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The advantage of a decreasing right-hand superiority: The influence of laterality on a selected musical skill (sight reading achievement)

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Abstract

In this study, the unrehearsed performance of music, known as 'sight reading', is used as a model to examine the influence of motoric laterality on highly challenging musical performance skills. As expertise research has shown, differences in this skill can be partially explained by factors such as accumulated practise and an early start to training. However, up until now, neurobiological factors that may influence highly demanding instrumental performance have been widely neglected. In an experiment with 52 piano students at a German university music department, we could show that the most challenging musical skill, sight reading (which is characterized by extreme demands on the performer's real time information processing), is positively correlated with decreasing right-hand superiority of performers. Laterality was measured by the differences between left and right-hand performance in a speed tapping task. SR achievement was measured using an accompanying task paradigm. An overall superiority of 22% for non-right-handed pianists was found. This effect is gender-related and stronger in non-right-handed males ($r(24) = -0.49$, $p < 0.05$) than in non-right-handed females ($r(28) = -0.16$, $p > 0.05$). We conclude that non-right-handed motoric laterality is associated with neurobiological advantages required for sight reading, an extremely demanding musical subskill.

Keywords: Music performance; Handedness; Brain asymmetry; Musical ability; Interhemispheric communication

An increased prevalence of non-right-handed laterality has been found in musicians (Götestam, 1990) and in some athletes (for an overview see Gorynia & Egenter, 2000, p. 15) and can be a neurological advantage. It has been hypothesized that non-right-handed laterality may be associated with neurobiological advantages required for music making. As could be shown in previous studies, creative musical abilities in males, such as improvising or composing, are positively correlated with a tendency to left-handedness (Hassler & Birbaumer, 1988). However, nothing is known about the influence of motoric laterality on the acquisition of extremely demanding sensorimotor skills in music performance. In our study, we investigated the influence of hand laterality on the unrehearsed performance (so-called 'sight reading' [SR]) of piano accompaniment. SR is one of the most challenging performance skills (McPherson, 1995). The immediate translation of the music score's symbolic notation into finger movements and the extremely time-critical accompaniment of a singer or instrumentalist require excellent pianistic skills, as well as an extensive knowledge of stylistic musical features. However, excellent piano technique alone is not sufficient to be a good sight reader. Expertise, as measured by the lifelong accumulated amount of SR practice, is a strong predictor for SR achievement (Lehmann & Ericsson, 1996), but it remains open as to whether performance differences in SR could also be attributed to the brain's functional asymmetry as represented by laterality bias in hands.

Motoric laterality is a well-known phenomenon and about ninety percent of humans are self-declared right-hand writers (Perelle & Ehrman, 1994). According to the majority of studies, this asymmetry in the use of hands is a result of differences in brain organisation (see for example Annett, 2002; Halpern, 1996; Jones & Martin, 2000; Laland, Kumm, Van Horn, & Feldman, 1995). Since the 19th century it has been known that language is also lateralized and primarily controlled by the left hemisphere (for a review see Price, 2000). The reasons for laterality have been discussed intensively, but without

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a clear preference for the evolutionary or the ontogenetic perspective (Corballis, 2003). To obtain a better understanding of the relationship between brain asymmetry and psycho-motor performance, we decided to use a selected music performance task as a model. For our study we chose the unrehearsed (sight read) accompaniment of a solo instrument. SR in the field of piano accompaniment is characterized by extreme demands on the performer's real time visual, auditory and sensorimotor information processing. It depends on the performer's capacity to process complex visual input (the score) under real-time constraints (e.g., the accompaniment of a solo instrument) and without the opportunity of error correction. As Sloboda (1985, p. 68) describes, many musicians find fluent SR very difficult. However, as McPherson (1993) and Rayner (1998) claim, sight reading is a skill which is required by all musicians, and is not only of particular interest for musical occupations such as the piano accompanist, the conductor, or the correpetiteur (for a more detailed explanation of the flow of influences between these skills see McPherson, 1995; McPherson, Bailey, and Sinclair (1997); McPherson and Gabrielsson (2002)). However, as Sloboda (1985, p. 69) states, it may well be that increased ability in SR is the result of other variables. In our study, we assume that the degree of brain asymmetry could be one of these influential variables. Nevertheless, up until now, there has been no study that considers the influence of neurobiological factors on musical achievement. As Lee (2004) and Lee and Kopiez (2005) could demonstrate in regression analyses, speed of information processing (so-called 'mental speed') plays a crucial role in SR and is assumed to be primarily determined by individual neurological conditions. Another influential factor, which, in this study, is assumed to be of importance for pianists, is the degree of left–right laterality. It is obvious that outstanding achievement in a bi-manual challenging task is only reached if performance differences between hands are minimal and bi-manual coordination is high. The degree of laterality could therefore be of central importance for the total achievement in a bi-manual task such as piano SR.

