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Experience-Dependent Effects in Unimanual and Bimanual Reaction Time Tasks in Musicians

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ABSTRACT. Engaging in musical training has been shown to result in long-term cognitive benefits. The authors examined whether basic cognitive–motor processes differ in people with extensive musical training and in nonmusicians. Musicians (n = 20) and nonmusicians (n = 20) performed a simple reaction time (RT) task under unimanual and bimanual conditions. Musicians' RTs were faster overall than were those of nonmusicians, and those who began their musical training at an earlier age (around age 7–8 years, on average) exhibited a larger bimanual cost than did those who began later (around 12 years, on average). The authors conclude that experience-dependent changes associated with musical training can result in greater efficacy of interhemispheric connections if those changes occur during certain critical periods of brain development.

Key words: bimanual coordination, bimanual planning, corpus callosum, musicians, plasticity

In the behavioral literature on bimanual coordination, comparisons of performance between unimanual and bimanual conditions during repetitive movements have been studied capaciously (Franz, 2000a, 2000b, 2003; Franz, Ivry, & Helmuth, 1996; Helmuth & Ivry, 1996; Ivry & Hazeltine, 1999). In direct contrast, studies of the level of attention paid to bimanual coordination in discrete tasks are noticeably subordinate, and thus the principles and mechanisms that underlie the ability to synchronize and regulate simple movements are poorly understood. Previous work in simple reaction time tasks has demonstrated that individuals take longer to plan and enact a response in bimanual conditions than they do in unimanual conditions. For example, Shen and Franz (2005) used a discrete speeded response to a centralized stimulus and found that the time required to plan and perform a bimanual response was longer than was the time necessary in unimanual conditions. That finding has been reported in a variety of experimental situations and is seemingly independent of task requirement and stimulus type (Di Stefano, Morelli, Marzi, & Berlucchi, 1980; Kerr, Mingay, & Elithorn, 1963; Ohtsuki, 1981; Shen & Franz; Steenbergen, Hulstijn, de Vries, & Berger, 1996). Although sometimes referred to as a *bilateral deficit*, in the present article we use the term *bimanual cost*, given that the word *deficit* can have different implications. In addition to the bimanual cost, Shen and Franz found that the average time difference in responses of the two hands is actually smaller in the bimanual condition (suggesting high temporal coupling) than in unimanual conditions.

Although it has become common practice to investigate planning and movement-related psychological and neural mechanisms in individuals with cognitive disorders, individuals with advanced musical experience are another exemplar group in which researchers can examine cognitive functions. Engaging in musical training has been shown to result in long-term visuospatial, verbal, and mathematical cognitive benefits in children, as well as in an assortment of auditory and fine motor skills. Those benefits may be attributed to years of practice at integrating the limbs in a coordinated fashion, and it is thought that any differences in performance levels result from experience and practice rather than from inherent cognitive differences (Ericsson, Krampe, & Tesch-Römer, 1993; Sloboda, Davidson, Howe, & Moore, 1996). Precise operations or cognitive components that underlie those effects have not

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been elucidated, however. With respect to the motor domain, neuroanatomical and physiological data support the supposition that experience from playing a musical instrument results in superior bimanual coordination (Ridding, Brouwer, & Nordstrom, 2000; Schlaug, 2001). Our primary purpose in the present study was to directly examine unimanual and bimanual differences in reaction time between musicians and nonmusicians to elucidate whether differences can be found on a very basic cognitive–motor variable: simple reaction time. Although musical training only sometimes involves speeded responses to stimuli (as, e.g., in the case of sight-reading, particularly with fast-paced musical styles), we hypothesized that the visuomanual process of responding to a visual stimulus is one basic cognitive operation that is influenced by extended training with musical instruments.

