LATERALITY, 2010, 15 (4), 385–414

Psychology Press
Taylor & Francis Group

The relation between lateralisation, early start of training, and amount of practice in musicians: A contribution to the problem of handedness classification

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This study investigates the influence of extensive bimanual training in professional musicians on the incidence of handedness in the most basic form of right-handedness (RH) and non-right-handedness (NRH), according to Annett's "right shift theory". The lateralisation coefficients (LCs) of a total sample of 128 bimanually performing music students were calculated for speed, regularity, and fatigue of tapping by using the speed tapping paradigm. Additionally, the accumulated amount of practice was recorded by means of retrospective interviews. The proportion of designated right-handers (dRH) and non-right-handers (dNRH) in hand performance was identified by binary logistic regression from LCs. A proportion of 30.8% designated NRH in the group of musicians was found, while in the control group of non-musicians (matched for age range) a proportion of 21.7% designated NRH was observed. Incidence of dNRH was higher in string players (35.6%) than in pianists (27.1%). As an effect of the extensive training of the left hand, tapping regularity increased and tapping fatigue decreased among those participants who evidenced an increased amount of accumulated practice time on the instrument. However, speed difference between hands (as indicated by LCs) remained uninfluenced by bimanual training. This finding is in contrast to those of Jäncke, Schlaug, and Steinmetz (1997). Finally, our study provides a more reliable (statistical) classification as an external criterion for future genetic analyses of handedness.

Keywords: Music performance; Handedness classification; Laterality.

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We would like to thank three reviewers for very helpful comments on an earlier version of this study.

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http://www.psypress.com/laterality DOI: 10.1080/13576500902885975

For musicians, practice plays an important role (Ericsson, Krampe, & Tesch-Römer, 1993). However, it remains open as to why some professional musicians become exceptional and others remain average. We argue that an additional factor for the achievement of a successful career should be considered, namely particular neurobiological prerequisites. Results from a previous study (Kopiez, Galley, & Lee, 2006) gave evidence for an enhanced left hand performance in pianists. A reduced bias towards the right hand also indicates a reduced hemispheric specialisation. In some bimanually played instruments (e.g., the piano) an enhanced left hand performance can result in a reduced sensorimotor performance difference between hands and an increased total instrumental performance of about 20% (Kopiez et al., 2006). However, up until now the questions have remained unanswered as to how well hand asymmetry can be overcome with practice (Peters, 1986) and whether particular manifestations of handedness are the result of intensive bimanual training or the neurobiological prerequisite for year-long successful practising. In other words, for particular instruments a reduced hand skill asymmetry could function as a selection variable in the population of professional musicians and could be the result of year-long training of the left hand.

According to Annett's (2002) "right shift theory" handedness is a continuous variable "plus or minus right loading" (p. 48) and should best be measured by the performance differences between both hands. The "right loading" has a genetic origin, called the "right shift factor", and can be located in either maternal or paternal genes. This factor is called the RS++ factor. The RS+– type is the most frequent heterozygous type, and the RS–– type is the homozygous type when both right shift factors are missing. This genetic group of non-right-handed individuals is distributed around the point of equality of left and right hand performance in terms of small differences between performances of hands. However, as Bryden, Roy, and Spence (2007) could show by means of a pegboard task, the threshold between right- and non-right-handers must be located in the positive vicinity, and not at the zero point. Both groups with the genetic right shift (RS+– or RS++) show more or less right hand superiority. The main problem remains that atypical right-handers cannot be separated from "true" (in terms of genetics) right-handers by means of an inventory. In other words, hand performance measurement and preference inventory tell different stories, and the atypical right-handed person would be misclassified as a right-hander in an inventory-based classification method.[1] Thus, to detect all RS–– individuals, the only effective methods are

[1] Additionally, we see no alternative to separating the genotypes C and D (C = chance and D = dextral) in the forms of CC, DD, and DC as postulated by McManus (1985) by means of hand performance measurement, because the author did not provide a chance factor for the DD genotype. In contrast, performance data always show a high degree of variability. Furthermore, McManus (2002) assumed that hand preference precedes hand performance and is widely independent of performance, while Annett (2002) took an opposite view.

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performance measurements, but it is necessary to bear in mind that the border with RS + – individuals lies to the right of the zero point on a LC distribution, and not exactly at the zero point, which is the point of no differences between the right and the left hand performance. From numerous studies, it can be derived that performance of both hands is also influenced by bimanual training (Aoki, Furuya, & Kinoshita, 2005a; Fujii & Oda, 2006; Jäncke et al., 1997; Koeneke, Lutz, Wüstenberg, & Jäncke, 2004; Krampe, 2002; for an overview see Schlaug & Chen, 2001). Of course, this long-term training also influences neuroplasticity and functional adaptivity of the musician's brain (for an overview see Elbert, Pantev, Wienbruch, Rockstruh, & Taub, 1995; Jäncke et al., 1997; Münte, Altenmüller, & Jäncke, 2002; Schlaug, 2006; Schlaug & Chen, 2001). However, this line of research is beyond the scope of our study.

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GENERAL MEASUREMENT OF HANDEDNESS

Measurement of handedness is a critical point in laterality research and cannot be conducted without an underlying theory. In most studies handedness is conceptualised as a solely dichotomous variable (e.g., right-handed vs left-handed) and verified by a questionnaire, which asks for the preferred hand in everyday activities, such as in the questionnaires used by Oldfield (1971), Annett (1970), or Peters (1998). The inherent validation and classification problems with questionnaires were discussed, for example, by Peters (1992) and Bishop, Ross, Daniels, and Bright (1996), but they rarely had consequences for researchers using handedness as an independent variable. Contrary to the clear-cut simple genetic types (see above), the consideration of degree, strength, or frequency of handedness in different activities often reveals multiple types of mixed- or left-handers (Peters & Murphy, 1992). However, as Annett (2002, p. 43, Fig. 2.7) has shown, preference classification from consistent left-handers to consistent right-handers corresponds to the performance differences of the eight observed preference types. That there is a relationship between hand preference and hand performance data could be shown, for example, by Brown, Roy, Rohr, and Bryden (2006). The authors were able to predict about 83% of variance of the handedness scores on a preference questionnaire by using handedness performance data as predictors in a statistical model (multiple regression analysis). In this model, the number of taps for both hands in a finger-tapping task was found to be the strongest predictor for handedness inventory scores. Brown et al. (2006, p. 2) concluded that "performance measures afford a more objective measurement of handedness". However, the question of a reliable and objective method of handedness classification by any performance indicator whatsoever remained open in their study.

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Moreover, if we have a thorough look at the tapping data of those participants who showed a consistent right-handedness in a handedness inventory (e.g., by answering all items with a clear preference for the right hand), it remains unclear as to how many participants within the group of inventory-based right-handers could possibly be non-right-handers. As far as we know, this important point has not been discussed in the literature. Finally, it remains to be investigated whether the speed tapping method with the resulting parameters of tapping speed, tapping regularity, and tapping fatigue is superior to Annett's pegboard method, which uses the parameter speed only for the determination of the threshold between dRH and dNRH.

