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No disadvantage for left-handed musicians: The relationship between handedness, perceived constraints and performance-related skills in string players and pianists

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Abstract

Two studies investigate the influence of handedness on a musical performance. In Experiment 1 we compared designated non-right-handed (dNRH) and designated right-handed (dRH) string and piano players performing in the (non-inverted) standard playing position with respect to (1) performance-related variables (e.g., musical expression) and (2) health-related variables (e.g., discomfort). The 47 professional instrumentalists (pianists: $n = 23$, string players: $n = 24$) were classified for handedness (performance handedness) and participated in a survey study on sensorimotor skills and their sense of well-being at the instrument. In Experiment 2, we tested for differences in sensorimotor performance of both hands in right- and left-handed pianists: 19 professional pianists (music students) were classified for handedness (preference handedness). Participants performed scale playing. In Experiment 1 no evidence was found for a performance-related or well-being-related disadvantage in dNRH instrumentalists playing in the standard position. In Experiment 2 temporal sensorimotor precision in the right hand was superior to that of the left hand in both right- and left-handed pianists. We conclude that professional musicians adapt to the standard playing position regardless of their objective handedness. However, it cannot be ruled out that a subgroup of dNRH instrumentalists subjectively feel constricted when playing in the standard position.

Keywords

handedness, music performance, pianists, sensorimotor skills, string players

This study investigates a widely neglected yet important aspect of music performance: namely handedness, and how it may affect performance skills in string players and pianists. In two experiments we examined whether non-right-handed instrumentalists experience a disadvantage in instrumental performance and bodily well-being by their handedness when performing on an instrument intended for right-handers. This study is meant as a contribution to the research concerning the relationship between handedness, bimanual training and music performance.

In recent years, musical performance research has found evidence for the relevance of neurobiological factors for music-related sensorimotor achievement. For example, speed of information processing plays an important role in the unrehearsed performance (so-called "sight reading") from a musical score (Kopiez & Lee, 2006, 2008; Lehmann & Kopiez, 2009). As another neurobiological factor, handedness in terms of cerebral asymmetry or "cerebral dominance" (Annett, 2002, p. 6) seems to be relevant for sensorimotor achievement in instrumentalists. For example, in exercising a musical sub-skill, the unrehearsed performance of music, pianists with a tendency to ambidexterity showed an improved performance of about 22% compared with right-handed pianists (Kopiez, Galley, & Lee, 2006).

In our study, we refer to handedness as the "functional asymmetry" of hemispheres which can be identified by the measurement of performance differences between hands in a standardized task (see Preilowski, 2005). As long as there are no reliable methods for the analysis of the genetic handedness, the measurement of performance handedness seems to be an objective approach for determining functional brain asymmetry (for an extensive discussion of this point see Kopiez, Galley, & Lehmann, 2010). The role of sensorimotor practice in the neuroplasticity of the musician's brains has also been considered in recent research. For example, Pascual-Leone et al. (1995) demonstrated by means of two-hour daily practice sessions of a one-handed five-finger piano exercise over five days that the acquisition of new fine motor skills was accompanied by immediate cortical reorganization in the respective motor areas. Using transcranial magnetic stimulation (TMS), they observed a decrease of the activation threshold for the long finger extensor and flexor muscles of the trained hand already after two days of practice, which continuously decreased until day five. The authors concluded that acquisition of motor skills was associated with a modulation of the cortical motor outputs in the muscles involved in the task. They assumed that the extended practice unmasked pre-existing, but unused, synaptic connections. Elbert, Pantev, Wienbruch, Rockstroh, and Taub (1995) demonstrated long-term plasticity effects of extensive motor training. They investigated the cortical representations of the left-hand digits of string players and found larger representations in musicians compared with non-instrumentalists. The dipole moment (as an indicator of total neuronal activity) for the left little finger increased with the decreasing age at instrumental commencement. Bangert and Schlaug (2006) observed the so-called "Omega sign" (a gross anatomical structure in the precentral gyrus associated with hand movement representations) in right-handed string players and pianists. The visual salience of the Omega sign was greater in the right hemisphere of string players as compared with the left hemisphere. The reversed pattern was observed in pianists. For string players, results were interpreted in terms of an adaptation effect due to high demands of sensorimotor control (intonation, vibrato, etc.) in the left hand. In contrast, piano literature is dominated by higher demands on the right hand in general, resulting in a more left-hemispheric prominence of the Omega sign. This seeming contradictory to the findings of Amunts et al. (1997), who observed a more symmetrical intrasulcus length of the precentral gyrus (ILPG; as a measure of the size of the primary motor cortex) in professional pianists, can be explained by a group inhomogeneity in the Amunts et al. study: nine out of 21 right-handed pianists also played string instruments. Although Amunts et al. (1997) interpreted their findings in terms of a structural adaptation effect (which increases with decreasing age at the commencement of instrumental training), they could not rule out a selectional effect for the ILPG differences (p. 212), which means that an individual could become a skilled musician due to his larger motor cortex. The relevance of intensive bimanual training for the general effect of a reduced degree of hand skill asymmetry in pianists, as, for example, observed by Jäncke, Schlaug, and Steinmetz (1997), is still under discussion, and a final answer could only be given by a longitudinal study on the relationship between functional asymmetry and early commencement of instrumental training (see Kopiez et al., 2010).

Against the background of the current state of handedness research, Annett (2002) posited, however, that "years of practising scales with both hands may not remove the superiority of the preferred hand, whether right or left" (p. 18). In other words, the chicken-or-egg question of what comes first, the preference for one hand (which is strengthened by practice) or the performance advantage of one hand (which is extended by sustained practice), can currently be considered in light of the performance hypothesis. In experiments consisting of long-term speed tapping practice over a couple of weeks for both the preferred and non-preferred hand, both hands showed improvement in tapping speed through practice, but the relative magnitude of the between-hand performance difference remained stable for most subjects (Peters, 1981).

This view of functional asymmetry of hand movement differences as a prerequisite for, rather than a consequence of, handedness is supported by a few neurobiological reports; however, the picture is equivocal. Using magnetoencephalography (MEG), Volkmann, Schnitzler, Witte, and Freund (1998) showed that individual asymmetry in hand motor performance (as measured by a hand dexterity test) covaried with the asymmetry of the hemispheric hand area size of the primary motor cortex. Significant group differences between right- and left-handers revealed a stronger leftward asymmetry of hand motor representations for right-handers and vice versa. The authors argued that this expansion of hand motor cortex in the dominant hemisphere may provide extra space for encoding greater motor skills of the preferred hand, and they suggested that it is more likely a prerequisite for than a consequence of handedness. Using magnetic resonance imaging (MRI) Klöppel, Mangin, Vongerichten, Frackowiak, and Siebner

(2010) investigated the sulcal surfaces in consistent adult right- and left-handers and in adult "converted" left-handers who had been forced to become dextral writers in childhood. In consistent right- and left-handers, they found an interhemispheric asymmetry in the surface area of the central sulcus with a greater surface contralateral to the dominant hand. This pattern was reversed in the converted group which showed a larger surface of the central sulcus in their left, non-dominant hemisphere. The authors concluded that this finding in converted left-handers indicated plasticity of the primary sensorimotor cortex as a consequence of forced use of the non-dominant hand.

If, as shown by Volkmann et al. (1998), the degree of performance asymmetry between hands is a reliable indicator of lateral asymmetry, the questions remain if handedness influences motor learning and if it is perhaps influenced through learning itself. The current state of research shows an ambiguous picture: in an early review, Provins (1967) discussed the anthropological foundations of human motor behaviour (in terms of spatio-temporal movement patterns) and concluded that there must be a hereditary as well as an environmental basis for the asymmetry in human preferential hand usage. The author assumed that training plays a crucial role in the development of handedness and that the differential development of skill asymmetry depends on previous experience. However, Cho, Park, Kim, and Park (2006) demonstrated that skill learning (as measured by a repeated tracking task) was not correlated with the degree of hand performance asymmetry in a speed tapping task (as an indicator of handedness) and argued that handedness might not directly influence skill learning. However, the simplicity of their motor task and the restriction to right-handed subjects only limits the validity of their conclusion. More convincing support for the assumption of a general advantage of non-right-handedness in complex motor tasks was given by Judge and Stirling (2003): left-handers (classified by a preference handedness inventory and the writing hand as an additional criterion) outperformed right-handers in a bimanual assembly task with alternating hands (Purdue pegboard test). Our re-analysis of means revealed a medium effect size (Cohen's $d = 0.6$). In regard to music-related motor tasks, there is some evidence that non-right-handed musicians have a sensorimotor advantage over right-handed musicians in selected instruments. For example, in a survey study, Christman (1993) observed weaker degrees of lateralization in players of instruments requiring temporally integrated bimanual motor activity (e.g., strings and woodwinds), as opposed to those instruments requiring more independent motor control (e.g., keyboard instruments). He assumed that ambidexterity could be beneficial for "integrated" instruments with a higher demand of bihemispheric sensorimotor control. In regard to instrumental creative achievement, Christman (2010) argued, using the example of Jimi Hendrix, that ambidexterity in terms of greater hemispheric intereaction could be beneficial for the sensorimotor integration of the roles of left and right hands in guitar playing and the writing of lyrics (for more information on left-handed guitar players see Engel, 2006).