We attribute the longer reaction times (RTs) on bimanual than on unimanual responses of normal participants to a form of callosally mediated mutual inhibition of the two cerebral hemispheres when both are activated in a task. The mutual inhibition influences bimanual but not unimanual responses, given that there is ultimately only one response in the unimanual case (Shen & Franz, 2005). Convergent support for that model comes from studies in which the initiation of movement has been shown to simultaneously activate both the left and right motor cortices, resulting in inhibition of the antagonist transcallosal pathway (see also Ohtsuki, 1994). The role of callosal connections in mediating interhemispheric inhibition has also been inferred from studies in which magnetic stimulation over the motor cortex was used (Di Lazzaro et al., 1999; Ferbert et al., 1992; Salerno & Georgesco, 1996). Results of recent research on plasticity in concert pianists demonstrated increases in myelination of fiber tracts of the corpus callosum in participants who began playing piano at a mean age of 5.8 years, a time when the corpus callosum is engaged in a rapid procession of maturation (Bengtsson et al., 2005). On the basis of that result, we hypothesized that people who begin learning a musical instrument at a younger age (as opposed to later in life) should show an exaggerated bimanual cost because of increased myelination of the callosal fibers that mediate the mutual inhibition underlying the effect. In other words, in a comparison between a sample of musicians with early onset of musical training and a sample of musicians with late onset of musical training, the earlier group should show a larger bimanual cost.

Another facet of bimanual coordination that has garnered recent attention is the influence of handedness on response times and hand lead. Results of previous research have demonstrated that, on average, the dominant hand tends to lead the nondominant hand in continuous mirror-symmetrical bimanual tasks (Amazeen, Amazeen, Treffner, & Turvey, 1997; Franz, 2004a; Franz, Rowse, & Ballantine, 2002; Swinnen, Jardin, & Meulenbrock, 1996; Treffner & Turvey, 1996; Wuyts, Summers, Carson, Byblow, & Semjen, 1996). However, hand dominance does not necessarily determine which hand leads in bimanual movements, particularly when the coordination mode does not involve mirror-symmetrical movements of the two hands (Franz, 2004b; Franz et al., 2002). Shen and Franz (2005) found, using a discrete RT task to a centralized stimulus, that, on average, in right-hand-dominant individuals, the right hand responded before the left hand 69% of the time, whereas in left-handers, the dominant hand led only 48% of the time. They proposed a hemisphere-competition model that is based on differential response activation in the two cerebral hemispheres to account for those hand-lead effects. The model builds on the commonly accepted assumption that right-handers are left-hemisphere dominant, although the precise reasons for that pattern of dominance are not known. One possibility is that the left hemisphere has a lower threshold for response activation than does the right hemisphere in right-handers, thereby making the right hand more likely to respond first when both hemispheres are involved (see also Miller & Franz, 2005). Examining people with extensive practice on bimanual coordination tasks, such as skilled musicians, therefore also affords an opportunity to examine whether extensive experience on skills that involve bimanual temporal coupling may influence the balance between the two hemispheres when the two are required for simultaneous responding.

Method

Participants

Ten right-handed pianists and 10 right-handed guitarists comprised the musician group in this study (14 men, 6 women; age range = 18–24 years, $M = 19.9$ years, $SD = 1.9$ years). All pianists had played for an average of 11.95 years, with approximately 3.6 hr of practice per week; and guitarists had played for an average of 8.4 years, with about 5.3 hr of practice per week. Moreover, our group of musicians started their musical training at varying ages, making it possible for us to divide it into early and late commencement groups to test our more specific hypotheses. We assessed handedness by using the Edinburgh Handedness Inventory (Oldfield, 1971). Based on hand preferences given on a battery of common tasks on the inventory, handedness scores for the musicians ranged from .1 to 1.0 with a mean of .65 (SD = .26) on a scale ranging from –1.0 (*strongly left-handed*) to 1.0 (*strongly right-handed*).