The difficulty in using performance methods is deciding (a) at what point to put the threshold between right- and non-right-handers, and (b) which evidence substantiates the total number of handedness groups. A similar objective method of handedness measurement would be either genetic or based on functional imaging. Despite advances in behavioural genetics (e.g., Francks et al., 2007; van Agtmael, Forrest, Del-Favero, van Broeckhoven, & Williamson, 2003), the genetic verification of human handedness is still missing, and chromosomal localisation is under discussion (chromosome 2: Francks et al., 2007; X chromosome: Laval et al., 1998; chromosome 10: van Agtmael et al., 2003). However, genetic analyses will not manage without objectively pre-classified handedness groups. Statistical criteria as proposed in our study could be helpful for this purpose. As a future perspective, functional and morphometric measurements could also become additional ways to measure functional asymmetry of the brain (for an overview see Amunts, Jäncke, Mohlberg, Steinmetz, & Zilles, 2000; Aoki et al., 2005b; Dassonville, Zhu, Ugurbil, Kim, & Ashe, 1997; Gut et al., 2007; Jäncke, Lutz & Koeneke, 2006; Kamada et al., 2005; Volkmann, Schnitzler, Witte, & Freund, 1998).

We are convinced that performance measurements come closest to determining a participant's "true" handedness through the separation of right-handers from right-preferred non-right-handers. Annett's "right shift theory" (Annett, 2002) served as a theoretical basis of our study. However, the assumed close relationship between hemispheric specialisation for speech and handedness in Annett's conception (2002, 2003) is not addressed in our study. Preference-based data of handedness (in our case, the self-declared handedness) are only used as a necessary external criterion to define a group of participants who are very probably non-right-handed (the self-declared left-handers).

For the quantification of hand performance differences we used the so-called Lateralisation Coefficient ($LC = 100 * (L–R)/(L+R)$) of different tapping parameters. Participants on the right side of the statistically defined border (not the zero point as argued above) in some critical tapping parameters were classified as so-called designated right-handers (dRH), and those on the left side as designated non-right-handers (dNRH). We used the LC of tapping speed and in addition regularity, as a measure of the underlying asymmetry gradient, to find the threshold between non-right- and right-handedness in a probability distribution of LCs.

PREVIOUS STUDIES ON THE INCIDENCE OF HANDEDNESS IN MUSICIANS

The measurement of handedness in the population of musicians may be an important field of research because all existing theories of handedness using preference- or performance-based classifications are grounded on the assumption of no additional specific training of the non-preferred hand, as is the case in most normal people. However this is not the case in musicians whose left hands receive intensive training. As a first approach, and to obtain a comparable data set, we conducted a short review of studies reporting incidence of handedness in the population of musicians. Table 1 shows a confusing picture of handedness incidence in musicians: First, left-handers show an incidence within the range from 2–3% (Byrne, 1974; Chouard, 1991) to about 21% (Oldfield, 1969); second, due to different methods of measurement, studies are hardly comparable; third, due to a missing statistical criterion there is no objective or theory-based separation of genetic right-handers from right-preferred, genetic non-right-handers, and class boundaries are defined arbitrarily; fourth, except for the study by Chouard (1991), no incidence for different groups of instrumentalists is given; finally, no quantification of the amount of instrumental practice or initial age is indicated. Thus, this review demonstrates that preference inventories are an unreliable method for the classification of handedness as none of the reviewed studies can draw conclusions about the influence of extensive bimanual training on the incidence of handedness.

RATIONALE AND HYPOTHESES OF THE PRESENT STUDY

Our study followed two main aims: (a) to establish a strict statistical criterion, based on hand performance measurement, for classifying designated right-handers and non-right-handers; (b) to apply this criterion to the population of professional musicians and investigate the influence of extensive bimanual training on their designated handedness. It was assumed that the genetically determined handedness (right-handedness and non-right-handedness) cannot be strictly switched, but that the non-preferred hand—mostly the left hand—would benefit from additional practice (Peters, 1976, 1981; Schulze, Lüders, & Jäncke, 2002). This would result in (a) a negative correlation between the amount of bimanual training and the

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TABLE 1
Review of studies concerning the incidence of handedness in musicians

Author	*Method*	*Participants*	*Proportion of handedness**	*Comment*
Oldfield (1969)	Handedness inventory (22 items)	School of Music, students and staff (instrumentalists; $n = 129$)	RH = 79.1% LH = 20.9%	Proportion of affirmative answers to the question "Have you ever had any tendency to left-handedness?"
Byrne (1974)	Edinburgh handedness inventory (10-item version)	Conservatory of music, students and staff (instrumentalists; $n = 108$)	RH = 66.5% LH = 3.0% MH = 30.5%	Mixed-handers classification: laterality quotient (LQ) = ± 50 (total range: +100 to −100)
Götestam (1990)	Handedness inventory (four items, 3-point scale)	Conservatory of music, students (instrumentalists and singers; $n = 88$)	RH = 21.7% LH = 4.8% RM = 63.6% LM = 9.9% LH+LM = 14.7% RH+RM = 85.3%	Left-handers classification: laterality index = 4 (range: 4–12)
Chouard (1991)	Handedness inventory (researcher developed)	Orchestra musicians ($n = 352$)	LH = 2% (pianists); 14% (strings); 11% (wind instruments); 14% composers	Left-handers classification: writing hand and preferred playing position
Aggleton, Kentridge, & Good (1994)	Edinburgh handedness inventory and writing hand (10-item version)	Professional musicians (instrumentalists, composers and choir singers; $n = 1538$)	SRH = 77.5% MRH = 10.2% MLH = 5.3% SLH = 7.0% (LQ, instrumentalists only)	Handedness classification: LQ and writing hand; LQ ranges: SRH = 60 to 100; MRH = 1 to 59; MLH = −59 to 0; SLH = −100 to −60
Hering, Cataraci, & Steiner (1995)	Self-declared handedness	Orchestra musicians ($n = 382$)	NRH = 10.2% (LH = 6.3%; MH = 3.9%)	Handedness classification by show of hands
Kopiez et al. (2006)	Speed tapping (lateralisation coefficient)	Music students (pianists; $n = 52$)	dRH = 86.5% dNRH = 13.5%	Designated handedness classified by LC threshold

*RH = right-handers, LH = left-handers, MH = mixed-handers, RM = right-mixed-handers (write with right hand, other activity with left hand), LM = left-mixed-handers (write with left hand, other activity with right hand); SRH = strong right-handers; SLH = strong left-handers; MRH = moderate right-handers; MLH = moderate left-handers; dRH = designated right-handers, dNRH = designated non-right-handers.

lateralisation coefficient, and (b) a higher proportion of NRH in musicians performing on bimanually played instruments (pianists, violinists) compared with the normal population. Additionally, our study attempted a partial replication of the findings by Jäncke et al. (1997). These authors found a positive correlation between the initial age of instrumental instruction and lower tapping speed asymmetry as adults. Finally, our study should be viewed as a contribution to the development of an "objective" method of handedness classification by providing a statistically derived threshold between designated non-right- and right-handers following the most basic assumption of Annett's handedness theory.