1. Laterality and psychomotor performance

Laterality has an influence on psychomotor performance differences between hands. As Gorynia and Egenter (2000) could show, intermanual coordination in alternating finger tapping is higher in left-handers than in right-handers, especially in those left-handers who are less lateralized. The authors conclude that handedness is a decisive factor for intermanual coordination. In the study by Nalçacr, Kalaycioglu, Çiçek, and Genc (2001), the authors were able to show that the distribution of hand preference is associated with left-hand speed.

A possible explanation for the observed performance difference is given by the testosterone hypothesis of Geschwind and Galaburda (1985): here, the authors assume that the intrauterine environment (hormones) influences laterality and the cerebral dominance in early stages of foetal development. An enlargement of the right hemisphere (resulting in a tendency to non-right-handedness) could result in higher than average levels of abilities related to the right hemisphere (however, for a contrary opinion see Mathews et al. (2004)). With this background in mind, some findings from psychomotor research are of particular interest: Peters and Durding (1979) found that inter-hand differences in a finger tapping task were smaller in left-handers than in right-handers, but Peters (1981) also found that the relative magnitude of the inter-hand performance difference remained stable for most subjects even after a period of prolonged practice. Kilshaw and Annett (1983) found that left-handers tend to be faster than right-handers in a peg-moving task. However, this effect was only clear-cut for the non-preferred hand. In general, these studies support the assumption that weaker right-hand superiority (and a stronger tendency to non-right-handedness) can result in better motor skills and various other types of performance skills (Annett & Kilshaw, 1982; Annett & Manning, 1989).

1.1. *Laterality and mental performance*

Laterality can also have an influence on general mental performance (Annett & Manning, 1990; Newcombe & Ratcliff, 1973). Annett and Kilshaw (1982) give a review of the relationship between a reduced degree of right-handedness and a superior performance in numerical reasoning. Peters (1987) observed that right-handers have a directional bias in attention while performing a simple dual task, whereas no such bias was evident in left-handers. Crow, Crow, Done, & Leask, 1998 observed substantial deficits in verbal ability for those subjects close to the point of equal hand skill (hemispheric indecision thesis). However, Mayringer and Wimmer (2002) deny a general relationship between mental ability and handedness. To summarize, there is currently no proven coherent pattern for a relationship between general mental capacity and laterality.

1.2. *Laterality and music performance*

There are only a few studies on the relationship between laterality and musical achievement. For example, Hassler and Birbaumer (1988) found that musical talent – as measured by the Wing test of musical intelligence – and the ability to compose and improvise were related to left-handedness, but only in boys. Hassler and Gupta (1993) found that musical talent was also related to anomalous dominance of verbal materials and to immune vulnerability. A small increase in the proportion of left and mixed-handedness in accomplished musicians compared to the general population (+4%) was found in the study by Aggleton, Kentridge, and Good (1994). The authors assume that this could be an effect of positive selection within the group of musicians. Due to a bias in performance, strongly lateralized instrumentalists could be deselected from a professional career through early elimination. In a very recent study, Kopiez, Weihs, Ligges, and Lee (2006) and Kopiez and Weihs (2004) found evidence for the role of laterality as a classifying variable in the classification of SR achievement.