Twenty naive participants (age = 20.4 years) served as controls. Those individuals had never played a musical instrument; nor had they received any musical training beyond that associated with normal school education. Based on the Edinburgh Handedness Inventory (Oldfield, 1971), handedness scores for controls ranged from .40 to .90 with a mean of .66 (SD = .15). The ethics committee of the University of Otago approved the study. Informed consent was obtained from all participants before testing, and each participant received $10.50 as reimbursement for their time.

Apparatus

RTs for the left and right hands in both the unimanual and bimanual conditions were measured on a personal computer enabled with millisecond timing routines that used Pascal. The visual stimuli appeared on a 14-in. computer monitor. A fixation point (1 cm × 1 cm on the screen) was presented on each trial, followed by a green dot (1.5 cm in diameter) in the center of the monitor on each trial. Following precise procedures of Shen and Franz (2005), we asked participants to respond at the appearance of the green dot by pressing one response key on unimanual trials and both response keys on bimanual trials.

Design

The experiment consisted of three conditions: (a) left hand alone (unimanual left), (b) right hand alone (unimanual right), and (c) both hands together (bimanual). We ran each of the three condition types three times to make nine fully randomized blocks, except for the constraint that no two identical blocks should ever occur consecutively. Within each of the nine blocks, there were 36 trials, yielding a total of 324 responses.

Procedure

Participants sat on a height-adjustable chair in front of the table, with the computer monitor 57 cm away. We asked them to rest their hands on a response board, with the left index finger on the left response key and the right index finger on the right response key. For the unimanual conditions, they used only one index finger and the other hand rested on their lap. The response board was situated in front of midline so that the left hand produced responses in the space just left of midline (by approximately 4 cm) and the right hand produced responses in the space approximately 4 cm to the right of midline. Participants' arms were bent at the elbows, so they used only the fingers to respond. Because the condition varied from block to block, we reminded participants about which hand or hands to use at the beginning of each trial block.

At the onset of the trial, a white fixation cross on a black background was displayed in the center of the monitor. After a variable forewarning period that ranged from 500 to 1,000 ms (during which the fixation cross remained on), a green dot (1 cm in diameter) appeared and remained on the screen for 1,200 ms or until participants responded, whichever came first. Following the response in the unimanual trials, or the second of two responses during bimanual trials, an intertrial interval of 1,000 ms occurred before the next trial. We emphasized speed of responding, but we warned participants not to respond before seeing the green dot. The experimenter monitored all participants for the entire testing session.

An experimental session began with 36 practice trials of each condition. The experiment took approximately 40 min per participant. We debriefed participants after all nine blocks had been tested.

Data Analysis

Before data analysis, we excluded RTs that were less than 100 ms or exceeded 450 ms from further analysis. The total number of rejected trials included 2.6% of the data, and those were approximately equally distributed across condition types and participants.

We computed mean RT and standard deviation of RT (*SD*RT) for each hand. We computed *SD*RT as a within-participants measure across trials, and we then averaged it across participants. In addition, we computed the between-hands RT difference and the absolute value of the between-hands RT difference for bimanual trials. We calculated on each trial the signed between-hands RT difference by subtracting the left-hand RT values from the right-hand RT values and then averaging across trials. Faster left-hand RTs were indicated by positive values, and faster right-hand RTs were indicated by negative values on the signed RT differences. We computed the absolute value of the RT difference on a trial-by-trial basis as a measure of the magnitude of the hand lead or the degree of synchronization of the two hands. That calculation involved computing the absolute value of the between-hands RT difference on each trial and then averaging across trials. A large value indicated that the performance of the two hands was not in close synchrony. In contrast, a value close to zero indicated a tight coupling between the two hands.

Results

We conducted a 2 × 2 × 2 mixed effects analysis of variance (ANOVA) on overall mean RTs and on *SD*RT to assess differences between the two groups (musicians, nonmusicians) and the within-participants variables condition (unimanual vs. bimanual) and hand (left, right). We assessed only the group effects for the bimanual variables alone.