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METHOD

Participants

A total of 128 music students from three German Schools of Music (*Musikhochschule*) participated in our study (see Table 2). The participants majored in piano ($n = 76$) or string instruments ($n = 47$). Additionally, four percussionists and one accordion player were considered. This group of five instrumentalists represents the right end distribution of age at commencement of musical training (age range: 8–21 years). The control group of non-musicians (matched for age) comprised psychology students ($n = 1198$) from the University of Cologne. No statistical difference was found between the mean age at commencement of musical training in pianists ($M = 6.6$ years, $SD = 2.5$) and string players ($M = 6.8$ years, $SD = 2.8$), $t(121) = -0.30$, $p = .72$ (two-tailed), the mean playing experience (pianists: $M = 16.5$ years, $SD = 4.2$; strings: $M = 15.5$ years, $SD = 3.4$), $t(121) = 1.40$, $p = .16$ (two-tailed), or between the mean amount of practice (pianists: $M = 14{,}901$ hours, $SD = 7{,}859.6$; strings: $M = 12{,}757.6$ hours, $SD = 7{,}523.5$), $t(121) = 1.49$, $p = .13$ (two-tailed).

Procedure

Performance handedness as an indicator of "objective" handedness was measured by means of tapping speed (Peters & Durding, 1978) regularity, and fatigue. Regularity of tapping speed has also been considered in previous studies and seems to be largely independent of tapping speed (McManus, Kemp, & Grant, 1986; Peters & Pang, 1992). Tapping fatigue was discussed as an interesting parameter at the beginning of the twentieth century (see Wells, 1908), and is used as a third parameter to describe hand performance. However, measurement of fatigue presumes a minimum tapping duration between 20 and 40 seconds. Thus in our study we used tapping over

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TABLE 2
Groups of participants studied (SD and range in parentheses)

	Women (n)	*Men* (n)	*Mean age (years)*	*Mean age of instrumental beginning (years)*	*Mean playing experience (years)*	*Mean amount of practice (hours)*
Pianists	45	31	23.2 (4.0, 17–40)	6.6 (2.5, 3–16)	16.5 (4.2, 3–31)	14901 (7859.6, 1424–36127)
Strings	35	12	22.3 (2.1, 19–27)	6.8 (2.8, 3–17)	15.5 (3.4, 7–23)	12757.6 (7523.5, 1948–35308)
Other instruments	1	4	26.4 (3.6, 22–31)	13.0 (5.0, 8–21)	13.0 (3.3, 8–16)	11961.2 (2007.8, 9282–14812)
Non-musicians (controls)	594	604	25.1 (4.7, 17–40)	–	–	

30 seconds for both hands. Participants tapped twice with a recovery phase of at least 15 minutes between trials. A Morse key (model by Junker Ltd., Germany; trigger point = 300 g) was used, connected to a PC, and tap intervals were recorded using the Software TAPPING (Tapping, 2008). To avoid a start hand effect (Schulze et al., 2002), the start hand was allocated randomly and finger tapping (index and middle finger together) with a fixed wrist position was used. The tapping position was controlled by resting the forearm on the desk. To avoid vibrations on the Morse key, which could speed up tapping, we instructed the participants to release the key: the active fingers released the key after each tap.

We conducted retrospective interviews (Lehmann & Ericsson, 1996) about the number of accumulated hours of practice per week and the number of years of instrumental lessons. Based on these interviews, the number of accumulated hours of practice up to the ages of 10, 15, 18 and that at the time of interview was calculated on a basis of 52 weeks per year. Additionally, each participant filled out a handedness questionnaire (Peters, 1998) comprising 24 items, such as self-declared handedness, preferred writing hand, or preferred hand for everyday activities (i.e., throwing a ball or picking up a book). These items were used to control for plausibility of self-declaration. Additional tests for speed of information processing, intelligence, and bodily disorders were conducted as control variables, which will be the subjects of forthcoming papers. The entire procedure lasted about 2 hours. Participants gave written consent and received €20 as reimbursement (musicians only).

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Classification of handedness

For the classification of handedness, binary logistic regression was used (method: backward elimination; likelihood ratio). This type of regression analysis is useful for situations in which the presence of a dependent dichotomous variable (such as right- and non-right-handedness) should be predicted based on continuous predictor variables (Harrell, 2001; Pampel, 2000). The most important option for binary logistic regression analysis in handedness classification is the determination of a cut-off for classifying cases. In our study we had to determine a proportion of handedness that is unanimously correct. This is only the case for the small group of self-declared left-handers, the plausibility of which we controlled for by examination of the respective filled-in handedness questionnaire (Peters, 1998). As long as there is no external criterion for validation of handedness (such as a genetic analysis), we can only go on the self-declaration of this group. Thus, nine self-declared ambidextrous participants (7%) were allocated to the group of right-handers in the regression analysis. Finally, the resulting incidence of self-declared left-handed musicians (11.7%) was entered as a cut-off value in the regression analysis. Before entering covariates into the regression analysis, a lateralisation coefficient (LC), which indicated the performance difference between hands, had to be defined. According to Peters and Durding (1978), the LC was defined as follows: LC = 100 * (L–R)/(L+R) with an increasing positive LC for time measurements as an indicator of a dominating right hand and vice versa. LC values could be calculated not only for tapping speed (defined as the difference of medians of all inter-tap intervals for both hands), but also for regularity of tapping (defined as the difference between the 16th and 84th percentiles of the distribution of the tap intervals, the equivalent of the standard deviation in linear statistics) and fatigue (defined as the difference between the median of the taps in the last 5 seconds and the median of the first 5 seconds).

The following variables were entered as covariates into the binary logistic regression analysis: LC tapping speed (based on the averaged medians for each hand for two trials over 30 seconds with randomly assigned start hand), LC tapping regularity as defined above (based on means of medians for each hand for two trials), and LC tapping fatigue (i.e., the difference between tapping interval 25–30 s and 0–5 s, based on means of medians for each hand for two trials). Because binary logistic regression only results in a regression equation for all statistically relevant covariates, separate thresholds were needed for the classification by selected tapping parameters (speed, regularity, and fatigue). These thresholds were defined by a graphical solution, based on the probabilities for group allocation, obtained from the binary logistic regression as follows: as Figure 1 shows, the probable handedness class of each participant has been plotted on the x-axis; in a second step, a curve fit (method: Loess; kernel: Epanechnikov with 50% of points to fit) was applied; in a last step, a crosshair was drawn for the cross-point in which the line from the probability point of 11.7% (corresponding to the value of .883 of the distribution) contacts the fitted curve, resulting in a threshold value for the respective LC on the y-axis. All participants above this threshold were allocated to the group of designated right-handers and below this threshold to the group of designated non-right-handers.