1.3. *General measurement of laterality*

The classification of subjects into the two groups of right-handed and non-right-handed people is a crucial point in laterality research, which requires an underlying theory. This study is based on the widely accepted 'right-shift theory' by Annett (1985, 2002). The two-component theory assumes that handedness as a consequence of asymmetry in brain functions in humans and non-human primates is determined by chance, but that difference in handedness in humans is weighted towards right-handedness in most people by the genetic factor of left-hemisphere advantage and right-hemisphere disadvantage of hand skill. This means that only the preference for right-handedness is determined genetically, and whether non-right-handed people end up left-handed or ambidextrous is a matter of chance and of social pressure on behavior. Annett distinguishes between a 'subjective' preference for handedness (as measured, for example, by the Edinburgh Inventory; see Oldfield, 1971) and the 'objective' or 'true' performance handedness, which refers to the underlying random and genetically determined hand skill differences. She believes that the degree of hand skill is strongly related to preference behavior. McManus (1999, 2002) and McManus and Bryden (1992) proposed an alternative genetic theory of handedness, which is, however, similar to Annett's theory in several respects: he differentiates between a genetically determined right-handedness (D = dexterality) and a chance factor (*C*). According to McManus, the determination of phenotypical handedness should primarily be based on hand preference in general and on the preferred writing hand in particular. He argues that preference precedes performance and that the latter cannot be used to determine handedness. For example, he argues for a view of handedness as a dichotomous category. For the unresolved issue of the relationship between preference and performance in handedness research see discussion in Bishop (1990, p. 70 ff.), Peters (1998, pp. 78 and 92) or Rigal (1992). However, as new evidence has since come up for gradual hemisphericity – which is related to handedness and speech lateralisation – (see Knecht et al., 2000, 2001), gradual laterality in handedness remains a useful variable.

To check for the influence of factors related to general mental capacity, an altered version of the ZVT (Zahlen–Verbindungs-Test) [number combination test, NCT], which is well correlated with intelligence (see Oswald & Roth, 1997), was used. Series D of the Raven standard progressive matrices (Raven, 2000), comprised of 12 items, were also used in our study.

1.4. Rationale of the study

This study investigates the influence of laterality on a selected musical task. As a model, an extremely challenging musical task was chosen, the unprepared accompaniment of a solo instrument (so-called sight reading). This task is characterized by extraordinary demands on real time information processing. It is hypothesized (a) that a weaker laterality of hands will result in a higher SR achievement due to better balanced hand skills, and (b) that laterality effects are gender-related.

2. Method

2.1. Subjects

Fifty-two pianists (28 females, 24 males) from the Hanover University of Music and Drama served as subjects (mean age = 24.5, S.D. = 4.9). The subjects had to have piano as a major subject or be experts in piano chamber music or accompanying (mean professional playing experience, 19.3 years; minimum, 12.0 years). A group of 1185 students of psychology (mean age = 26.3, S.D. = 5.3), parallelized for age and gender distribution, served as controls for laterality scores (Galley, Ottensmeier, Hopmann, & Kopiez, 2005).

2.2. Materials

For the SR task, the paradigm of a pre-recorded pacing melody was used (Lehmann & Ericsson, 1993). This method creates time constraints that force the subjects to play in tempo. Materials consisted of two warm-up pieces and five pieces of increasing complexity. These were taken from existing piano SR literature (UNISA, 2005), rearranged by a composer for solo melody and bi-manual piano accompaniment. The pre-recorded solo melody was played metronomically (i.e. synchronized to a metronome) by a violinist. Before each piece, tempo indications were given by clicks, which were also pre-recorded. These clicks were usually for two full bars, which also gave the subjects an indication of when they should start playing. Table 1 shows the number of notes for each hand at each task level and the total sum of notes. In this study, we only considered the total matches between the performance and the musical score for levels 1–5.

2.3. Procedure

Subjects were required to accompany the pre-recorded violin part on a MIDI piano. The violin part was played back through loudspeakers. The accompaniment was recorded onto a PC using the sequencer software 'Cubase'. retrospective interviews and

Table 1
Physical surface complexity of the sight reading stimuli

Level	Left-hand	Right-hand	Both hands	Average no. of notes per bar	Average time per bar (s)
1	80	89	169	7.34	1.95
2	98	90	188	9.4	2.45
3	103	188	291	7.86	1.45
4	93	105	198	9.42	2.38
5	188	222	410	19.52	4.38
Sum of total notes (L1–L5)	662	694	1256		

Number of notes per hand, per bar and time per bar in the score files of each task level.

measurement of predictor variables were carried out after the SR tasks. The entire procedure lasted approximately 2 h.

