions. There was a significant relationship between Tapping Side and Finger-tapping Rate, and

TABLE 2
FINGER- AND FOOT-TAPPING RATES FOR ALL CONDITIONS EXAMINED

Task	Hand Preference	Side	Interference Condition					
			Baseline		Verbal Interference		Difference	
			M	*SD*	*M*	SD	*M*	*SD*
Finger Tapping	Right-handed	Right	68.70	6.45	67.04	6.02	−1.66	3.00
		Left	67.94	8.30	69.66	9.84	1.72	3.59
		LQ	.69	3.88	−1.66	4.50		
	Left-handed	Right	66.16	7.41	65.52	8.94	− .64	3.72
		Left	69.49	6.54	70.18	6.81	.69	4.39
		LQ	−2.56	4.70	−3.66	5.42		
Foot Tapping	Right-handed	Right	51.78	5.86	45.58	5.54	−6.21	3.94
		Left	47.90	5.53	45.35	4.37	−2.55	3.49
		LQ	3.90	4.03	.13	3.29		
	Left-handed	Right	50.22	4.91	47.80	4.54	−2.42	5.20
		Left	50.40	5.29	48.53	3.01	−1.88	4.00
		LQ	− .17	2.71	− .87	4.73		

Note.—Scores indicate the mean Tapping Rate averaged across three 15-sec. trials. The column labeled "Difference" shows the mean change in Tapping Rate associated with the presence of Verbal Interference (Verbal Interference − Baseline). The final row for each Hand Preference group shows Laterality Quotients (LQ). Total $N=24$; $n=12$ for each hand preference group.

this relationship varied significantly across levels of the Interference variable ($F_{1,22}=8.13$, $p<.01$). Specifically, mean Right-Hand Tapping Rate was lower with Verbal Interference ($M=66.28$, $SD=7.49$) than for Baseline ($M=67.43$, $SD=6.91$), while the converse was true for the left hand. Mean Left-Hand Tapping Rate was higher with Verbal Interference ($M=69.92$, $SD=8.28$) than for Baseline ($M=68.71$, $SD=7.35$). There were no other significant main effects or interactions for the Finger-tapping Rate analysis.

What follows are results for the dependent variable of Foot-tapping Rate. Across levels of the Tapping Side and Hand-Preference variables, Foot-tapping rates were lower with Verbal Interference than for Baseline ($F_{1,22}=19.99$, $p<.0005$), and this relationship was significantly modified by Tapping Side; specifically, the difference in mean Foot-tapping Rate between Baseline and Verbal Interference conditions was greater for the Right foot ($M=51.00$, $SD=5.35$ vs $M=46.69$, $SD=5.08$, respectively) than for the Left foot ($M=49.15$, $SD=5.44$ vs $M=46.94$, $SD=4.01$, respectively; $F_{1,22}=5.38$, $p<.05$).

For Foot-tapping Rates, Left Handers and Right Handers did perform significantly differently; the relationship between Tapping Side and Foot-tapping Rate varied significantly across Hand-Preference groups ($F_{1,22}=4.65$, $p<.05$). While both Hand-Preference groups obtained higher mean Foot-tapping Rate when tapping with the dominant foot than with the nondominant foot, the difference between Left and Right Foot-tapping Rates was significantly larger in Right Handers ($M=46.62$, $SD=5.04$ vs $M=48.67$, $SD=6.42$, respectively) than in Left Handers ($M=49.47$, $SD=4.32$ vs $M=49.01$, $SD=4.79$, respectively), apparently owing to low mean Foot-tapping Rate for the Right Handers when using the Left Hand.

In summary, Verbal Interference was associated with reduced Finger-tapping Rate in the Right hand but increased Finger-tapping Rate in the Left hand. Foot-tapping Rates were lower in the presence of Verbal Interference and significantly more for the right foot than the left. Finally, Left Handers' mean Right and Left Foot-tapping Rates were higher than those of Right Handers, and this difference was significantly larger in the left foot than the right foot.

Discussion

Kinsbourne and Hiscock (1983) have explained the interference effects produced by the dual-task paradigm by means of the cerebral distance model. This model purports that, when two tasks, e.g., speaking and right-hand tapping, activate brain regions that are anatomically close and show high neural interconnectivity, then neural demands associated with performing one of the tasks will necessarily interfere with concurrent performance of the other task. For example, right-hand motor performance may be slower in the presence of concurrent speech because speech and right-hand motor performance involve shared neural substrates. These interference results have been replicated in many studies (for review, Hiscock & Chipuer, 1986; Hellige & Kee, 1990), but variable responses have been found for left handers (van Strien & Bouma, 1988; Bathurst & Kee, 1994; Murphy & Peters, 1994; van Hoof & van Strien, 1997). In the present study, effects of concurrent verbalization were studied in right- and left-handed males with Hand and Foot Preferences lateralized to the same side to investigate whether activation of the left cerebral hemisphere due to a verbal task produced a decremental response in Right-side Finger-tapping Rate in both Hand-Preference groups or whether the dual-task paradigm had different effects in Right and Left handers. Asymmetric interference was observed in both Right and Left handers, as verbal interference was associated with a decrease in Right-hand Finger-tapping Rate and an increase in Left-hand Finger-tapping Rate. These results suggest that the left cerebral hemisphere was selectively activated by verbalization in both Right and Left handers. While at Baseline the preferred hand tapped faster than the nonpreferred hand for both Right and Left handers, verbal interference was associated with a decrease in Right-hand Finger-tapping Rate for both groups. There is considerable evidence that language functions are lateralized to the left cerebral hemisphere in most right and left handers, although the proportion of left handers with left hemispheric language dominance is reduced relative to right handers. Estimates from direct and indirect behavioral studies of language laterality suggest that about 90 percent of right handers have language lateralized to the left, compared to 70 percent of left handers (for review, Hellige, 1993; Foundas, Leonard, & Heilman, 1995). Our data are consistent with the notion that verbalization activated the left hemisphere in Right and Left handers, as interference was seen with Right- but not Left-hand Finger-tapping Rate in both groups.