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RESULTS

Writing hand and hand performance measurements

The result from the binary logistic regression analysis is shown in Table 3. According to the regression coefficients, the probability p of a designated handedness class for a particular participant's regression value z was

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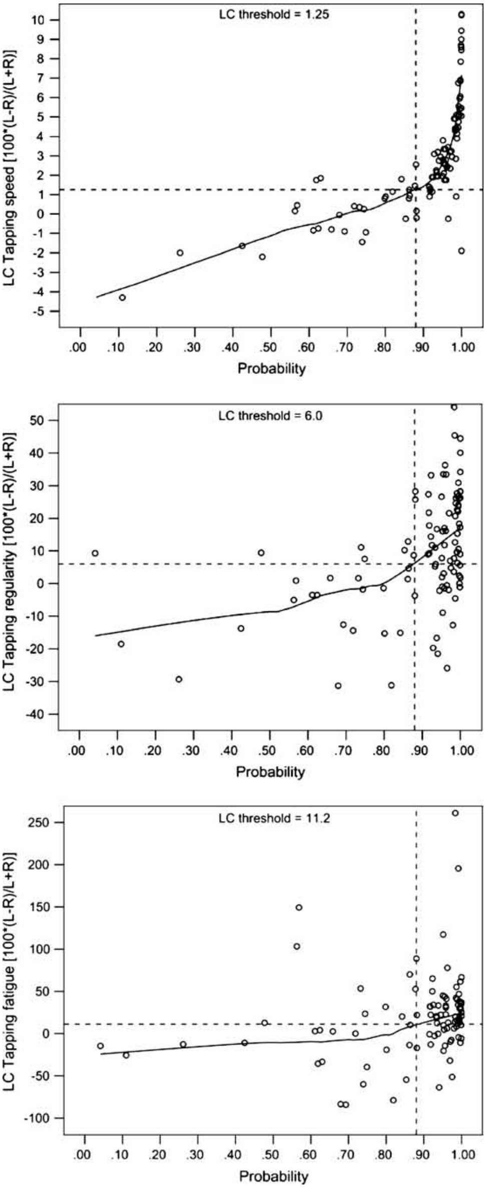

Figure 1. Definition of LC thresholds for handedness classification based on the three tapping parameters LC tapping speed (upper graph), LC tapping regularity (middle graph), and LC tapping fatigue (lower graph). The x-axis indicates the probability obtained from binary logistic regression (see text for further explanations). Participants above the determined threshold are allocated to the group of designated right-handers, below the threshold to the group of designated non-right-handers.

calculated by the following equations: logit $z = 1.150 + .66$ * LC Tapping speed + .033 * LC Tapping regularity – .008 * LC Tapping fatigue; with $p = 1/1 + e^{-z}$. Table 4 shows the LC threshold and incidence of designated handedness groups for right-handers (dRH) and non-right-handers (dNRH) in musicians and controls. Classification was based on the procedure described in the previous sections.

The relationship between self-declared handedness, designated handedness, and preferred writing hand is shown in Table 4. Of the self-declared right-handers, 100% preferred the right hand for writing. The same was the case for left-handers. The most significant relationship between writing hand and designated handedness could be observed for the group of designated non-right-handers (classified by the statistical criterion of binary logistic regression): 27 dNRH participants (73%) preferred the right hand for writing and only 10 participants (27%) used the left hand. First, this finding seems to demonstrate that the preferred writing hand is a person's subjective (and inconsistent) decision; second, this finding confirms previous results which showed that the writing hand is under highest cultural pressure of all hand activities (see Gilbert & Wysocki, 1992)

To control for an influence of different ages in the main groups of pianists and string players, a comparison of the LC tapping values between the younger and the older group (median split at age of 22 years) was conducted. As we had predicted, no significant effect of age on tapping LC was found in the case of an age-dependent enhanced left hand performance—age group 17–22 years ($n = 58$): mean LC tapping = 2.83, $SD = 3.13$; age group 23–40 years ($n = 57$): mean LC tapping = 2.86, $SD = 3.13$, $t(113) = -0.06$, $p = .95$.

Measurements of tapping speed for separate hands, groups of instrumentalists, and controls are given in Table 5. According to previous studies (e.g., Jäncke et al., 1997) pianists showed a higher tapping speed (ITI = 161 ms) compared to string players (ITI = 165 ms) $t(113) = -1.65$, $p = .05$ (one-tailed), (see Table 5). Further analyses of speed differences between separate groups, hands, and so forth are beyond the scope of this study.

TABLE 3
Coefficients obtained from binary logistic regression analysis

	Regression coefficient (Beta)	*Standard error*	*Wald*	*Df*	*p*	*Exp (Beta)*	*95% CI Exp (B)*	
							Lower	*Upper*
LC Tapping	.660	.209	10.00	1	.002	1.934	1.285	2.911
LC Regularity	.033	.018	3.228	1	.072	1.034	.997	1.072
LC Fatigue	–.008	.007	1.365	1	.243	.992	.979	1.005
Constant	1.150	.398	8.344	1	.004	3.159		

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TABLE 4
Preferred writing hand in self-declared and designated handedness groups

	Preferred writing hand		
	Right	*Left*	*Right and left*
Self-declared right-handers	104 (100)	0 (.0)	0 (.0)
Self-declared left-handers	0 (.0)	15 (100.0)	0 (.0)
Self-declared ambidexters	8 (88.9)	1 (11.1)	0 (.0)
Designated right-handers	78 (94.0)	5 (6.0)	0 (.0)
Designated non-right-handers	27 (73.0)	10 (27.0)	0 (.0)

Numbers indicate frequencies and percentages (in parentheses).

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Incidence of handedness in musicians and non-musicians

The incidence of designated NRH in musicians was higher than in non-musicians (see Table 6), independent of the parameter used for classification of designated handedness. For example, based on the LC for tapping speed, the incidence of dNRH in musicians was 30.8% and in non-musicians 21.7%. In all other groups of designated handedness (tapping regularity and tapping fatigue), the incidence of dNRH in musicians was always higher compared

TABLE 5
Handedness performance in tapping speed of designated right- and non-right-handers for different groups of instrumentalists and non-musicians

	Right hand	*Left hand*	*Both hands (mean)*	*N*
Pianists				
Designated RH	158/159 (13.0)	157/158 (12.2)	158/159 (12.2)	51
Designated NRH	160/166 (18.3)	164/167 (19.1)	160/166 (17.7)	19
Total	159/160 (14.9)	158/161 (14.8)	158/161 (14.2)	70
String players				
Designated RH	166/163 (12.3)	161/162 (12.4)	163/162 (11.4)	28
Designated NRH	170/169 (14.7)	168/171 (15.5)	164/169 (13.5)	17
Total	167/165 (13.3)	163/165 (14.1)	164/165 (12.5)	45
All instrumentalists				
Designated RH	160/150 (13.0)	158/159 (12.5)	159/159 (12.1)	83
Designated NRH	167/167 (16.4)	166/168 (17.2)	164/167 (15.5)	37
Total	161/162 (14.5)	160/162 (14.6)	160/162 (13.7)	120
Non-musicians				
Designated RH	158/159 (20.4)	180/182 (25.1)	169/170 (21.4)	938
Designated NRH	165/167 (20.7)	162/163 (20.5)	164/165 (19.5)	260
Total	159/160 (20.7)	177/178 (25.4)	168/169 (21.2)	1198