Scoring for the SR performances (target variable) was done using a researcher-developed computer program called 'Midicompare' (Dixon, 2002). This program matches the pitches of a subject's recorded SR performance with the score. Sight reading achievement was calculated for three categories: (a) matched played notes (matches), unmatched played notes (missed) and extra notes (extra). In this study, achievement analysis is focused on the category 'matches'. The output shows the number of events in each category within an adjustable critical time frame of ±0.25 s. The total performance score (as a percentage) of each subject for both separate and combined hands was used (100 × [matches/total pitches in the score]). Statistical computations were done with SPSS V11.

2.4. Measurement of laterality

Handedness as an environment-reduced indicator for genetically determined 'true' or 'objective' handedness was measured by means of a hand performance task (speed tapping). This method was adopted from Peters and Durding (1978). In our study we used a speed tapping task over 30 s for both hands. A morse key (model by Junker Ltd., Germany; trigger point = 300 g) was used, connected to a PC, and tap intervals were recorded using researcher-developed software. The start hand was allocated randomly. Wrist tapping was used and movement was controlled by resting the forearm on the desk. Fingers 2 and 3 were used together and released from the key after each tap. The degree of laterality for each subject was calculated by the performance difference between the left and right-hand in a speed tapping task over a total tapping duration of 30 s.

Following Annett's (1985, 2002) right-shift theory, the 'objective' performance differences constitute the preference handedness. Since measures of performance differences between hands result in near normal distributions, the allocation to handedness groups has to be determined by a laterality threshold. Because there is no generally accepted consensus as to where such a threshold should be placed, we decided to choose the most conservative value to separate right-handers from non-right-handers: subjects who tapped faster with their right-hand were designated as (performance) right-handers, while subjects with a difference value smaller than zero or a faster tapping speed with the left-hand were designated as non-right-handers.

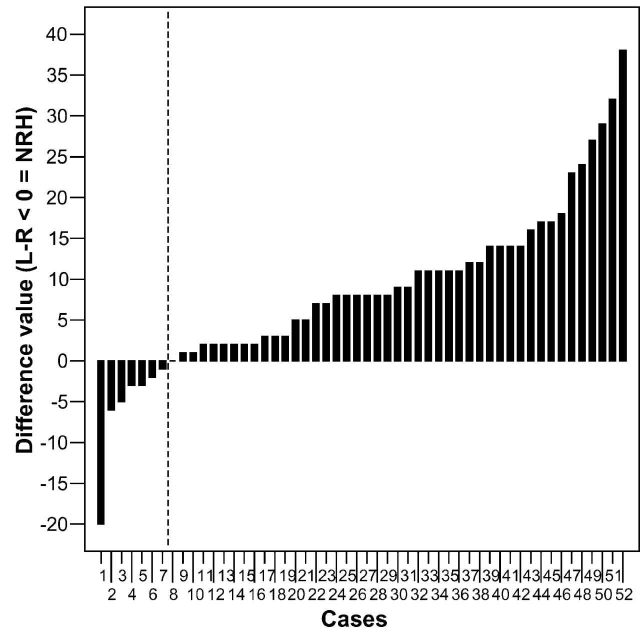

Fig. 1. Distribution of designated handedness in 52 pianists as indicated by the difference value of their tapintervals (in ms). Cut-off value of 0 for non-right-handed (NRH) vs. right-handed (RH) laterality was calculated based on the differences between both hands (median of left hand speed minus median of right-hand speed). Dotted line indicates the cut-off value.

3. Results

The difference values of tap intervals of all subjects are shown in Fig. 1. The dotted line shows the cut-off for designated right- and non-right-handedness. The distribution of handedness according to the self reports in musicians and controls is shown in Table 2. Compared to the controls, the distribution of self-reported right-handedness (RH) and non-right-handedness (NRH) in musicians shows a tendency towards the overestimation of NRH, but only in female subjects ($\chi^2(1, N = 637) = 3.32$, $p = 0.07$) while there is no significant difference for males. The distribution of the designated handedness shows also no significant difference between controls and musicians. Comparing the prevalence of designated handness in relation to self-reports in the control population, we find a small, but significant increase of non-right-handedness from 15.0% to 15.6% ($\chi^2(1, N = 1185) = 322.9$, $p < 0.01$), which is caused exclusively by the increase in the number of female subjects while the pro-