Finally, non-right-handed subjects seem to have an advantage in selected music-related perceptual tasks. As Deutsch (1978) showed, moderately left-handed subjects were superior in a pitch memory task. A re-analysis of her results revealed a medium effect compared to the performance of strongly left-handed (Cohen's $w = 0.28$; see Cohen, 1988), and strongly right-handed persons (Cohen's $w = 0.34$) and a medium to large effect compared to the performance of strongly left-handed, and moderately right-handed subjects (Cohen's $w = 0.45$). The superiority of moderate left-handers was explained in terms of a duplication of representation of pitch information in both hemispheres, resulting in a more efficient retrieval of information from two separate loci and an increased overall probability of correct judgment. Perceptual differences between the right and left ear in right- and non-right-handers in a hearing task were also observed by Dane and Gümüstekin (2006). When subjects had to indicate the fade away of a test tone, right-handers showed a longer hearing duration for the right ear (large effect, Cohen's $d = 0.9$) and non-right-handers for the left ear (small effect, Cohen's $d = 0.2$). These results are in line with the assumption of handedness-specific advantages in auditory processing by Deutsch (1978).

In contrast to the aforementioned studies, some musical practitioners claimed that left-handed instrumentalists playing in a standard position might experience disadvantages, such as reduced musical expressivity, well-being and motor control (e.g., Mengler, 2004). Jäncke et al. (2006) reported on a left-handed professional pianist, who initially learned to play on a regular piano but, at a point in his professional career, switched to a reversed keyboard. Two-thirds of the time he played on reversed pianos, both for professional recordings and international performances. Laeng and Park (1999) compared the correctness of notes in piano playing of left-handed and right-handed amateurs, whose average keyboard training was two years, and novices. Subjects played simple scores (with a fast-moving melody in the right hand and a slow-moving accompaniment in the left hand) on a normal keyboard and inverted scores (with the fast-moving melody in the left hand) on a reversed keyboard. While both right-handed groups and the left-handed amateurs performed better on the normal keyboard (with the normal score), the left-handed novices performed better on the reversed keyboard (with the inverted score). The authors concluded that right-handed keyboards may well be an inept tool for the hands of left-handers.

On a more anecdotal level, early attempts to construct pianos with inverted keyboards were made already in the 19th century. For example, the Russian pianist and composer Joseph Wieniawski tried to stimulate the construction of inverted keyboards for left-handed pianists. In the 20th century, the left-handed German-Hungarian pianist Geza Loso felt constrained in his musical expressivity playing on a standard keyboard and decided to continue his career on a grand piano with an inverted keyboard. As he stated, "Geza Loso hopes that left-handed piano students may one day express their music abilities with the hands they are born with." (Loso, 2004) However, Loso's engagement for left-handed pianists has also been determined by commercial interest: as the owner of a publishing company for left-handed piano scores, he holds a patent on left-handed pianos. (For more details on the historical background of inverted instruments see also Kopiez & Galley, 2010.)

To summarize, from a scientific perspective, although there seems to be a slight advantage, it is not quite clear whether non-right-handedness is generally advantageous or disadvantageous for sensorimotor expert performance on a bimanually played instrument. However, from the perspective of musical practitioners, the question has yet to be answered whether there is potentially a general disadvantage for non-right-handed expert musicians playing in the standard position.

Rationale of the study and hypotheses

The aim of our study was to answer the question of whether playing in the standard position is disadvantageous for non-right-handed instrumentalists. The critical point is the operationalization of the dependent variable, "disadvantage". Thus, we employed two complementary approaches in our study: (1) On a subjective level we asked right- and non-right-handed string and piano players to rate their contentment with their expressive and technical skills, and to list the frequency of bodily discomfort (Experiment 1); (2) on an objective level we measured the performance skills of the dominant and non-dominant hands in right- and left-handed pianists in a standardized music-related performance task (scale playing with separate hands, see Experiment 2). In Experiment 1 we tested the hypothesis that a negative influence of non-right-handedness on the instrumental performance in standard playing position would be reflected in more frequent negative statements of dNRH musicians on the items (dependent variables) of general hand problems, bodily discomfort, problems with the playing position, expressive skills, and general sensorimotor skills.

Scale playing is a fundamental aspect of piano technique in classical music as well as in jazz, rock and pop music. The difficulty of temporal evenness in scale playing is a central aspect in the training of pianistic fluency in both hands and a well-established measurement of pianistic expertise (Jabusch, Alpers, Kopiez, Vauth, & Altenmüller, 2009). Therefore, in Experiment 2 we tested the sensorimotor performance of separate hands in the subgroup of right- and left-handed expert pianists. Against the background of existing studies on the relationship between handedness and hand performance in musicians (e.g., Jäncke et al., 1997), we would argue in favour of the observations of musical practitioners (e.g., Loso, 2004; Mengler, 2004, 2010) and predict a superior performance of the left over the right hand in left-handed and the right over the left hand in right-handed musicians (directional hypothesis). Our decision to include pianists only in Experiment 2 was motivated mainly by technical reasons. MIDI-based scale analysis provides a precise, reliable and valid measure of motor performance in pianists in a relevant and standardized motor task. As far as we know, there is currently no method available for the objective assessment of motor performance of individual hands in non-keyboard instrumentalists with a resolution, reliability and validity comparable with those of the MIDI-based piano performance measurement.

Experiment 1

Method

Participants. A total of 47 professional music performers (students and teachers at the Hanover University of Music, Drama and Media, Germany, mean age = 22.6 years, $SD = 3.6$ years, minimum = 17 years, maximum = 40 years) participated in the experiment (for details see Table 1). We conducted retrospective interviews (see Jabusch et al., 2009; Lehmann & Ericsson, 1996) to assess accumulated lifetime practice. Participants reported their practice quantity for each year of their musical careers. Values were summed up for the total duration of their piano training. Both handedness groups did not differ in age ($t(45) = 0.23$, $p = 0.82$), age at commencement of instrumental training ($t(45) = -0.5$, $p = 0.59$) or total accumulated practice time ($t(45) = 1.2$, $p = 0.23$).

Table 1. Description of sample of participants in Experiment 1

	n	Sex		Age	Age at beginning of musical training	Total accumulated practice time (hrs)
		Female	Male			
dRH	21	14	7	22.5 (2.7)	6.95 (3.3)	10120.5 (5981.5)
dNRH	26	17	9	22.7 (4.2)	6.54 (2.0)	12455.5 (7010.8)

Note. dNRH = designated non-right-handers, dRH = designated right-handers. Numbers in brackets indicate standard deviations.

Classification of handedness groups. The objective classification of handedness was assessed using a methodological approach based on speed tapping (see Peters & Durding, 1978) and a statistical classification procedure which has been recently introduced to handedness research (Kopiez et al., 2010). Participants performed speed tapping on a Morse key for 30 seconds with each hand. Participants tapped twice with a recovery phase of at least 15 minutes between trials. A Morse key (model by Junker Ltd., Germany; trigger point 300g), connected to a PC, was used, and tap intervals were recorded using the Software TAPPING (Tapping, 2008). Tapping was executed with the index and middle finger in combination while the wrist, the forearm and the other fingers were held in a fixed position on the desk. To avoid a start hand effect (Schulze & Vorberg, 2002), the start hand was allocated randomly. All scores were averaged over two trials. To avoid vibrations on the Morse key (which could result in accelerated tapping speed), we instructed the participants to break contact with the key after each tap. A lateralization coefficient [LC], which indicates performance differences between left and right hand, was calculated, $LC = 100 \times (L-R)/(L+R)$, with R being the median of inter-tap intervals for the right hand and L for the left hand. A high positive LC value indicated a dominance of the right hand, and a positive value near zero or a negative LC value was an indicator for a more balanced cerebral asymmetry or non-right-handedness (Bryden, Roy, Rohr, & Egilo, 2007). Annett's (2002) "right shift theory," with its basic discrimination between genetic right-handers (RH) and non-right-handers (NRH), served as the theoretical basis of our study. In a previous study (Kopiez et al., 2010), we were able to determine a classification threshold of $LC = 1.25$ for a participant's allocation to the group of designated RH ($LC > 1.25$) and designated NRH ($LC < 1.25$) by applying binary logistic regression. We use the term "designated" (d) handedness, resulting in the denomination "dRH" and "dNRH". Our methodological approach of statistical classification tries to approximate the "true" or genetic handedness as closely as possible.