Consistent with Shen and Franz (2005), there was a significant main effect of condition on RT, revealing longer RTs for bimanual than for unimanual responses, $F(1, 38) = 6.795$, $p = .013$. We noted no indication of a Condition × Group interaction in that effect, $F(2, 27) < 1.00$. In fact, all two-way interactions yielded $F < 1.00$, and higher order interactions were not close to being significant (all p values were greater than .17). Despite the overall slower mean RTs in bimanual than in unimanual responses, *SD*RT was significantly smaller for bimanual than for unimanual conditions for both groups, $F(1, 38) = 4.193$, $p = .048$. As in the mean RT, there was no hint of a Condition × Group interaction in that effect. The mean RTs and *SD*RTs are shown in Table 1. As can be seen by viewing the mean values, there was a near-significant three-way interaction in *SD*RT in which the nonmusicians produced an apparently exaggerated variance in unimanual right-hand responses compared with those in all other conditions, $F(1, 38) = 4.097$, $p < .06$. In addition, musicians produced less variance overall than nonmusicians did, $F(1, 38) = 8.246$, $p = .007$.

TABLE 1. Mean Reaction Time and Standard Deviation (in ms) for Each Hand in Unimanual and Bimanual Conditions in Musicians and Nonmusicians

	Unimanual				Bimanual			
	Left hand		Right hand		Left hand		Right hand	
Group	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Nonmusicians	246	59	245	72	251	57	249	58
Musicians	213	51	216	50	219	46	219	46

A highly significant overall difference in RT revealed that the musicians responded faster, on average, than did the nonmusicians, $F(1, 38) = 15.44$, $p < .001$. In addition, *SD*RT was smaller for musicians than for nonmusicians, $F(1, 38) = 5.20$, $p < .05$. Planned contrasts revealed that there were no significant differences between the trained guitarists and pianists on either of those effects on RT; both $Fs(1, 18) < 1.00$.

Of specific importance, when we analyzed the data of our musicians on the basis of an early start (mean age at start of musical training = 7.75 years) versus a late start (mean age at start of musical training = 12.1 years), we found a significantly larger bimanual cost in the early-start group compared with that of the late-start group, $F(1, 18) = 4.17$, $p = .04$.

Mean signed and absolute RT differences and percentage lead for each hand on bimanual trials are shown in Table 2. There were no group differences that showed any hint of a reliable difference; all $Fs(1, 38) < 1.00$.

Discussion

The pattern of results across participants revealed three findings of primary importance. First, we found overall faster unimanual and bimanual RTs and smaller variability in musicians than in nonmusicians, suggesting that musical experience reduced the level of cortical inhibition. The reduction in inhibition may influence both unimanual and bimanual movements. That finding may reflect adaptations to innate cognitive mechanisms, such as cortical inhibition, resulting from skill-related experience associated with musical training (Brochard, Dufour, & Despres, 2004). The finding illustrates that although our task was not musical in nature, musical training is correlated with an increase in speed and reduction in variability of the processes associated with simple RT. Although we cannot be certain that our effects on RT were related directly to other effects on reorganization, it is intriguing that results of previous research have illustrated functional and anatomical reorganization in brain motor areas in musicians compared with those of nonmusicians (Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Pantev, Engelien, Candia, & Elbert, 2001; Schlaug, Jäncke, Huang, Staiger, & Steinmetz, 1995).

Second, consistent with our hypothesis and with previous studies, bimanual RTs were generally longer than were unimanual RTs (Di Stefano et al., 1980; Kerr et al., 1963; Ohtsuki, 1981; Shen & Franz, 2005; Steenbergen et al., 1996). We attribute the bimanual cost to a form of callosally mediated mutual inhibition. Thus, in movements in which both hands have to respond as quickly as possible to a central stimulus, the proposed mutual inhibition slows bimanual responses, compared with its effects on unimanual responses, and is present in musicians and nonmusicians.