Table 2
Distribution of right-handed (RH) and non-right-handed (NRH) subjects in musicians and non-musicians (controls), parallelized for age and gender distribution

Method	*N*	Subjects	RH (%)			NRH (%)		
			m	f	$\sum$	m	f	$\sum$
Self-report	52	Piano students	83.3	75.0	78.8	16.7	25.0	21.2
Designated	52	Piano students	79.2	92.9	86.5	20.8	7.1	13.5
Self-report	1185	Controls	82.8	87.0	85.0	17.2	13.0	15.0
Designated	1185	Controls	83.2	85.6	84.4	16.8	14.4	15.6

Note: For significant trends see text. Comments on the methods: 'designated' handedness is based on a cut-off value of 0 obtained from hand differences in a speed tapping task (median of left-hand speed minus median of right-hand speed); right-handers (RH) showed shorter tap intervals and non-right-handers (NRH) showed longer or same tap intervals with their right-hand; 'self-report' is based on the subjects' own classification.

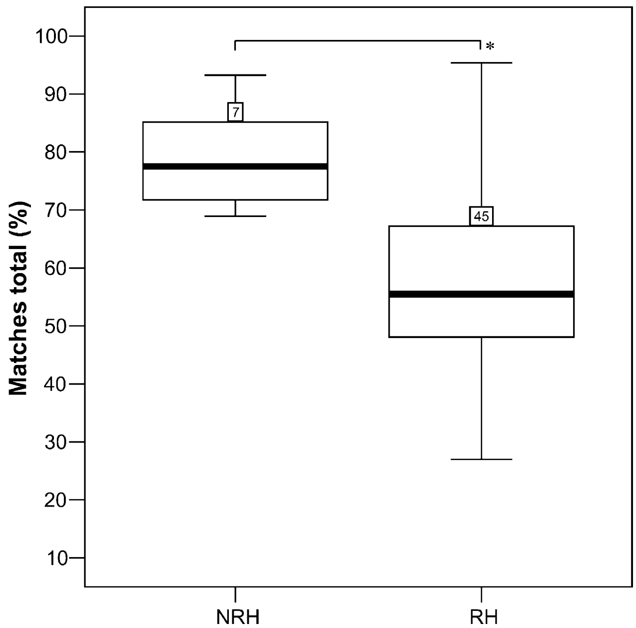

Fig. 2. Boxplot of differences in sight reading achievement (matched notes) between right-handed (RH) and non-right-handed (NRH) subjects. (Mann–Whitney U test: $^{*}p < 0.05$ [two-tailed]).

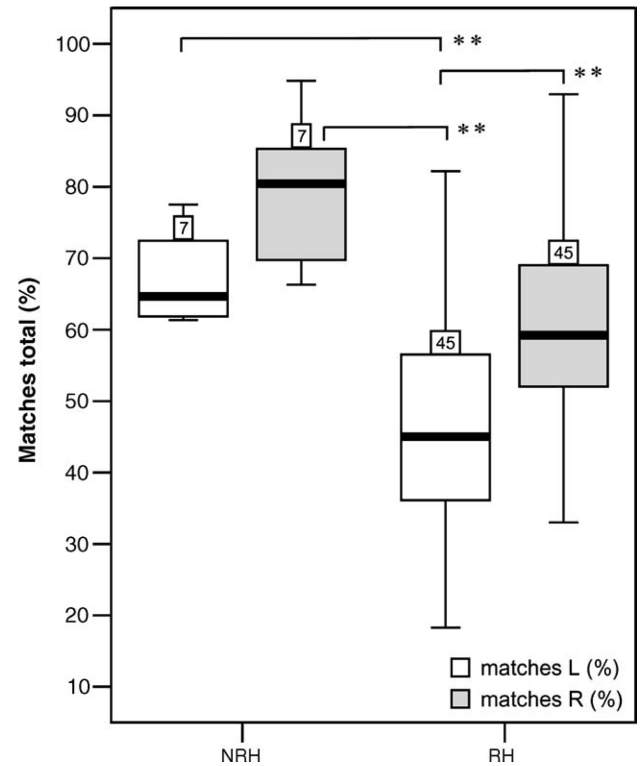

Fig. 3. Boxplot of differences in sight reading achievement (matched notes) between right and left-hand in right-handed (RH) and non-right-handed (NRH) subjects. (Mann–Whitney U test: $^{*}p < 0.05$, $^{**}p < 0.01$ [two-tailed]).