Tapping speed is indicated in milliseconds. Values show median/mean (standard deviation) of tapping speed averaged over two trials.

to the controls. The lowest incidence of self-declared NRH was predicted by binary logistic regression (musicians: 8.8%, non-musicians: 6.0%). However, we should bear in mind that the several predictors, such as tapping speed, regularity, and fatigue, are involved in this calculation: the LC of tapping speed was the most reliable parameter, because it received the highest beta weight in the regression equation (see Table 3). Based on this most valid criterion, the incidence of dNRH in musicians (30.8%) was 9.1% higher than in non-musicians. In contrast, the LC threshold based on tapping regularity resulted in an incidence of 42% of dNRH and the LC threshold for tapping fatigue in an incidence of 44.7% in musicians. This proportion is higher than

TABLE 6
Incidence of designated right-handers (dRH) and non-right-handers (dNRH) in musicians and non-musicians as obtained from different methods of measurement

		N		%	
Method	*LC threshold*	*dRH*	*dNRH*	*dRH*	*dNRH*
Musicians ($n = 128$)					
Handedness as correctly predicted by binary logistic regression*	–	72	9	70.6	8.8
Self-declared handedness**	–	113	15	88.3	11.7
Designated handedness (Tapping speed)	1.25	83	37	69.2	30.8
Designated handedness (Tapping regularity)	6.0	69	50	58.0	42.0
Designated handedness (Tapping fatigue)	11.2	57	46	55.3	44.7
Non-musicians ($n = 1198$)					
Handedness as correctly predicted by binary logistic regression***	–	951	73	79.4	6.0
Self-declared handedness**	–	81	1117	93.2	6.8
Designated handedness (Tapping speed)	1.89	938	260	78.3	21.7
Designated handedness (Tapping regularity)	7.11	853	345	71.2	28.8
Designated handedness (Tapping fatigue)****	16.2	644	230	73.7	26.3

*Calculation was based on a proportion of 11.7% of left-handers, as identified by self-declaration. Due to technical problems with the tapping device, tapping data were only available for 120 participants; the following predictors were used for regression analysis: LC Tapping speed, LC tapping regularity, and LC for tapping fatigue; percentage of correct classification between self-declared handedness and handedness as predicted by binary logistic regression was 79.4% (RH = 80.0%, NRH = 75.0%; $n = 120$); **self-declared handedness was recoded: Left-handers were classified as NRH, mixed-handers and right-handers as RH; ***calculation for the non-musicians group (matched for age range) was based on a proportion of 6.8% of "true" non-right-handers, as identified by self-declaration; the following predictors were used for binary logistic regression analysis: LC tapping, and LC tapping regularity; LC for tapping fatigue was removed by binary logistic procedure; percentage of correct classification by binary logistic regression was 85.5% (RH = 85.1%, NRH = 90.1%); ****due to missing data for the LC fatigue in the group of non-musicians, the number of participants for this tapping parameter is smaller ($n = 874$) than the total number of participants in the group of non-musicians.

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any incidence of NRH reported in previous studies (see Table 1). This result supports our hypothesis that objective NRH cannot be identified by handedness inventories, and thus the incidence of true NRH is underestimated by preference item scores. Further analyses examined whether the three tapping parameters could be influenced by the training component and whether musicians could benefit from bimanual training with the result of reduced positive LC values.

Finally, by using the most important speed parameter, we found differences between 11.7% of self-declared NRH and 30.8% of designated NRH in musicians and 6.8% of self-declared NRH and 21.7% of designated NRH in controls. Thus, we could further show that true non-right-handedness is significantly underestimated by the method of self-report.

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Incidence of handedness in different groups of instrumentalists (pianists and string players)

Although string instruments and piano are played bimanually, the different demands on both hands could play a role in the influence of instrumental training on tapping LC. For example, as Wiesendanger, Baader, and Kanzennikov (2006) could show by means of an optoelectronic video system, the mean asynchronicity between bow and finger actions in a "one bow stroke per tone" task can be up to 50 ms. Pianists are subordinated to much higher time constraints: as Jabusch (2006) found by means of a MIDI-based scale analysis system, highly accomplished pianists can play scales—not tone repetitions—with a mean standard deviation of inter-onset intervals of 9.5 ms. Bangert and Schlaug (2006) assumed that string players have to acquire highly developed fine hand and finger motor skills for their left hand, while pianists have to develop those skills more in both hands and not only in their right hand. Thus, we calculated separate incidences of designated handedness for both groups of instrumentalists. The same procedure and handedness thresholds as used for the previous analyses were applied. Results of the incidence of designated handedness in pianists and string players are shown in Table 7. The main result is the difference in dNRH incidence for designated handedness (LC tapping speed): Pianists showed an incidence of 27.1% of dNRH while string players an incidence of 35.6%. Against the background of the total incidence of dNRH in the entire sample of musicians (30.8%), string players have an above average incidence of dNRH. On the other hand, based on the tapping regularity, the incidence of dNRH in pianists was slightly higher (43.5%) compared with that of string players (37.8%). The same tendency can be observed for designated handedness, based on the LC tapping fatigue.

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TABLE 7
Incidence of designated right-handers (dRH) and non-right-handers (dNRH) in pianists and string players (music students)

	Self-declared handedness		*Designated handedness (Tapping speed) LC threshold = 1.25*		*Designated handedness (Tapping regularity) LC threshold = 6.0*		*Designated handedness (Tapping fatigue) LC threshold = 11.2*	
	n	%	*n*	%	*n*	%	*n*	%
Piano								
dNRH	8	10.5	19	27.1	30	43.5	28	47.5
dRH	68	89.5	51	72.9	39	56.5	31	52.5
Total*	76	100	70	100	69	100	59	100
Strings								
dNRH	6	12.8	16	35.6	17	37.8	18	45.0
dRH	41	87.2	29	64.4	28	62.2	22	55.0
Total*	47	100	45	100	45	100	40	100

*Due to technical problems with the tapping device, there were some missing data. Thus, total group sizes for self-declared and designated handedness differ slightly.

Finally, the question remains as to how much the performance of left and right hand (speed, regularity, and fatigue) can be influenced by extensive and year-long practice. Thus, in a next step, correlation analyses were conducted to test the hypothesis of a reduced bias towards right hand lateralisation (and enhanced left hand performance) in musicians through extensive training of the non-preferred hand.