Questionnaire on bodily discomfort, instrumental skills, and somatic-emotional lability. The assessment of bodily discomfort in instrumental performance was based on two questionnaires: first, we used a researcher-developed questionnaire for bodily discomfort (see Appendix 1) in which we assessed present and previous diseases, injuries and the subjectively-felt constraints in instrumental playing. Second, we used the 24-item inventory, recently developed by von Georgi (2006), to assess the so-called "negative bodily affectivity" (INKA-h, see Appendix 2) as a trait. Compared with other inventories for measuring somatic-emotional lability, such as the two-dimensional Positive Negative Affect Schedule (PANAS; see Watson, Clark, & Tellegen, 1988), the advantages of the inventory INKA-h are as follows: first, INKA-h measures discomfort (*Beschwerden*) on a five-point rating scale; second, INKA-h is a validated, one-dimensional inventory that results in a score for somatic-emotional lability as a trait (with only a weak correlation to bodily arousal). Additionally, there are statistical norms for INKA scores from a healthy German sample ($N = 797$). Finally, the problem of a skewed distribution of inventory raw scores (with a higher proportion of participants with minor discomfort) is solved by a double logarithm (ln) of (1) each item score and (2) the total INKA-h score. Thus, scores represent double logarithmic values (dln) which are characterized by normal distribution and can be analyzed with parametric statistical procedures. To control for a potential association between INKA-h scores and neuroticism traits, we conducted the NEO-Five Factors Inventory (NEO-FFI; Costa & McCrae, 1992; McCrae & John, 1992). The NEO-FFI is a multidimensional personality inventory that consists of 12 items (descriptions of behaviours), scored on five-point Likert scales, in each of five personality domains: (1) extraversion; (2) agreeableness; (3) conscientiousness; (4) neuroticism; and (5) openness to experience. The NEO-FFI has been shown to be reliable, valid, and consistent. For this study, only the dimension of neuroticism was considered.

Table 2. The relationship between handedness and different self-reported aspects of instrumental performance in all designated non-right-handed (dNRH) and right-handed (dRH) instrumentalists of Experiment 1. Values indicate frequencies of answers and proportion in percent (in brackets)

	Hand problems		Bodily discomfort		Playing position beneficial		Influence on expressive skills			Influence on general sensorimotor skills		
	yes	no	yes	no	yes	no	pos.	neg.	no	pos.	neg.	no
All musicians												
dRH ($n = 21$)	10 (47.6)	11 (52.4)	17 (80.9)	4 (19.1)	13 (61.9)	8 (38.1)	3 (14.3)	3 (14.3)	15 (71.4)	5 (23.8)	4 (19.0)	12 (57.2)
dNRH ($n = 26$)	15 (57.7)	11 (42.3)	23 (88.5)	3 (11.6)	21 (80.8)	5 (19.2)	11 (42.3)	2 (7.7)	13 (50.0)	11 (42.3)	3 (11.5)	12 (46.2)
χ^2	0.47		0.52		2.06			4.43			1.89	
Df	1		1		1			2			2	
p*	0.49		0.47		0.15			0.11			0.39	
Effect size (w)	0.10		0.10		0.21			0.30			0.20	
Pianists												
dRH ($n = 11$)	6 (54.5)	5 (45.5)	9 (81.8)	2 (18.2)	3 (27.3)	8 (72.7)	3 (27.3)	2 (18.2)	6 (54.5)	4 (36.3)	3 (27.3)	4 (36.3)
dNRH ($n = 12$)	7 (58.3)	5 (41.7)	10 (83.4)	2 (16.6)	10 (83.4)	2 (16.6)	5 (41.7)	1 (8.3)	6 (50.0)	5 (41.7)	2 (16.6)	5 (41.7)
χ^2	0.03		0.01		7.34			0.79			0.38	
df	1		1		1			2			2	
p*	0.85		0.92		< 0.01			0.67			0.83	
Effect size (w)	0.04		< 0.02		0.56			0.19			0.13	
String players												
dRH ($n = 10$)	4 (40.0)	6 (60.0)	8 (80.0)	2 (20.0)	5 (50.0)	5 (50.0)	0 (0.0)	1 (10.0)	9 (90.0)	1 (10.0)	1 (10.0)	8 (80.0)
dNRH ($n = 14$)	8 (57.2)	6 (42.8)	13 (92.8)	1 (7.2)	11 (78.5)	3 (21.5)	6 (42.8)	1 (7.2)	7 (50.0)	6 (42.8)	1 (7.2)	7 (50.0)
χ^2	0.68		0.88		2.14			5.74			3.05	
Df	1		1		1			2			2	
p*	0.41		0.35		0.14			0.06			0.22	
Effect size (w)	0.17		0.19		0.30			0.49			0.36	

Note. * = all p values two-tailed; ** = effect sizes in this section have been calculated based on the equation $w = \sqrt{\frac{x^2}{N}}$. Small effect size = 0.1, medium effect size = 0.3, large effect size = 0.5. For the theory of effect sizes see Cohen (1988).

Procedure. Retrospective interviews and tapping tests were conducted in a controlled lab. situation. The entire lab. procedure lasted about 60 minutes. After the classification of handedness, participants received questionnaires on discomfort and sensorimotor problems by mail. The filling in of the questionnaire took about 30 minutes. Subjects were blinded to the aim of the study, and no reimbursement was paid. All participants gave written informed consent. Institutional ethic committee approval was not required.

Results

The main results can be summarized as follows: a negative relationship between non-right-handedness and the rating of instrumental performance could not be observed either for all 47 participants or for the subgroups of pianists and string players (see Table 2). Although 80.8% of the dNRH musicians rated their playing position as beneficial, compared with 61.9% in dRH, this relationship between handedness and playing position remains non-significant ($\chi^2(1) = 2.06$, $p = 0.15$). The only significant result was observed for the subsample of pianists: 72.7% of the dRH pianists evaluated their playing position as non-beneficial compared with only 16.6% of the dNRH pianists ($\chi^2(1) = 7.34$, $p < 0.01$, $w = 0.56$). A similar, non-significant relationship could be observed for the influence of handedness on expressive skills for the whole sample: dNRH musicians indicated a positive influence in 42.3% of all cases, and no influence in 50.0%, while dRH reported a positive influence in 14.3% of all cases and no influence in 71.4% ($\chi^2(2) = 4.43$, $p = 0.11$). For the subsample of string players, a significant association between non-right-handedness and positive expressive skills was found ($\chi^2(1) = 5.74$, $p < 0.01$, $w = 0.49$). No other statistical significance for a negative relationship between non-right-handedness and items related to discomfort or performance skills was found. In the subgroup of string players, an inverse relationship between non-right-handedness and positively rated expressive skills could be observed, which nearly reached statistical significance (despite a large effect size of $w = 0.49$): 42.8% of dNRH string players rated this influence as positive and 50% reported no influence ($\chi^2(2) = 5.74$, $p = 0.06$) whereas none of the dRH string players reported a positive influence and 90% reported no influence.

Removal of participants with medical symptoms from the analysis. In the next step of data analysis, all participants with previous medical symptoms (e.g., tenosynovitis, back pain, scoliosis, or herniated disk) were removed from the data set, so as not to confound subjectively experienced bodily discomfort with medical symptoms of the musculoskeletal system. This decision affected six participants (two dNRH, four dRH). As Table 3 shows, no general statistical significance was reached in the relationship between non-right-handedness, discomfort, and performance-related skills. Due to the non-significant influence of previous medical symptoms on the relationship between handedness and the experience of discomfort at the instrument, we decided to include the aforementioned six participants in the sample for further analyses. Additionally, the non-reduced sample kept test power constant.

Handedness groups and somatic-emotional lability. To test for differences in the experience of general somatic-emotional lability, INKA-h scores were compared between handedness groups. As shown in Figure 1, there were no significant differences in mean somatic-emotional lability scores between dNRH and dRH (M dNRH = 2.34, $SD = 0.43$, M dRH = 2.47, $SD = 0.36$; $t(45) = -1.13$, $p = 0.26$ [two-tailed]). However, compared with a reference sample of healthy

Table 3. The relationship between handedness and different, self-reported aspects of instrumental performance for all designated non-right-handed (dNRH) and right-handed (dRH) instrumentalists in Experiment 1. Compared with Table 2, participants with previous disorders of the musculoskeletal system have been removed from data set. Values indicate frequencies of answers and proportion in percent (in brackets)

	Hand problems		Bodily discomfort		Playing position beneficial		Influence on expressive skills			Influence on general sensorimotor skills		
	Yes	no	yes	no	yes	no	pos.	neg.	no	pos.	neg.	no
All musicians												
dRH ($n = 17$)	8 (47.0)	9 (53.0)	14 (82.3)	3 (17.7)	11 (64.7)	6 (35.3)	3 (17.7)	2 (11.8)	12 (70.5)	5 (29.3)	3 (17.7)	9 (53.0)
dNRH ($n = 24$)	14 (58.3)	10 (41.7)	21 (87.5)	3 (12.5)	20 (83.3)	4 (16.7)	10 (41.7)	2 (8.3)	12 (50.0)	10 (41.7)	3 (12.5)	11 (45.8)
χ^2	0.50		0.21		1.87			2.65			0.69	
df	1		1		1			2			2	
p*	0.48		0.65		0.17			0.27			0.71	
Effect size (w)	0.11		0.07		0.21			0.25			0.13	

Note. * = all p values two-tailed.