portion of NRH male subjects decreases. The reverse tendency can be observed for the designated handedness in musicians: the proportion of NRH decreases from 21.2% to 13.5% ($\chi^2(1, N = 52) = 6.28$, $p < 0.03$) due exclusively to the decreasing proportion of female NRH from 25.0% to 7.1% (although considering the small number of subjects, this decrease is not significant). In males there is a non-significant increase from 16.7% to 20.8%. To summarize, the designation procedure has not substantially increased the prevalence of NRH as predicted by the theory (see discussion), mainly due to a fuzzy criterion for classification. However, this criterion was chosen for reasons of caution and to ensure a conservative approach with respect to the performance differences in the musical skill of sight reading.

3.1. Achievement differences between handedness groups

The total distribution of SR achievement for RH and NRH pianists is shown in Fig. 2 and Table 3. As a pattern of performance, we can see in Table 3 that NRH subjects performed with a higher proportion of matches (NRH: median = 77.5%; RH: median = 55.5%) in combination with a lower proportion of missed and extra notes. This pattern is valid for combined hands as well as for separate hands. The general advantage of 22.0% for NRH pianists in sight reading achievement is an impressive result (Mann–Whitney U test, $p = 0.03$ [two-tailed]).

3.2. Achievement differences of hands between and within handedness groups

After finding a general tendency towards better achievement in NRH subjects, we must now consider the reasons for this difference. Table 3 and Fig. 3 show the source of the perfor-

Table 3
Sight reading achievement (mean and median in percentage) of right-handed and non-right-handed pianists

	Left + right-hand			Left-hand			Right-hand		
	Mean	Med	S.D.	Mean	Med	S.D.	Mean	Med	S.D.
All right-handed subjects (N = 45)									
Matches	59.4	55.5	16.5	47.1	45.0	16.0	62.6	59.2	15.2
Missed	40.0	44.5	16.7	37.5	39.7	15.7	37.5	40.7	15.5
Extra	22.7	23.2	9.7	19.3	20.7	7.9	22.8	22.7	10.5
All non-right-handed subjects (N = 7)									
Matches	75.1	77.5	17.0	64.1	64.6	13.0	74.8	80.4	18.7
Missed	24.8	22.4	17.0	20.7	20.2	13.0	25.2	19.6	18.7
Extra	16.0	12.2	9.1	14.0	10.7	8.6	15.4	11.9	9.6

Percentage of performance is indicated for matched played notes (matches), unmatched played notes (missed) and extra notes (extra).

mance advantage for NRH pianists. Although we find a tendency towards a general superiority of the right over the left-hand in both groups (which is significant for the RH group), there are important differences in left–right performance between groups: hands in NRH differ by 15.8% (non-significant), while the difference between hands in RH is 14.2% (Mann–Whitney *U* test, $p = 0.00$ [two-tailed]). This means that the difference between hands in both groups is similar, but that the absolute level of performance for both hands is higher in the NRH group. Additionally, left-hand performance in NRH is significantly better than in RH (Mann–Whitney *U* test, $p = 0.00$ [two-tailed]). This performance pattern of NRH superiority for both hands can be found in the categories of matched notes, missed notes and extra notes.

3.3. Differences between gender groups and relationship between variables

No significant differences between male and female pianists were found (Mann–Whitney *U* test, $p = 0.27$ [two-tailed]). As Table 4 shows, the correlations between the predictors and the performance criterion change with a gender-related effect. For the entire sample, the correlation between percentage of matches and degree of laterality (as measured by the difference value between hands) was $r(52) = -0.37$ ($p = 0.00$). In males, this correlation increases to $r(24) = -0.50$ ($p = 0.01$), but decreases to a non-significant correlation of $r(28) = -0.16$ ($p = 0.42$) for females. This strong gender-related correlation between laterality and SR achievement is an important finding of our study. However, the curve fit in Fig. 4 reveals some evidence for the assumption of a non-linear relationship: the best fit for the regression curve is not obtained from a linear but from a quadratic curve fit (linear curve fit: $r^2 = 0.24$; quadratic curve fit: $r^2 = 0.43$). This means that there is an optimum range of laterality for best SR performance. Extreme laterality with a strong bias to right or to left-handedness will result in reduced SR achievement.