The influence of bimanual training on handedness lateralisation

The amount of instrumental training time was calculated by means of a retrospective interview. Studies in music performance have shown that the calculation of accumulated practice times based on retrospective interviews is a reliable and useful tool of expertise research (e.g., Lehmann & Ericsson, 1993, 1996). As Bengtsson et al. (2005) found, there is a high retest reliability of this method for different age groups (childhood: $r = .81$; adolescence: $r = .86$; adulthood: $r = .95$). As Table 8 shows, for all instruments there is only a weak correlation between accumulated practice time up to the ages of 10, 15, 18, and that at the time of the experiment and LC values. For all instruments, only higher practice time up to 10 years reaches a significant correlation with LC for *tapping regularity* ($r = -.175$, $p < .05$), which indicates a reduced right hand bias with increasing amount of early practising. The same tendency of a reduced right hand bias can be observed for the age of instrumental beginning and LC *tapping fatigue* ($r = .13$, $p < .05$). Surprisingly, the most important criterion for designation of handedness, the LC tapping speed of all instruments, is not influenced by the amount of bimanual training. As Figure 2 shows for LC tapping speed, the expected negative correlation between a small LC value and a high amount of total practice time could not be confirmed ($r = .10$; *ns*) and is even in the contrary (positive) direction. This result was controlled for in the accumulated practice time up to the age of 18; however, no difference between pianists and string players was found—pianists: $M = 8423$ hours, $SD = 5368$; strings: $M = 7151$ hours, $SD = 4954$, $t(121) = 1.31$, $p = .19$. The only LC value influenced by the amount of bimanual practice time was the LC tapping regularity. This means that, for pianists, practice time accumulated up to the ages of 10 and 18 resulted in an increased regularity in tapping. However this is not the case for string players. No correlation was found between the amount of practice and LC tapping fatigue. These findings could be interpreted in terms of a weak influence of practice time on LC values in the population of professional musicians and as evidence for a critical time window for the reduction of right hand irregularity up to the age of 18. The last line of Table 8 indicates the correlation between the initial

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TABLE 8
Correlation between accumulated practice time, the age at commencement of musical training and tapping LCs

	*All instruments (*n = *120)*			*Piano (*n = *70)*			*Strings (*n = *45)*		
	LC Tapping speed	*LC Tapping regularity*	*LC Tapping fatigue*	*LC Tapping speed*	*LC Tapping regularity*	*LC Tapping fatigue*	*LC Tapping speed*	*LC Tapping regularity*	*LC Tapping fatigue*
Practice time 10 years***	.095	–.175*	.028	.044	–.323**	.024	.184	.024	.236
Practice time 15 years***	.103	–.125	.072	.066	–.277*	.085	.192	.102	.225
Practice time 18 years***	.088	–.133	.087	.039	–.276*	.109	.194	.086	.199
Total practice time ****	.101	–.064	–.183*	.075	–.067	–.198	.171	.076	.076
Age of beginning Instruction	.066	.019	.130*	–.028	–.009	.033	.087	.061	.291*

*$p < .05$ (Pearson; one–tailed), **$p < .01$ (Pearson; one–tailed); number of cases is indicated in brackets; ***accumulated practice time (hours) up to the indicated age; ****accumulated practice time up to the experiment.

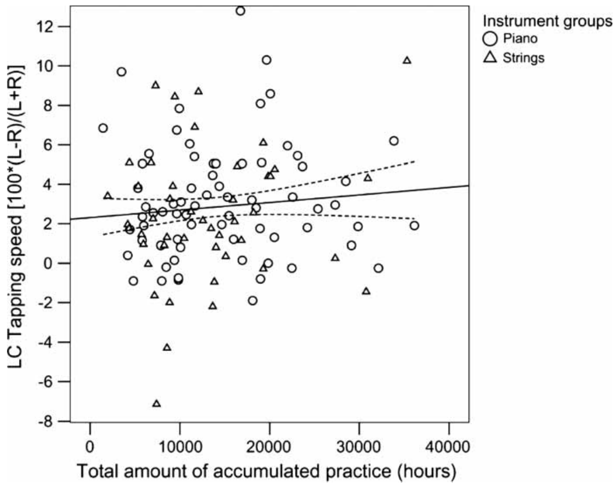

Figure 2. Correlation between instrumental training (amount of life-long accumulated practice time) and LC value (based on tapping speed) for two groups of instrumentalists—pianists: $r(70) = .07$, *ns*; string players: $r(45) = .17$, *ns*. Dashed lines indicate confidence interval of regression line (95%).

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age of instrumental lessons and LC values. We found no significant correlations for LC tapping speed and LC tapping regularity, and only weak correlations for LC tapping fatigue (all instruments: $r = .13$, $p < .05$; strings: $r = .29$, $p < .05$).

The main finding of a very limited influence of bimanual training on lateralisation as measured by LC scores is also reflected in the correlations between the total amount of accumulated practice (measured in hours) and tapping speed: for all musicians, practice time and average tapping speed were correlated with $r(120) = -.18$, $p = .02$ and only became statistically significant due to the high number of cases. Also practice and tapping speed for the left hand only became significant, $r(103) = -.18$, $p = .03$, as well as for the right hand, $r(103) = -.24$, $p = .01$. These are only very small effects. Finally, the prediction of an enhanced performance of the non-dominant hand in pianists only was tested. However, no significant correlations with the accumulated amount of practice were found either for the left hand in dRH, $r(51) = -.16$, *ns*, or for the right hand in dNRH pianists, $r(19) = -.29$, *ns* (all tests one-tailed).

Comparison of findings with those of Jäncke et al. (1997)

One aspect of our study was the replication of the previous finding of a correlation between reduced hand skill asymmetry and the early beginning of instrumental training by Jäncke et al. (1997). The authors found a correlation of $r = .45$ between these two variables in 31 pianists and violinists. This result was interpreted as an "adaptation process due to performance requirements interacting with cerebral maturation during childhood" (p. 424). Contrary to Jäncke et al.'s results (Figure 3 top), our results (Figure 3 bottom) show, surprisingly, a zero correlation between the age at commencement of musical training and hand skill asymmetry defined by the most important LC speed parameter—pianists: $r(51) = -.01$, *ns*; string players: $r(30) = -.01$, *ns*—this sub-sample of our study comprises the same

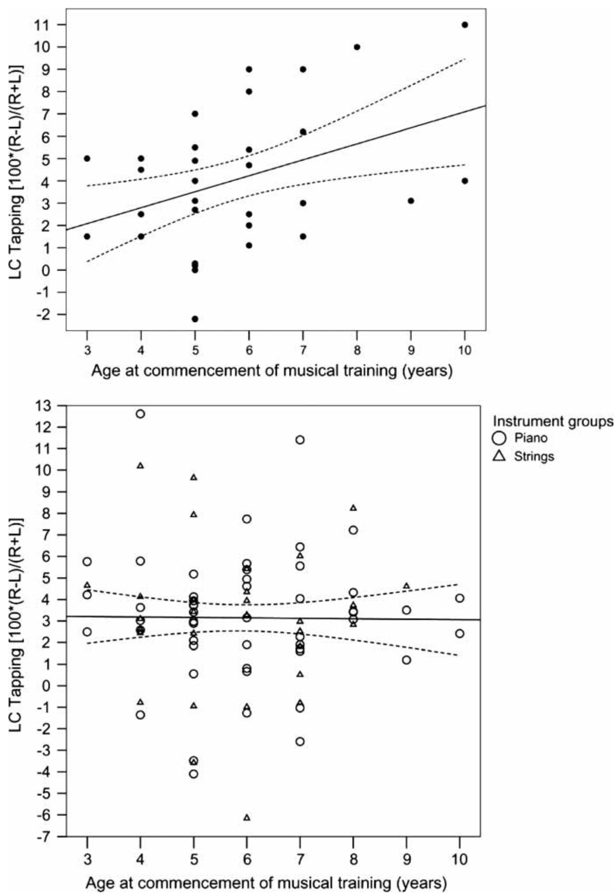

Figure 3. Relationship between the age at commencement of musical training and LC tapping speed based on the total number of taps for self-declared right-handed instrumentalists only. Upper graph is based on the re-analysis of data of the study by Jäncke et al. (1997), $r(31) = .45$, $p = .01$. Lower graph indicates results of the present study—pianists: $r(51) = -.01$, *ns*; string players: $r(30) = -.01$, *ns*. Dashed lines indicate confidence interval of regression line for the entire sample (95%).