Of corollary interest was the degree of coupling between the limbs during bimanual movements. Because the process of learning a musical instrument involves moving both limbs in a coordinated fashion, we hypothesized that musicians would show greater levels of temporal coupling than would nonmusicians during bimanual conditions. However, our data indicated that that was not the case. Perhaps the reason for the difference between our expectation and our results relates to how the present task differs from the act of playing a musical instrument. It would seem that any enhanced coordination evident in musical performance is likely a result of extensive practice of motor sequences and skills (Meister et

TABLE 2. Mean and Standard Deviations of Signed and Absolute Reaction Time Differences (dif.) and Percentage of Bimanual Trials Characterized by a Left- or Right-Hand Lead, for Each Group

	Signed RT dif.		Absolute RT dif.		Left lead	Right lead
Group	*M*	*SD*	*M*	*SD*	*M*	*SD*
Nonmusicians	−1.00	11.01	14.48	1.56	53%	47%
Musicians	0.55	8.45	15.81	2.07	44%	55%

al., 2005; Repp, 1996). Thus, it is possible that closer temporal coupling may occur on movements produced within a musical context or under other continuous conditions in which feedback processes may play a role. Comparisons of performance between unimanual and bimanual conditions in repetitive tapping (Franz et al., 1996; Helmuth & Ivry, 1996; Ivry & Hazeltine, 1999) have provided support for that view, illustrating that temporal consistency for each hand improves during continuous bimanual tapping as compared with those changes during continuous unimanual tapping. The smaller variance in bimanual trials compared with that in unimanual trials in the present RT task again suggests that bimanual responses are more stable overall. It seems reasonable to suggest that a more symmetrical system (e.g., bimanual) would also be less variable, and that notion is also consistent with the smaller degree of variance in the musicians than in the nonmusician group, given that musicians would be expected to have more extensive training in bimanual stability. However, the reductions in variability in the bimanual condition in comparison with that in unimanual conditions did not likely result from integration of timing signals, as has been suggested for continuous tapping (given that speeded RT tasks do not involve explicit timing). Rather, the smaller bimanual variance in the present RT task was likely a consequence of the integration of motor output signals.

Of additional importance is that when we grouped the musicians on the basis of the age, they began musical training, those who began their musical training at an earlier age (around age 7–8 years, on average) demonstrated a larger bimanual cost than did those who began later (around 12 years, on average). It is well documented that the corpus callosum undergoes a rostral–caudal growth wave (Thompson et al., 2000) and is one of the last neural networks to complete myelination (Farber & Knyazeva, 1991; Giedd et al., 1996; Pujol, Vendrell, Junque, Marti-Vilalta, & Capdevila, 1993; Yakovlev & Lecours, 1967). Moreover, in research on plasticity, investigators have recently found that musical training coupled with high rates of maturational growth of white matter tracts may lead to increased myelination (Bengtsson et al., 2005). Consistent with neuroanatomical findings, we suggest that the larger bimanual cost in the early-start group may have resulted from greater efficacy of the callosal fibers that mediate the mutual inhibition in bimanual responses. The behavioral evidence supports the proposal that commencing musical training at a critical period of callosal development can induce plastic changes.

In summary, it is well known that extensive musical training results in long-term enhancement of visuospatial, verbal, and mathematical performance in children (e.g., Bilhartz, Bruhn, & Olson, 2000; Costa-Giomi, 1999) and can also elicit structural and functional differences in the brains of adult musicians. Consistent with that finding were the group differences we found on overall RT, with faster RTs for musicians than for nonmusicians, and an increased bimanual cost in individuals who began musical training at a younger age. Our inability to find effects on specific bimanual variables suggests that extensive musical training affects speed of reactions in simple bimanual RT conditions, but we found no evidence to suggest that musical training has the potential to bring about changes in hemispheric dominance. Novel to this study in terms of behavioral reports are our findings related to the comparison of early and late onsets of musical training. We posit that experience-dependent changes as a consequence of musical training can result in greater efficacy of interhemispheric connections if those changes occur during certain critical periods of brain development.

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