To obtain a better understanding of the underlying relationship between the considered variables, correlations between the selected predictor variables and SR achievement were also taken into consideration. The following variables were used as input for a correlation analysis: percentage of score matches, difference values of the hands in tapping intervals as an indicator for laterality, number of Raven matrices and the speed of information processing as measured by the number combination test (NCT). Data analysis revealed significant correlations between the percentage of matches and NCT ($r(52) = -0.44$; $p = 0.00$ [two-tailed]). The correlation between SR achievement and speed of information processing (measured by the time needed for the NCT) remains constant for males, but increases significantly for females to $r(28) = -0.57$ ($p = 0.00$).

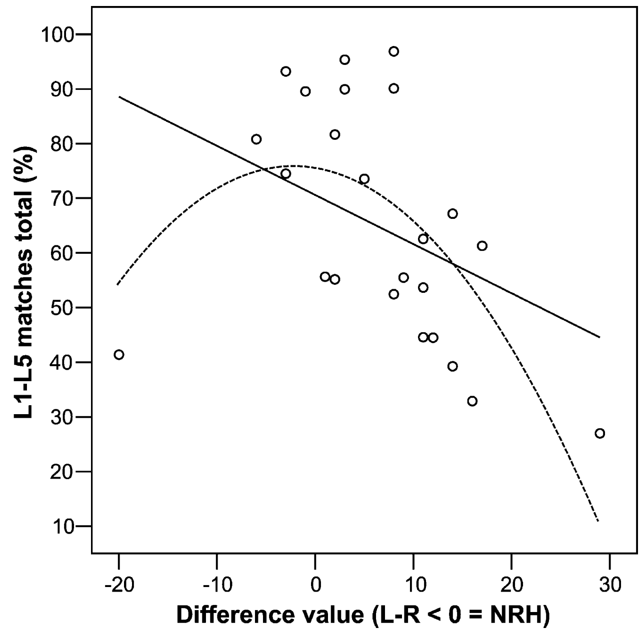

Fig. 4. Scatterplot of the relationship between sight reading achievement and laterality for 24 male subjects. (Spearman ρ, $r = -0.49$, $p < 0.05$ [two-tailed]). Linear curve fit: $r^2 = 0.24$; quadratic curve fit: $r^2 = 0.43$.

4. Discussion

4.1. Superior musical achievement of non-right-handers

Our main finding is the superior achievement in sight reading of non-right-handers with a performance advantage of 22% (see Fig. 2 and Table 3). The correlation was $r(52) = 0.37$ between the performance result and the decrease in right-hand superiority (see Table 4 and Fig. 4). In other words, the faster the left-hand the higher the sight reading performance. This correlation shows a strong gender effect, increasing up to $r(24) = 0.50$ for men and decreasing to $r(28) = 0.16$ for women.

Table 4
Correlations between sight reading achievement (percentage of score matches), laterality (difference value), total items of Raven D matrices, and number combination test (NCT) for musicians, males and females

	Matches %			Difference value			Raven D		
	All	Males	Females	All	Males	Females	All	Males	Females
Difference value	−.37**	−.50*	−.16						
Raven D	.12	.17	.00	−.29*	−.35	−.24			
NCT	−.44**	−.45*	−.57**	.28*	.40*	.13	−.48**	−.52**	−.35

Note: Spearman ρ (two-tailed; all subjects: $N = 52$, male subjects: $N = 24$, female subjects: $N = 28$).
* $p < 0.05$.
** $p < 0.01$.