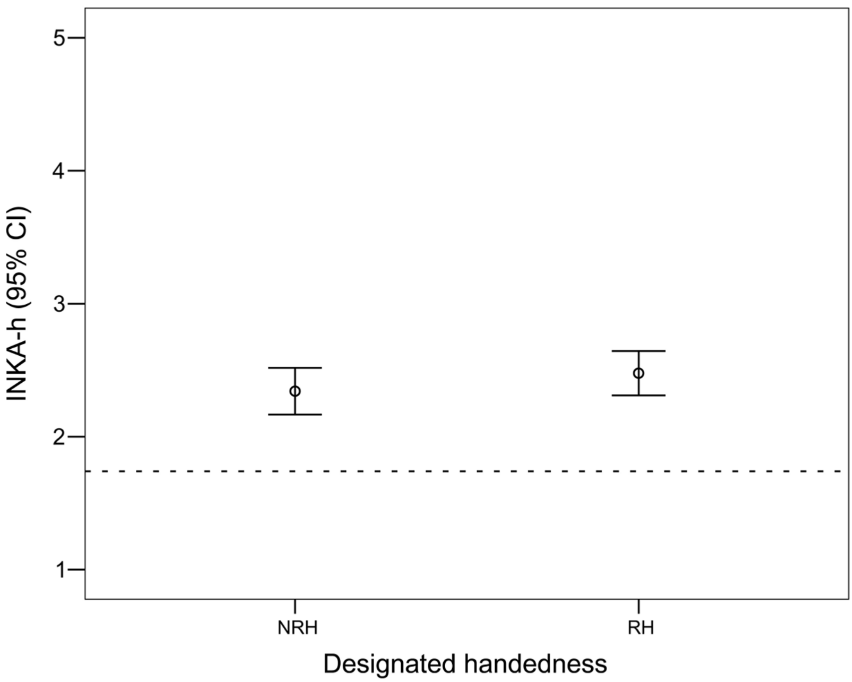

Figure 1. Ratings (error bars) of general discomfort (Inventory for Negative Bodily Affectivity, INKA-h) by two groups of handedness (designated right- and non-right-handers). Dashed line indicates average score for somatic-emotional lability of a healthy reference sample (N = 797).

subjects (N = 797), both handedness groups showed a significantly higher INKA-h score (dNRH: $t(25) = 7.03$, $p < 0.001$ [two-tailed], effect size $d = 1.32$, dRH: $t(20) = 9.22$, $p = < 0.001$ [two-tailed], $d = 1.94$).

Discussion

When looking at the whole sample together, in Experiment 1 none of the results were consistent with our hypothesis of a negative relationship between non-right-handedness and the performance in normal playing position regarding sensorimotor skills as well as the subjectively feeling of well-being at the instrument. If (statistically non-significant) associations between handedness and discomfort were to be discussed at all, tendencies would be observed in the opposite direction: dNRH musicians rated their playing position as more beneficial and less negative than did dRH musicians. The control for previous disorders (with medical symptoms) of the musculoskeletal system did not change this observation. In the subsample of pianists (Table 2), this positive association between dNRH and beneficial playing position becomes highly significant. The same positive relationship exists for the subsample of string players: the non-right-handed instrumentalist experienced a positive association with their expressive skills.

Does this mean that we can rule out a disadvantage of non-right-handedness on instrumental performance on a subjective level of evaluation? Against the background of current effect sizes, the answer is likely to be "yes". However, we have to bear in mind that all statistical relationships between handedness and subjectively perceived instrumental performance in Table 2 and Table 3 did not exceed an effect size of $w = 0.49$, with most effects being located between 0.10 and 0.30, corresponding to small and medium effects (Cohen, 1988; Rosnow & Rosenthal, 2009). For example, the question of hand problems in dNRH only achieved an effect of $w = 0.10$. Nearly the same indicators of magnitude of effects can be observed for the question of felt bodily discomfort in dNRH: Although 23 out of 47 musicians reported a subjectively-felt bodily discomfort in their actual playing position, this did not reach statistical significance and only indicates a small overall tendency.

Finally, handedness groups did not differ for general (habitual) somatic-emotional lability as measured by INKA-h. In fact, instrumentalists were characterized by a higher score of somatic-emotional lability, compared to the normal healthy population. Somatic-emotional lability seems to be related to other personality traits such as general emotional lability (e.g., neuroticism). For example, the correlation between INKA scores and N (neuroticism) scores of the NEO-FFI inventory (Costa & McCrae, 1992) in the general population is $r = 0.44$ (for more details see von Georgi, 2006, p. 285). In our sample of musicians, we could also observe a correlation between INKA-h and N scores from the NEO-FFI ($r(47) = 0.35$, $p < 0.01$ [one-tailed]). This finding is in keeping with previous observations by Kemp (1996) who concludes that "full-time music students display the highest levels of anxiety" (p. 93). Based on the close relationship between the INKA-h scores and tendencies toward neuroticism as well as Kemp's (1996) statement that "Cattell's anxiety is more or less equivalent to Eysenck's neuroticism" (p. 90), we might reason that instrumentalists in both handedness groups behaved "as usual" in their tendency towards an increased somatic-emotional lability. However, it remains questionable whether the result of non-significant differences between right- and non-right-handed professional instrumentalists is limited to this subjective approach (on the level of experienced discomfort and felt constraints), or if it may also be verified by an objective approach (for example, by the measurement of sensorimotor performance skills). This question will be addressed in Experiment 2.

Experiment 2

Method

Participants. A total of 19 professional pianists (students at the Hanover University of Music, Drama and Media, Germany, mean age = 23.1 years, *SD* = 2.4 years, minimum = 20 years,

Table 4. Description of sample of participants in Experiment 2

	n	Sex		Age	Age at beginning of musical training	Total accumulated practice time (hrs)
		Female	Male			
RH	10	6	4	23.3 (2.5)	5.6 (2.3)	18036.1 (8579.8)
LH	9	3	6	22.8 (2.6)	7.4 (2.3)	15489.1 (14382.5)

Note. RH = right handers (preference handedness according to the Edinburgh handedness inventory [LQ > 33]), LH = left handers (preference handedness according to the Edinburgh handedness inventory [LQ < -33]). Numbers in brackets indicate standard deviations.

maximum = 28 years) participated in the experiment (for details on the musical biography of participants see Table 4). No participant from Experiment 1 took part in Experiment 2. We conducted retrospective interviews (see Jabusch et al., 2009; Lehmann & Ericsson, 1996) to assess participants' accumulated lifetime practice. Participants reported their practice quantity for time periods of similar practice durations. Values were summed up for the total duration of their piano training. Both handedness groups did not differ in age ($t(17) = 0.45$, $p = 0.65$), total accumulated practice time ($t(17) = 0.47$, $p = 0.64$), or age at commencement of instrumental training ($t(17) = -1.78$, $p = 0.09$ [all *t*-tests two-tailed]). However, the right-handed group started slightly earlier with their instrumental training (mean age = 5.6 years, *SD* = 2.3) compared with the left-handers (mean age = 7.4 years, *SD* = 2.3).

Classification of handedness groups. In Experiment 1 we used an objective method of handedness classification (speed tapping) combined with a subjective evaluation of well-being at the instrument. In Experiment 2 we used a subjective method of handedness classification (preference handedness as measured by the well-established Edinburgh handedness inventory; see Oldfield, 1971) combined with an objective method of instrumental performance (scale playing). Our choice of the Edinburgh handedness inventory (EHI) instead of the speed tapping method for classification of handedness was mainly motivated by the constrained experimental situation: any measurement of hand performance differences always causes muscular exhaustion, which influences the subsequent measures. This effect can only be avoided by a sufficient time (e.g., one hour) for recovery. However, due to the limited total experimental time of one hour allowed by the participants (very busy expert pianists), our main interest was in the repeated scale playing performance data and thus no time was left for sufficient recovery. The EHI asks for the preferred hand used for a number of everyday activities. The laterality quotient is computed as $LQ = 100 \times (R - L) / (R + L)$, with the sum of activities performed by the left hand being L and the sum of activities performed by the right hand being R. This quotient indicates the self-assessed preference handedness of a participant. A positive value indicates the dominance of the right hand and vice versa. To accomplish a reliable separation of right-handers (RH) from left-handers (LH), the classification threshold for RH was set to $LQ > 33$ and for LH to $LQ < -33$ (entire scale range: −100 to +100). Only those participants with LQ values of > 33 (for right-handers) and $LQ < -33$ (for left-handers) were selected for participation in Experiment 2.