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age range of instrumental beginning (3–10 years) and of selected self-declared right-handers as in Jäncke et al., 1997.

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DISCUSSION

Handedness as a selection variable

The main finding of our study was a higher incidence of designated non-right-handers in the population of musicians. At the same time, neither the age at commencement of musical training nor the accumulated amount of practice time had an effect on the asymmetry gradient (LC of tapping speed), the most important designator of handedness by performance. However, this instrumental training was effective in increasing regularity and decreasing fatigue of the left hand. We prefer to explain this finding by a selection effect of non-right-handers for careers as professional musicians, which could, for example, occur due to an increased drop-out rate of strongly left-hemispheric lateralised players of bimanually played instruments within the first years of instrumental learning. Thus, a strong right-handedness with a high positive LC would result in a large performance difference between the preferred and the non-preferred hand. Although this is a new perspective on instrumental success and the study of these potential constraints have been advocated in previous investigations (Peters, 1986), the recent research in music education on drop-outs does not consider these neurobiological variables for learning success (e.g., Costa-Giomi, Flowers & Sasaki, 2005; McPherson & Renwick, 2001). However, a definite answer to the question of handedness as a drop-out variable can only be given by a longitudinal study on instrumental success.

Tapping as an objective method for handedness classification

Moreover, our study is also a contribution to the objective measurement of handedness by means of speed tapping. As long as there is no genetic criterion available for the "true" handedness, we are convinced that the "designated" handedness comes closest to the genetically founded asymmetry gradient, which should determine handedness following Annett's "right shift" theory. The great advantage of speed tapping over handedness inventories is the separation of right-handed from right-preferred non-right-handed (initial ambidextrous) participants by a time-critical performance task. In comparison with the peg-moving task (Annett, 1970, 1985, 2002), there is another advantage of tapping: the researcher gains three different indicators of performance differences—speed, regularity and fatigue—and the last two of these showed the influence of intensive training. In our study, intensive training had no influence on the designation of handedness when we considered the important criterion of speed. This finding is contrary to those findings by Jäncke et al. (1997).

To control for data reliability, we decided to use the average of two tapping trials. Additionally, the correlations of tapping parameters between trials were calculated to test for reliability of measurements: tapping speed for both hands $r(103) = .84$, $p < .001$; tapping speed for right hand: $r(103) = .83$, $p < .001$; tapping speed for left hand: $r(103) = .82$, $p < .001$; LC tapping speed: $r(103) = .67$, $p < .001$.

In our opinion, the higher incidence of designated NRH in musicians and controls in our study (see Table 7) compared with previous studies (see Table 1) gives evidence of a misclassification bias in handedness classification methods using preference-based methods. It is true that non-right-handers in Annett's concept not only lack the right-shift factor but they also have a random fluctuation in the asymmetry gradient which can lead to a preference for the right as well as for the left hand. Only by using performance differences as a method for handedness classification, should NRH be regarded as having a smaller preference towards right hand superiority. In other words, following our results the incidence of true NRH is underestimated by preference-based inventories by roughly 50%. The incidence of designated NRH in the group of non-musicians (21.7%; based on LC speed tapping), therefore, is an argument that the generally accepted 11.7% of self-declared left-handers represent only half of the true genetic NRH in the population.

We are aware that our procedure is based on some assumptions of Annett's model and that the final verification depends on finding the genes of handedness. However, the assumption of van Agtmael et al. (2002) that right-handed parents (identified by hand preference) of two left-handed children should be heterozygote (RS+− in Annett's concept) is a misunderstanding of the right shift theory. RS– – can be right-handed by preference just as a very few heterozygote people (RS+–) can be left-handed by preference due to the additional random fluctuation factor. Therefore, van Agtmael's model is *not* based on Annett's assumptions and thus cannot be interpreted as a falsification of Annett's model. In our study we found an influence of training on the degree of asymmetry along two tapping parameters (regularity and fatigue), but not along the parameter of speed, which was most important for designation of handedness.

For the first time in handedness research, to the best of our knowledge, this study uses the binary logistic regression on performance measures to find an objective criterion for handedness classification. The advantage of this method is in the gaining of information to obtain continuous

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probabilities for handedness classifications based on a merely dichotomous predictor variable (self-declared left-handedness) and its incidence (11.7% in the musicians group and 6.8% in controls). Based on the distribution of probabilities, we could first show that classification thresholds for separate covariates could be obtained by a graphical solution, and second that the resulting LC threshold value between designated NRH and RH is located on the right (positive) side from zero. This second finding is compatible with Annett's assumption that due to the random fluctuation factor, the RS– – can be right-handed by preference. This threshold also explains the difference between the higher proportion of NRH in this study compared with the smaller incidence of dNRH in pianists (13.5%) in our previous study (Kopiez et al., 2006) in which the classification threshold was set to zero. The theoretical decision for that study was motivated by more economical reasons. However, strictly following Annett's theory, that arbitrary decision did not support the conclusion that non-right-handedness begins at the point of left-hand superiority.

Finally, the binary logistic regression (Table 3) indicates the weight of a predictor for the classification of handedness by the value of so-called odds ratios: OR; column "Exp(B)". For example, the OR for LC speed tapping indicates that the probability of being classified as right-handed increases by the factor 1.93 (with a 95% confidence interval between 1.285 and 2.91), when this LC increases by one scale unit ($OR = e^{1 * .66}$). On the other hand, the probability decreases by the factor .51, when the LC tapping speed decreases by one scale unit ($OR = e^{-1 * .66}$) and by the factor of .37 for a decrease of 1.5 scale units ($OR = e^{-1.5 * .66}$). Thus, the odd ratio is interpreted as an indicator of a good selectivity for the predictor LC speed tapping for handedness classification (see also Figure 1, upper graph).