These findings offer support for Kinsbourne's functional model of cerebral space and replicate in part the findings of Murphy and Peters (1994), although other models may also explain our findings. For example, allocation of resources and limited attentional capacity may be contributing to the observed effects, especially with the facilitation of Left Finger-tapping Rate and the decrease in Right Finger-tapping Rate with concurrent verbalization. Murphy and Peters argued that task integration may be more important than interference when explaining these types of reciprocal interactions. It may be that our findings can be explained by a combination of interference due to an overload of demands for processing resources within the left cerebral hemisphere, and interhemispheric integration with the release of inhibition of the right hemisphere.

The relationship between verbal interference and Foot-tapping Rates was different from the effects observed on Finger-tapping Rates. There were no facilitation effects of verbal interference on foot-tapping, i.e., Foot-tapping Rates for both feet were lower in the presence of verbal interference than at baseline. Although the effect was bilateral, there was a larger decrement in Right Foot-tapping Rate than in Left Foot-tapping Rate, as evidenced by the significant interaction for Tapping Side by Verbal Interference discussed in the results section. Given the somatotropic representation of the limbs along the length of the motor cortex (Penfield & Boldry, 1937), distal unilateral foot movements are more dependent on input from both contralateral and ipsilateral hemispheres and the integration of bilateral motor systems, whereas distal unilateral hand movements are more exclusively dependent on contralateral motor systems (Penfield & Boldry, 1937; Brinkman & Kuypers, 1973; Hellige, 1993; Gabbard & Hart, 1996). The different cerebral control mechanisms for distal hand and distal foot movements may explain the different effects of verbal interference on Finger- and Foot-tapping Rates. Distal foot movements are more dependent on interhemispheric processing, thus the integration model may explain these findings (Hiscock, *et al.*, 1990; Murphy & Peters, 1994). Specifically, the left hemisphere involvement in both right and left foot movement may explain the bilateral reduction in foot-tapping rate caused by verbal interference, i.e., the absence of facilitation for Left-side Finger-tapping Rates.

The issue of "footedness" requires additional comment, and the assessment of "true footedness" based on preference and performance measures requires further study. Foot-performance measures, e.g., foot tapping, have not been widely used, and there are limited data comparing finger-tapping with foot-tapping as laterality measures (Augustyn & Peters, 1985; Kauranen & Vanharanta, 1996; Elias & Bryden, 1997; Elias, *et al.*, 1998). Of note, extent of handedness was significantly correlated with both Finger- and Foot-tapping Rates. Individuals with a strong right-hand preference had a right-sided tapping advantage and vice-versa. However, there was no significant correlation between finger-tapping and foot-tapping, and no significant relationships were found between extent of handedness and tapping with verbal interference. Further study is needed to consider whether unilateral hand and foot preference is an important factor when evaluating lateralized motor and speech-language functions. Of note, our sample was limited to individuals with hand and foot preferences on the same side, which may explain the differences in our data compared to other studies in which left handers or subgroups of left handers have shown reduction in Left Finger-tapping Rate associated with verbal behavior rather than the increase observed in the present study (Orsini, Satz, Soper, & Light, 1985; Simon & Sussman, 1987; van Strien & Bouma, 1988; van Hoof & van Strien, 1997). Gabbard and Hart (1996) have proposed that most footedness tasks are framed in a bilateral context; specifically, tasks require one limb for mobility and one limb for stability. From their review of footedness inventories, the mobilizing limb is the preferred (dominant) foot, and the stability limb is the nondominant foot. The task of kicking a ball, one of the initial inventory tasks employed in this study, is typically recognized as the predominant test of "foot dominance" (Gabbard & Hart, 1996). However, it is unclear whether foot performance, as employed in this study, may be a better predictor of foot laterality than measures from an inventory. Environmental "practice" may be less a confound in the lower extremity than the upper extremity, although the opposite effect can also be argued, as the most commonly performed foot task, walking, requires the integrated performance of both feet and reciprocal activation of the right and left motor systems.

One practical concern about the present study involves the mean education of the sample. With a mean of 17.3 yr. of education, some postgraduate education was typical of our sample, with many subjects being graduate students and medical students. We have no reason to suspect that the relationship between hand preference and lateralization-based verbal interference in motor performance would be dependent upon education; however, it is possible that in addition to education, our sample may also be different from the general population in ways that could affect motor or verbal behavior. The study should thus be replicated with samples more closely approximating the educational norms of the general population.

A second concern is that speech-rate data were not collected in this study. The theoretical bases of the prediction that concurrent speech would interfere with Right Finger-tapping Rate also would suggest that Right Finger-tapping Rate would interfere with speech production. Speech was not measured in this study; therefore, we were unable to examine whether tapping rate interfered with speech rate. Speech data should be collected within a dual-task paradigm in future studies.

Finally, it is worth noting that the differing pattern of results seen for Finger- and Foot-tapping Rates may be a function of the type of motor control associated with each task. Specifically, finger-tapping requires relatively fine motor control, whereas foot-tapping requires relatively gross motor control. Inclusion of a hand-tapping measure (involving wrist rather than knuckle movement) would allow study of whether the differences between finger- and foot-tapping are associated with type of motor control needed to complete the task.

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