For a better understanding of the reliability of this classification method by EHI, it is helpful to consider the LQ values against the background of the LQ distribution in a large sample. Based on a large database of LQ values from the EHI ($N = 1{,}636$, age range = 17–40 years), less than 6.5% show a LQ of −33 or smaller and 88.6% show a LQ of +33 and higher (S. Christman, personal communication, 6 August 2010). If we compare these proportions to those of the distribution of LC values from speed tapping (same age range, $N = 1{,}198$) from the study by Kopiez et al. (2010), the proportion of 6.5% (LQ = −33 or smaller) corresponds to an LC value of −3.0 or smaller and the proportion of 88.6% (LQ = 33 or higher) to an LC value of 12.9 or higher. With the cut off value of LC = 1.25 for the classification of right- and non-right-handers in the population of musicians (and of LC = 1.89 for the group of nonmusicians, see Kopiez et al., 2010), the choice of an LQ of −33/+33 as a classification threshold based on EHI data is far from the critical LC value of 1.25 and thus avoids handedness misclassification. Assessment of preference handedness according to this procedure resulted in a number of nine left-handers (LH) and 10 right-handers (RH) in the sample of Experiment 2 (for details see Table 4).

MIDI based scale analysis. The procedure of scale playing and analysis of temporal unevenness was performed in accordance with a well-established protocol (Jabusch, Vauth, & Altenmüller, 2004). Scales were performed on a digital piano (KAWAI MP 9000) which was connected to a computer. For recording and generating MIDI files, commercially available music editing software was used (Musicator Win, V. 2.12; Music Interactive Technology; Bergen, Norway). Before the test, participants had the opportunity to warm up for five minutes using their own warm-up habits and to get used to the keyboard. According to a standardized test protocol (Jabusch et al., 2004), sequences of 10–15 repetitions of C major scales were played over two octaves (range: C3–C5) in both playing directions (inward and outward), with each hand separately. Participants were asked to play in legato-style (notes were played in a smooth, connected manner). Fingering was according to the regular C major fingering (1-2-3-1-2-3-4-1-2-3-1-2-3-4-5 and reverse) for all participants. Scales were played in 16th notes, and the tempo was standardized at 160 beats per minute for a quarter note, paced by a metronome. Thus, scales were played with 10.66 note onsets per second (93.75 ms per note). Interonset intervals (time between onsets of two subsequent notes) for all individual notes of the scales were analyzed using the researcher-developed software *Scale Analysis* (Jabusch, 2005) which was originally developed for the quantification of movement disorders in pianists (Jabusch, 2006; Jabusch et al., 2004, 2009; Jabusch & Altenmüller, 2006). Scale analysis was performed for each hand and in both directions separately. Temporal unevenness of interonset intervals in scale playing was previously reported to be a precise and reliable indicator of pianists' motor control (Jabusch et al., 2004). Medians of the standard deviations of interonset intervals (medSDIOI in milliseconds) of all performances were calculated for each hand and playing direction.

Procedure. Participants first completed the handedness inventory in a controlled lab. situation and were then allocated to the respective groups (RH/LH). After performance of the scale-playing task, the retrospective interviews were conducted. The entire procedure lasted about 60 minutes. Participants were blinded to the aim of the study and received no reimbursement. All participants gave written informed consent. Institutional ethic committee approval was not required.

Results

Differences between handedness groups. The total descriptive results for all combinations of handedness groups, hands and playing directions are shown in Table 5. Due to the limited number of subjects, we decided to use non-parametric statistical procedures for data analysis. To evaluate

Table 5. Performance of right-handed (RH) and left-handed (LH) pianists in a standardized performance task (scale playing). Degree of evenness is indicated by the median of the standard deviation of interonset intervals (medSDIOI in milliseconds) based on repeated scale performance (10-15 repetitions, tempo: 16th notes at 160 bpm. For details regarding the analyses see text. Performance is indicated for separate hands and playing directions (inward vs. outward)

		Playing direction	
Handedness Group	Hand	Inward direction	Outward direction
RH ($n = 10$)	Left hand	12.7	13.2
	Right hand	10.1	9.7
LH ($n = 9$)	Left hand	12.7	15.6
	Right hand	11.1	11.7

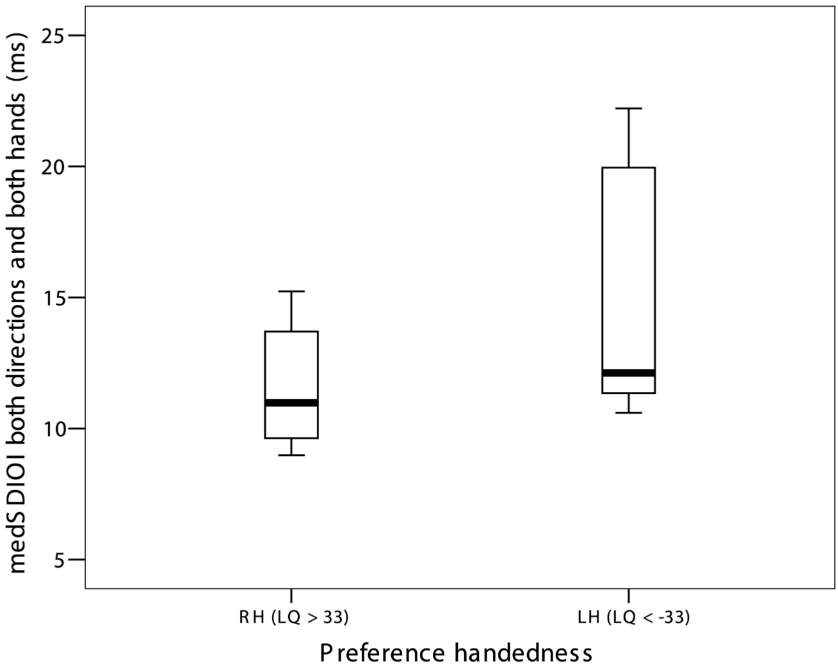

Figure 2. Boxplot of (statistically non-significant) differences in evenness of scale playing between handedness groups for both hands and playing directions. Higher scores indicate a higher temporal unevenness.

for differences in unevenness of scale playing between groups (medSDIOI in milliseconds), a Mann-Whitney *U* test was conducted for right-handers (RH) and left-handers (LH). The results for separate groups (Figure 2) did not show a significant difference between groups ($z = -1.38$, $p = 0.16$ [two-tailed]; average rank in RH: 8.30, average rank in LH: 11.89).

Differences between handedness groups, playing direction and hands. In a next step we analyzed differences between playing directions (inward vs. outward) in handedness groups. The reason for the analysis of different playing directions is the difference in hand and finger movements for each direction: scale playing in the outward (ulnar) playing direction requires so-called thumb-under movements (3-1 and 4-1 fingering), whereas scale playing in the inward (radial) playing direction requires finger cross-over manoeuvres (1-3 and 1-4 fingering). As previously described by Jabusch (2006), fundamental differences exist between the movement patterns of both playing directions, especially in the preparation phases of thumb-under movements and finger cross-over manoeuvres.

In the last step of data analysis, we analyzed differences in evenness for the interaction between the variables handedness group, playing direction and hand. Box plots of results are shown in Figure 3. To test our directional hypothesis of a general superiority in evenness of the left hand in LH and the right hand in RH, statistical group comparisons were conducted. For the evaluation of differences, Wilcoxon two-related samples tests were conducted. Four statistically-significant differences between hands were found: for RH in the inward playing