Influence of the amount of training on designated handedness: A comparison with the study by Jäncke et al. (1997)

We found only a non-significant correlation between the amount of musical training and the respective LC value (see Figure 2) for both instrument groups. The same zero correlation was found for the age at commencement of musical training and LC tapping speed. This finding is contrary to results of the study by Jäncke et al. (1997) in which the authors observed a significant correlation of $r = .45$ between age at beginning of training and LC tapping (see Figure 3, upper graph). It seems likely to us that the result by Jäncke et al. (1997) is due to a selection effect within a small sample size ($n = 31$) with some participants starting musical education at an early age (< 5 years) and having a low positive or negative LC. In our sample (parallelised for instruments, age range, and self-declared preferred hand), there were also some participants with an early age of commencement (<5 years) and a medium LC (<6); however, there were also some participants within this age range with a LC >6. A late beginning of musical training does not always result in a high LC: as we found in the group of "late bloomers" (age at commencement: >7 years), there were numerous participants with low LCs (between 0 and 4). However, Figure 3 (lower graph) makes clear that there is no "non-right-handed late bloomer" participant (lower right quadrant; 8–10 years, LC $\leq$ 1). Thus it could also be that the small sample size of Jäncke et al. (1997) randomly comprised some early-starting violinists; however, instrument groups were not indicated in their data.

Of course, there are some methodological differences between our study and that of Jäncke et al. (1997). The two main points are the use of wrist tapping and a tapping duration of 30 s in our study, as opposed to finger tapping and a tapping duration of 20 s in Jäncke et al.'s study. Concerning the aspect of finger vs wrist tapping, we considered that tapping speed depends on the method used: for example, as Peters and Pang (1992) could show, finger tapping is always faster than arm tapping with immobilised wrist and forearm. Our decision to use tapping with a fixed wrist was due to the force of the Morse key spring: the usage of two fingers in tapping produces less variability due to higher finger force. Finally, to answer the question whether different results between the two studies could be due to the two tapping methods used (finger vs wrist tapping), we conducted the following analysis. A direct comparison between the mean tapping speed of the designated right-handers in our group of musicians revealed an ITI of 159 ms compared with 158 ms found in finger tapping in the group of consistent right-handed musicians in the study by Jäncke et al. (1997), see Table 5; number of taps per 20 s indicated in the table were transformed into inter-tap intervals in milliseconds). For the group of non-musicians results were similar: we found a mean ITI of 184 ms in the group of designated right-handers, compared to 182 ms in the study by Jäncke et al. (1997). In other words, tapping performance in finger tapping seems to be similar to wrist tapping.

Concerning the second difference of tapping duration, we conducted a re-analysis of our data with (a) a tapping duration of 20 s and (b) of 30 s. Hand performance data were highly correlated between the two durations: the mean total tapping speed for both hands was $r(103) = .99$, $p < .001$; the mean tapping speed left hand was $r(103) = .98$, $p < .001$; the mean tapping speed right hand was $r(103) = .99$, $p < .001$. In other words, our comparisons between 20 s and 30 s of tapping duration revealed extremely high

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correlations and thus we conclude that different tapping durations cannot explain the different findings. Additionally, as our musician group showed a faster tapping speed compared to the non-musicians, we can also exclude a tapping in "convenient speed".

Finally, as Table 8 shows, LCs for tapping speed, tapping regularity, and tapping fatigue are influenced by the amount of training and age of commencement in different ways: in our sample, tapping speed was least influenced by training, but amount of training up to the age of 10 and 18 improved practice regularity (in pianists only). Small effects of training and the age at commencement of learning an instrument could also be observed for a reduced fatigue in tapping (mainly in string players). In other words, in our sample training effects for the non-preferred hand are small and have an influence only on tapping regularity and fatigue. This result supports our assumption that tapping speed serves as a reliable variable for the calculation of a LC as the basis of designation of handedness.

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How can our results be interpreted against the background of previous findings on the influence of prolonged practice on between-hand performance differences? There are only a few studies on this aspect; however, in a study by Peters (1981), 14 participants practised finger tapping (10 s trials) with both hands over a period of up to 10 days, with a practice duration of about 20 minutes per day. The pre–post comparison of hand performance showed an overall improvement of less than 10% for both hands, with a small training advantage for the non-preferred hand. However, pre–post performance differences between hands remained nearly constant (pre difference: 7.2 taps/10s, post: 6.8 taps/10 s). Peters concluded that due to the very basic aspect of the tapping task, "these differences appear of a permanent nature" (1981, p. 590). However, from this result we cannot exclude a training effect on more complex movements such as piano playing. In a more recent study (Schulze et al., 2002), authors found that unimanual training also improves bimanual hand performance in a tapping task; however, general training effects were greater for the non-dominant hand (3.42 s) compared to the dominant hand (2.8 s).

Intelligence and tapping speed

Because our sample comprised music students, it is one with an above-average IQ. As known from previous studies, there is evidence for an influence of IQ on motor performance. For example, Ullén, Forsman, Blom, Karabanov, and Madison (2008) found a correlation between IQ and variability in an isochronous tapping task of $r = -.39$. Thus in our study we also controlled for the influence of the IQ on hand performance (calculated from the Intelligence Structure Test, see Liepmann, Beauducel, Brocke, & Amthauer, 2001). Analyses revealed a significant correlation of $r(106) = -.24$, $p = .01$ (two-tailed) for mean tapping speed and of $r(104) = -.29$, $p < .001$, for tapping regularity. In other words, intelligence seems to have a stronger influence on tapping speed and accuracy than accumulated bimanual practice does.

Conclusions and limitations of the study

Results from our large sample of professional musicians consistently showed only very small effects of the amount of training or the initial age of instrumental instruction on lateralisation as measured by lateralisation coefficients and designated handedness. However, only longitudinal data in beginners of various instruments would confirm our hypothesis of handedness as a selective variable in bimanually played instruments. Additionally, our hypothesis could be supported by a handedness survey in unimanually played instruments (e.g., brass instruments). We would predict a higher incidence of strongly lateralised right-handers in this group of instrumentalists compared to pianists and string players. As Kopiez et al. (2006) could show for pianists, a tendency towards bilaterality can also be of advantage in highly demanding musical performance tasks, such as unrehearsed playing of musical notation (so-called sight reading). In string instruments the enhanced achievement of the left hand would even result in a performance advantage. In our opinion the incidence of 35.6% of designated non-right-handed string players in our sample (compared to 27.1% in pianists) gives further support for the selection hypothesis. In other words, bilateral string players have an advantage playing in a regular (instead of a reversed) playing position. However, highly skilled motor control is only one aspect of professional music making, and it remains open whether bilaterality or strong non-right-handedness could result in players' subjectively experienced confinements of expressive qualities of music performance. This question will be the subject of forthcoming studies. It would also be premature to conclude from our findings that more-bilateral musicians would be better musicians. As already discussed in the context of the basic tapping paradigm, complex movements such as instrumental performance offer a wide range of strategies for adaptation to particular task demands and compensation of individual limitations in hand performance. For example, the adequate choice of musical literature and the adaptation of practice strategies to the individual weaknesses and strengths of a musician's sensorimotor possibilities can open up numerous ways to become a successful musician.

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Finally, further development of handedness classification by means of the tapping paradigm used on a large sample is currently under preparation (Galley, Kopiez, Ottensmeier, & Hopman, 2009). This will help future research to determine true non-right-handers in a group of phenotypical right-handers. We are convinced that our analytical approach will result in a more reliable (statistical) classification of participants, which will be helpful as an external classification criteria for future genetic analyses of handedness.

Manuscript received 18 June 2008
Manuscript accepted 10 March 2009
First published online 21 May 2009

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