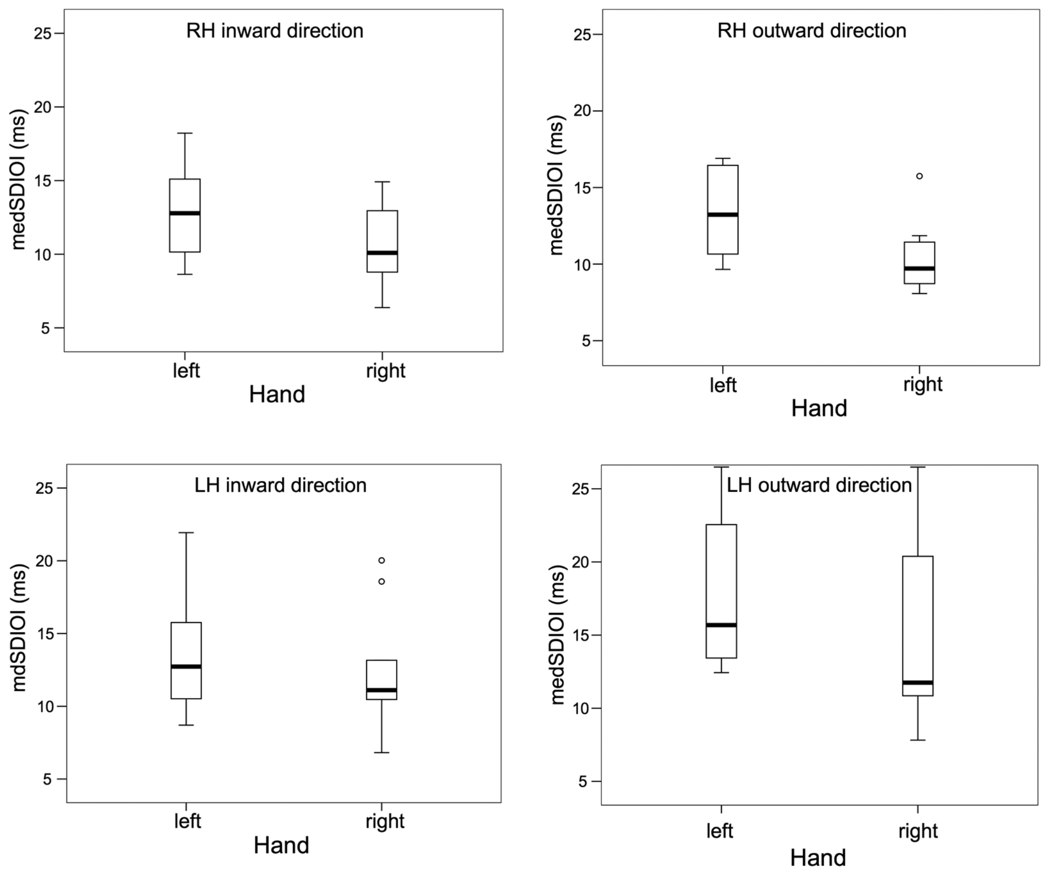

Figure 3. Boxplots of differences in evenness in scale playing between handedness groups, playing directions and hands in pianists. Degree of evenness is indicated by the median of the standard deviation of interonset intervals (medSDIOI in milliseconds). All differences between hands became statistically significant (Wilcoxon signed ranks test, upper left panel: p = 0.05, upper right panel: p = < 0.01, lower left panel: p = 0.03, lower right panel: p = 0.02 [all tests one-tailed]).

Table 6. Correlations between variables of musical expertise and scale performance: Results are indicated for the total sample of participants (right-handers and left-handers)

medSDIOI (ms)	Age at beginning of piano playing	Number of years at the piano	Accumulated practice time (hrs)	Actual practice time (hrs)
Left hand inward	0.32	−0.39	−0.47*	−0.48*
Left hand outward	0.53*	−0.33	−0.23	−0.19
Right hand inward	0.37	−0.46	−0.46*	−0.62**
Right hand outward	0.28	−0.43	−0.50*	−0.59**

Note. Spearman's rho: * = $p < 0.05$; ** = $p < 0.01$ (two-tailed).

Table 7. Correlations between indicators of expertise and asymmetry between evenness of hands in scale playing in right- and left-handers (L minus R value > 0: better right hand performance, L minus R value < 0: better left hand performance)

medSDIOI (ms) L minus R (outward)	Number of years at the piano	Accumulated practice time (hrs)	Actual practice time (hrs)
Right-handers ($n = 10$)	−0.10	0.06	0.20
Left-handers ($n = 9$)	0.60	0.68*	0.56

Note. Spearman's rho: * = $p < 0.05$ (two-tailed).

direction (upper left panel; $z = -2.39$, $p = 0.05$, effect size $d = 0.92$)[1], for RH in the outward playing direction (upper right panel; $z = -2.80$, $p < 0.01$, $d = 1.27$), for LH in the inward playing direction (lower left panel; $z = -1.95$, $p = 0.05$, $d = 0.78$), and for LH in the outward playing direction (lower right panel; $z = -2.07$, $p = 0.02$, $d = 0.87$ [all tests one-tailed; due to the robust non-parametric statistical procedure, repeated analyses with removed outliers from Figure 3 did not show different results]). We would like to point out that all effects are contrary to the directional hypothesis and that the right hand performance was always characterized by a better performance (higher degree of evenness).

Relationships between indicators of instrumental expertise and scale performance. In the last step of data analysis we looked at relationships between the degree of unevenness in scale playing and indicators of musical expertise as obtained from the musical biography questionnaire. We conducted correlational analyses between the performance data (medSDIOI) for the left and right hands in the inward and outward playing directions and the four biographical variables: (1) age at commencement of piano training; (2) number of years at the piano; (3) total accumulated practice time; and (4) actual practice time. As indicated by Table 6, significant results were found for each of the four selected indicators of expertise. Two indicators correlated significantly with the right-hand performance in outward playing direction: accumulated practice time (Spearman's rho = −0.50, $p < 0.05$, $d = -1.15$)[2] and actual practice time (Spearman's rho = −0.59, $p < 0.01$, $d = -1.46$). In other words, little accumulated practice time, and little actual practice time were associated with a high degree of unevenness in scale playing for the right hand in the outward direction. Concerning the right hand inward direction, the actual practice time correlates most with a low degree of unevennes in scale playing (Spearman's rho = −0.62, $p < 0.01$, $d = -1.58$), followed by the accumulated practice time (Spearman's rho = −0.46, $p < 0.05$, $d = -1.03$) and number of years at the piano (Spearman's rho = −0.46, $p < 0.05$, $d = -1.03$). For the left hand outward playing direction, we observed a significant correlation only between the age at commencement of piano playing and degree of unevenness (Spearman's rho = 0.53, $p < 0.05$, $d = 1.25$). For the left hand inward direction, significant correlations were found for the accumulated practice time (Spearman's rho = −0.47, $p < 0.05$, $d = -1.06$) and the actual practice time (Spearman's rho = −0.48, $p < 0.05$, $d = 1.09$ [all tests two-tailed]).

Is the asymmetry between hand performance and the performance advantage of the right hand observed in left- and right-handers (Figure 3) influenced by the practice quantity? To answer this question, we conducted a correlational analysis between (1) the degree of asymmetry between hand performance (medSDIOI left minus right hand, with a positive value indicating the superiority of the right hand) for both handedness groups and (2) the indicators of instrumental expertise (number of years at the piano, accumulated practice time, and actual practice time; see Table 7). Results indicated one statistically-significant relationship in left-handers between hand performance asymmetry (in favour of the right hand) and total accumulated practice time as an indicator of instrumental expertise (Spearman's rho = 0.68, $p < 0.05$, $d = 1.85$).

Discussion

The main finding of Experiment 2 was that there was no evidence for a sensorimotor disadvantage of left-handedness in expert pianists performing a standardized music-related motor task. Overall, no differences in the evenness of scale playing were found between handedness groups (see Figure 2). Rather, there was a general tendency of the right hand to play with a higher degree of evenness compared with the left hand (see Figure 3). This asymmetry in favour of the right hand was seen in right-handers and left-handers. We assume that this asymmetry bias in favour of the right hand is influenced by the long-lasting intensive practice at the piano. Support for this assumption was given by correlational analyses between indicators of musical expertise and hand asymmetry scores: the best indicator of expertise, the total accumulated practice time, was significantly correlated with the right-hand performance superiority in left-handers in the (difficult to play) outward playing direction (see Table 7). This finding is in line with

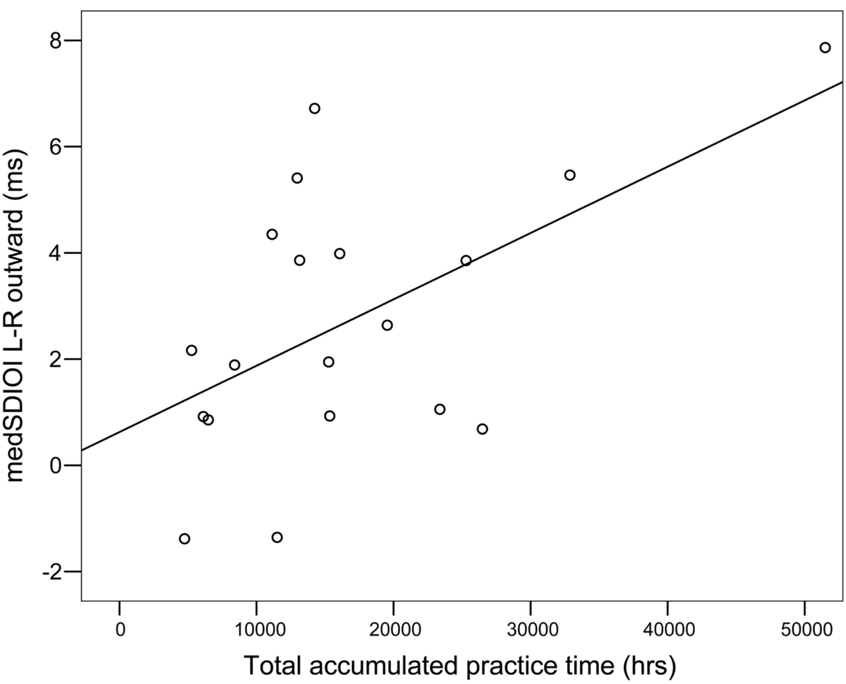

Figure 4. Correlation between left minus right hand performance asymmetry (scales in outward playing direction) in 19 pianists and total accumulated practice time (Spearman's rho = 0.43, p = 0.03 [one-tailed]). Scatterplot indicates an increased evenness of right hand performance with increasing accumulated practice time.

previous studies on the role of accumulated practice time for the acquisition of outstanding musical skills (e.g., Ericsson, Krampe, & Tesch-Römer, 1993; Lehmann, 1997). We found no significant correlations between indicators of expertise and asymmetry in scale performance between hands for right-handers. The significant correlation between total accumulated practice time and the asymmetry in scale performance for the entire sample is shown in the scatterplot of Figure 4 (Spearman's rho = 0.43, $p = 0.03$ [one-tailed], $d = 0.95$). This correlation strongly suggests that the right-hand performance superiority observed in left-handers was a consequence of a practice-induced improvement of the right hand. However, due to the limited number of participants in each handedness group, we should bear in mind that this correlation remains sensitive to outliers. For example, the removal of the upper right participant (Figure 4) from the sample changes the statistical significance of the correlation, although it still has a medium effect size (Spearman's rho = 0.32, $p = 0.09$, $d = 0.68$).

But how can the superiority of the right hand be explained? A first explanation might be based on a perceptual focus effect: the melodies in the classical-romantic piano repertoire constitute predominantly the highest voice that is performed with the right hand. Furthermore, the melodies are performed more loudly and sound slightly earlier than the usually softer accompaniment (Goebl, 2001). These performance behaviours render the perceptual salience of melodies considerably higher than those of other parts of the music texture, so that the right hand receives closer attention by the practicing pianist over the years (and thus establishes a finer timing control) than the left. This explanation is supported by results from previous studies on pitch errors in piano performance which found fewer errors in the melodies (performed by the outer right-hand fingers) than in the non-melody parts (Palmer & van de Sande, 1993).

How can long-term piano practice induce a performance advantage in the right hand as compared to the left hand? Although the above perceptual explanation is worth considering, we would like to discuss another explanation for the right hand superiority: the hypothesis of an overall right-hand bias effect of the piano literature.

Right hand bias in piano literature. Aside from other aspects of technical difficulties in piano playing, a right hand bias in the piano literature should result in a positive difference score of right minus left hand note counts. To test this assumption, we calculated the note counts (in the printed score) from three 19th century collections of piano music: Beethoven's 32 Piano sonatas (notes in the left hand: 122,650; notes in the right hand: 133,064); Chopin's 24 Preludes Op. 28 (notes in the left hand: 9,290; notes in the right hand: 9,415); and Chopin's collection of 52 Mazurkas (notes in the left hand: 26,308; notes in the right hand: 28,087).

As Figure 5 shows, the difference scores for note counts (right minus left hand) supports our assumption of a higher number of notes to be performed by the right hand. Although this right hand bias might be considered small (Beethoven Sonatas, median: 4.84%, min.: −35.90, max.: 33.53%; Chopin Preludes, median: 10.05%, min.: −70.66, max.: 58.60; Chopin Mazurkas: median: 1.03%, min.: 27.00%, max.: 38.45%), we should bear in mind that these small differences in increased right hand training may accumulate over the years of practice and result in a significant sensorimotor training effect that compensates (and even over-compensates) for the naturally-given hand asymmetry with a left hand dominance in left-handers. As a result of this bias, left-handed pianists adapt to the demands of the piano repertoire and improve the precision of their non-dominant right hand to the same superior level (compared with the left hand) as do right-handed pianists. This assumption of a neurological adaptation effect is supported by the findings of Gaser and Schlaug (2003). The authors investigated structural changes in response to long-term motor training in right-handed pianists and found a

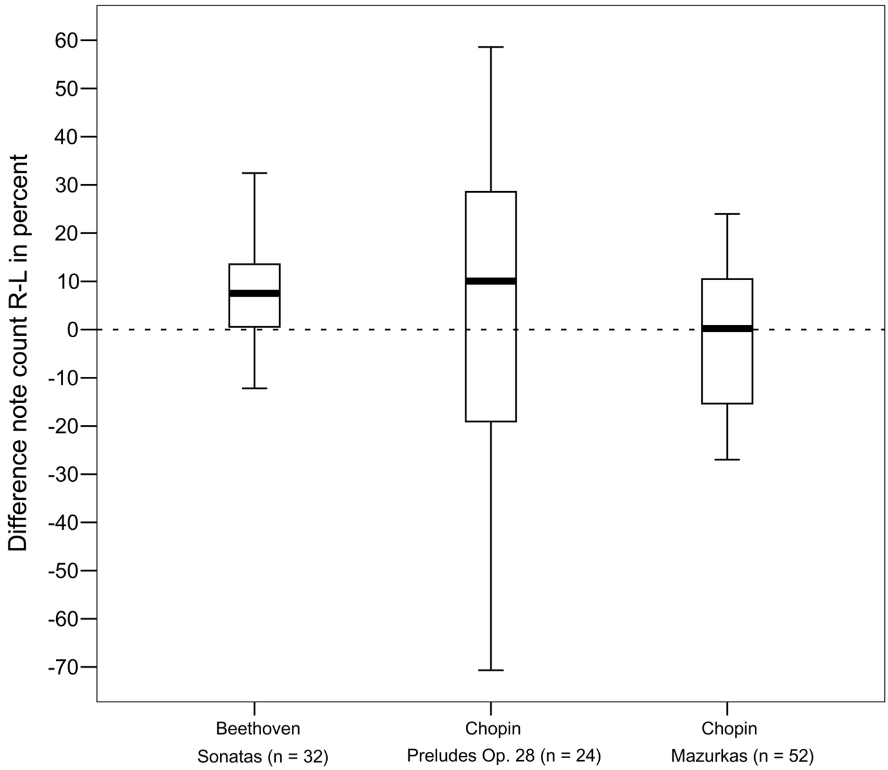

Figure 5. Boxplots of differences in note counts (right minus left hand) for three collections of piano music. Positive medians indicate a higher proportion of notes in the right hand.

correlation between gray matter volume in the left cerebellum and left inferior frontal gyrus, and the degree of pianistic expertise. This left hemispheric bias in neuroplastic changes is in line with the right hand bias in note counts of our collection of piano music.

General discussion

In the two studies conducted, we inquired about the potential disadvantage of non-right-handedness on instrumental performance in expert musicians. This hypothetical disadvantage was based on statements of musical practitioners (e.g., Mengler, 2004) who hypothesized that non-right-handed string players performing in the standard playing position might experience disadvantages in sensorimotor and expressive skills. There are also similar reports on perceived disadvantages from left-handed pianists (Loso, 2004; Seed, n.d.). However, arguments for an advantage of non-right-handers in motor learning have also been made (e.g., Judge & Stirling, 2003). We employed two complementary approaches in our study: (1) on a subjective level we asked right- and non-right-handed string and piano players to rate their contentment with their expressive and technical skills, and to list the frequency of bodily discomfort (Experiment 1); (2) on an objective level we measured the performance skills of the dominant and non-dominant hands in right- and left-handed pianists with a standardized music-related performance task (Experiment 2). The results of Experiment 1 were not consistent with the hypothesis of a disadvantage for non-right-handers performing in the non-inverted playing position – either for pianists or string players. In Experiment 2, the influence of handedness on a standardized and music-related performance task was investigated by scale playing at the piano. Temporal unevenness of interonset intervals in scale playing has previously been identified as a precise and reliable indicator of pianists' motor control (Jabusch, 2006; Jabusch et al., 2004). In terms of a directional hypothesis, it was predicted that non-right-handers (or phenotypical left-handers) perform with a higher precision (temporal evenness) when playing scales with their dominant left hand and right-handed pianists when playing with their right hand. However, results gave no support for this prediction: irrespective of handedness, significantly higher temporal precision was found for the right hands in both groups. Thus, we assume that professional musicians adapt to the standard playing position regardless of their individual handedness. Handedness-based asymmetry in motor performance is compensated, and even over-compensated, for by intensive and long-lasting practice on a non-inverted instrument. This assumption of a long-term adaptation process is supported (1) by the strong influence of variables related to expertise acquisition (accumulated practice time, years at the instrument etc.) on motor control in scale playing and the right hand performance superiority, and (2) by the right-hand-biased piano literature. One of the best predictors for right-hand superiority for the scale performance in the difficult outward playing direction was found to be the accumulated and actual practice time (see Tables 6 and 7) – and not the mere years of piano playing. This finding is in line with past research on the eminent role of deliberate practice in skill acquisition and maintenance (e.g., Ericsson, 1996; Ericsson et al., 1993; Krampe & Ericsson, 1996).

If non-right-handedness is disadvantageous for instrumentalists who want to become professional musicians (but are forced to play in the standard position), we could expect a reduced incidence of non-right-handers in music students. However, the main result of our previous study (Kopiez et al., 2010) was that the proportion of designated non-right-handers in both groups of instrumentalist (pianists and string players) is significantly higher than the incidence of about 10–12% of self-declared left-handed musicians as generally reported in other studies. Surprisingly, among string players we found a proportion of 35% designated non-right-handed players and among pianists one of 27%. This means that the incidence of (presumptively genetic) non-right-handers (NRH) in the population of instrumental performers has been significantly underestimated up to now. Our finding is in keeping with the survey study by Laeng and Park (1999): the authors found no evidence for a reduced incidence of left-handers in students at a school of music. In the case of an assumed disadvantage effect for NRH performing an instrument in the standard (right-handed) position, a significantly lower proportion of NRH would be expected in professional musicians. Finally, professional classical musicians only very rarely perform their instrument in the inverted playing position as did the pianist reported by Jäncke et al. (2006). None of our string player subjects did so.

Our results have much relevance for music education. Due to the small body of controlled studies on the influence of handedness on instrumental performance, we propose to be very cautious about premature recommendations to instrumental beginners to invert the playing position. This aspect is of particular relevance to string players. Given the strong traditions in the classical music business, playing in an inverted position might even result in a life-long difficulty for a string player to get a position in a classical orchestra. Moreover, switching to an inverted playing position would require a change in the instrument (e.g., restringing of string instruments).

Despite our main conclusion that non-right-handed expert musicians playing in the standard position do not show reduced sensorimotor or other performance-related skills or a limited well-being, we cannot rule out completely that there might be a minority of non-right-handers who feel uncomfortable or constricted when playing in the standard position. However, currently available methods do not allow us to identify those non-right-handed individuals who would definitely benefit from an instrumental training in the inverted playing position at the beginning of their music education.

Limitations and suggestions for future research

The main problem of handedness research is the small number of non-right-handed subjects. In our study, it took much effort to identify those persons and convince them to participate in a study. To avoid small cell frequencies in statistical analyses it would be necessary to look for a large number of non-right-handed musicians, although this might take up more resources than were available for our study. In Experiment 2 some statistical tendencies would have more easily reached significance with a higher number of subjects. In Experiment 2, it would also have been worthwhile to have additional tasks to the standardized scale playing, such as the performance of technically-difficult passages. These tasks might have increased the validity of measurement and given additional information about technical proficiency.

Although scale playing is a well-established and validated protocol in movement analysis at the piano, there is currently no comparable procedure for string instruments. The movement coordination in string instruments needs a different approach. As Mengler (2010, p. 80ff.) mentioned, the bowing hand (the so-called "action hand") initiates the movements of the left hand. Thus, the bowing (right) hand requires high demands in spatial coordination and force control which is indispensable for constant sound production. As a consequence, a measurement of sensorimotor performance in string players should consider movement evenness in slow bowing tasks or in fast tone repetitions (see Mengler, 2010, p. 812; von Hasselbach, Gruhn, & Gollhofer, 2010). However, this measurement requires technically-demanding facilities such as motion capture systems.

Our reasoning that the higher demands of piano literature cause adaptive effects in pianists was based on note counts for the right and left hand. We could imagine that the expert rating of difficulty for right and left hand separately would be more informative than mere note counts. Finally, all our findings cannot be interpreted in terms of causality. The only way of identifying the processes of sensorimotor adaptation would require a prospective long-term study, starting from the beginning of instrumental lessons. This approach remains a challenge to handedness research.

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Notes

1. Post hoc calculation of effect sizes in this section were conducted with the software G*Power V 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007).
2. For the calculation of effect size *d* for correlations we used the equation $D=\frac{\sqrt{\frac{1}{pq}}\times r}{\sqrt{1-r^2}}$ with *p* and *q* representing the proportion of the sub-samples at the total sample (see Sedlmeier & Renkewitz, 2008, p. 298).

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Appendix 1. Questionnaire for bodily discomfort in musicians

A. General data

Surname, first name ________________________ Subject # ___________

1. Do you have serious health problems or did you have such problems in the past (e.g., injuries or other diseases such as hypertension, diabetes, depression)?

Please mark:

Diseases:	❒ yes ❒ no	if yes, which and since when?: ____________________
Accidents:	❒ yes ❒ no	if yes, which and since when?: ____________________
Surgery:	❒ yes ❒ no	if yes, which and since when?: ____________________

Long-term and regular intake of drugs:

❒ yes if yes, which and since when?: ____________________
❒ no

B. General sensorimotor discomfort

2. Have you ever had sensorimotor problems at the instrument since the beginning of your study? (e.g., trilling difficulties or velocity problems in one hand).

Please mark:
❒ no, never
❒ yes, rarely
❒ yes, occasionally
❒ yes, frequently
❒ yes, always

If yes, with what kind of playing technique problems was it associated?

____

If yes, which hand was affected?

❒ right hand ❒ left hand ❒ both hands

If yes, how do you estimate the severity of problems?

❒ marginal ❒ moderate ❒ considerable

3. If you have ever had pain at the instrument, how would you rate the strongest ever experienced pain on a scale from 0 to 10? (0 = no pain, 10 = unbearable)

Please mark:

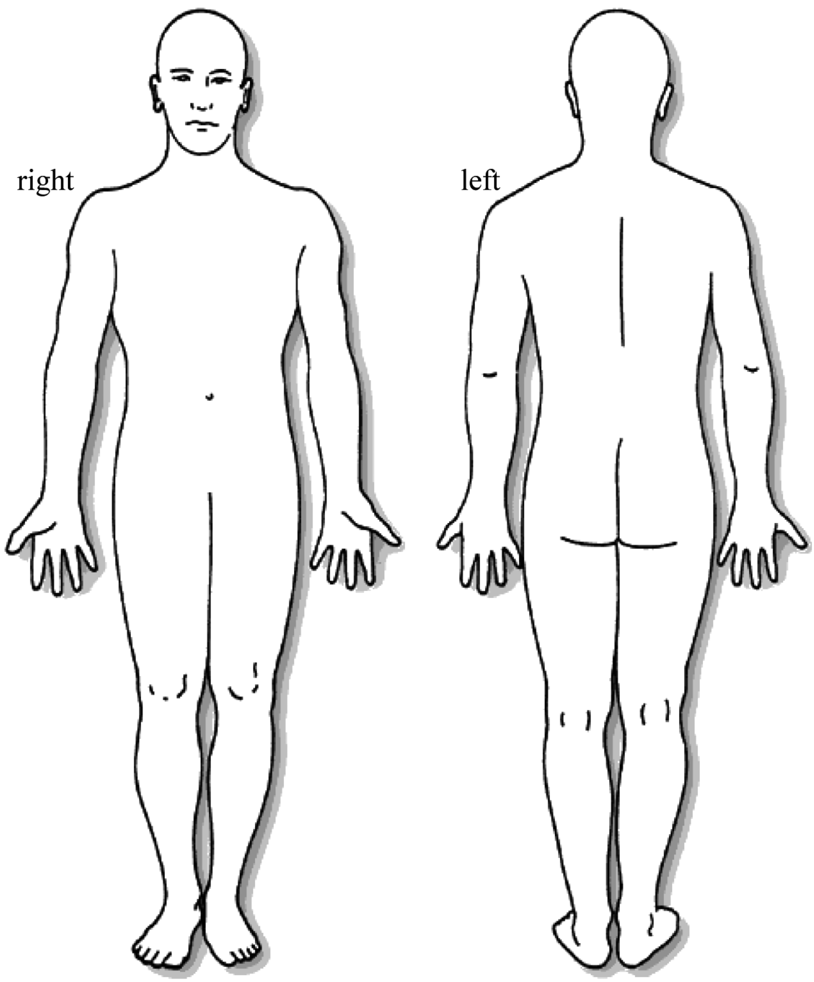
❒ 0 ❒ 1 ❒ 2 ❒ 3 ❒ 4 ❒ 5 ❒ 6 ❒ 7 ❒ 8 ❒ 9 ❒ 10

4. Do or did you have bodily discomfort in relation to instrumental performance?

❒ no ❒ yes, namely ______________________________

If no, please continue with question #6

If yes, please mark in the figure below the affected regions with a cross (X), where you experienced the strongest discomfort and with a circle (O) any additionally affected regions.



C. Current playing situation

5. How would you rate your current (conventional) playing position with regard to your performance skills?

❒ the conventional playing position is advantageous
❒ the conventional playing position is disadvantageous

Why is the current playing position disadvantageous? ______________________________

6. Do you think your handedness has a positive/negative/no influence on your performance skills?

On playing technique and dexterity:

❒ positive
❒ negative
❒ no effect

On expressive skills:

❒ positive
❒ negative
❒ no effect

Appendix 2. Inventory for Negative Bodily Affectivity (INKA-h) (von Georgi, 2006).

The table shows a number of items related to bodily discomfort. Please mark which discomfort you tend to suffer from. Please rate the degree you feel constricted by the respective discomfort.

	○ not present	○ marginal	○ mild	○ vastly	○ severe
Exhaustibility					
Lightheadedness					
Palpitations					
Feeling of fullness					
Pressure-sensations in the head					
Stabbing chest pains					
Disequilibrium					
Hot flushes					
Insomnia					
Nausea					
Headache					
Heart trouble					
Leg fatigue					
Shortness of breath					
Aching limbs					
Fatigue					
Neck pains					
Shivers					
Back pain					
Dizziness					
Lump in the throat					
Feeling of weakness/languor					
Tiredness					
Numbness					