Surprisingly, the distribution of handedness shows no significant difference from a control group and only a small non-significant tendency ($\chi^2(1, N=637)=3.32$, $p=0.07$) towards female NRH (see Table 2). In the control group, the designation procedure for handedness reclassification yields a small increase in NRH, but the same procedure in the musicians group produces a decrease in NRH. We believe there could be two reasons for this: firstly, self declaration as well as preference classification contains an inherent bias towards culturally favored right-handedness. For example, according to Gilbert and Wysocki (1992) the percentage of NRH in the USA has doubled in the last 50 years, most likely caused by a decline in culture pressure to use the right-hand. When using performance measures of handedness, Rigal (1992) estimated a result of 24% for NRH; roughly 14% more than when using self-reports or preference methods, which yield a proportion of about 10%. Secondly, the criterion of zero difference in tapping speed for the designation of NRH may be too diffuse. It was chosen to minimise the possibility of getting RH in the NRH group and to avoid any bias related to our advantage hypothesis in sight reading. Additionally, there is no consensus as to where and how to position the borderline between RH and NRH in performance measures. However, the reclassification of five women out of seven self-declared NRH pianists as RH by our designation procedure is an argument in favour of a cut-off threshold on the upper side of zero in the difference score. It must therefore remain open as to whether there is a higher percentage of NRH in musicians until a more sophisticated procedure is established to find the 'true', i.e. the genetically determined NRH.

The distribution of handedness in musicians has been thoroughly investigated over the last 30 years. However, there are no unambiguous results: for example, compared to non-musicians, Oldfield (1969) found no evidence for a higher proportion of left-handers among musicians. This finding was confirmed by Götestam (1990), who found a proportion of 14.7% for left and left-mixed-handers and 85.3% for right and right-mixed-handers among musicians (results for non-musicians: left and left-mixed = 15.8%; right and right-mixed = 84.2%). Both studies were based on handedness questionnaires. Aggleton et al. (1994) found a slight increase of left and mixed-handers in the group of professional musicians, but the authors argue that differences are not merely a result of training, as the proportion of left-handed writers in musicians is also larger compared to the general population. Using the Edinburgh inventory, Hering, Catarci, and Steiner (1995) found a proportion of about 10% of non-right-handers in musicians and non-musicians, and argued in favour of an independence of musical abilities and handedness.

In our sample of male musicians, we found a correlation between a superiority in sight reading and a decrease of right-hand laterality which seems not to be dependent on difficulties in defining handedness. This could be an independent confirmation for the assumption that non-right-handedness provides an advantage in selected musical skills. But the substantial lower correlation in females confirms the well known gender differences in laterality research.

Two questions remain open: (a) the question of incidence and relevance of reduced laterality for other professional musical or non-musical skills; and (b) the 'chicken–egg question' of a possibly higher proportion of NRH in musicians. The first question cannot be answered with the current results, and additional research is required to find out whether hand performance scores, such as the difference value used in this study, are comparable to those of pianists in subgroups of the musician population with less demands on bi-manual motor skills (e.g., violinists, percussionists, brass players).

The second question can only be answered by a long-term study, starting at a very early age (e.g., with 4–5-year-old piano pupils), in order to test the effect of bimanual practice on laterality in later adulthood. It may be that such a study will reveal a possible selection effect: only less lateralized pianists with a less functional hemispheric asymmetry will be successful as professional accompanists or correpetiteurs. Such a tendency of positive selection for ambidexterity is supposed to be effective in other occupations, such as orthodontic specialists (Henderson, Stephens, & Gale, 1996) or in sports (for an overview see Gorynia & Egenter, 2000, p. 15). Our considerable correlations between sight reading and the NCT (number combination test, see Table 4) give support for another selection effect for superior sight reading, namely intelligence. In intelligence research, the NCT has shown a substantial relationship to general intelligence (Oswald & Roth, 1997).

With the current state of research, there is little evidence that functional neuroanatomy of hemisphere laterality changes through practice. In a recent study, Siebner et al. (2002) investigated the influence of switched handedness in handwriting of converted adult left-handers. In a PET study, authors found persistent features of left-handedness during right-hand writing. In contrast to innate right-handers, converted left-handers showed a more bilateral activation pattern with a focus on the right lateral premotor, parietal, and temporal cortex. The right-hemispheric activation pattern may reflect suppression of unwanted left-hand movements. The authors conclude that human handedness has a neural substrate in premotor and parietal motor association areas.

Finally, the relationship between handedness and brain lateralization remains complex: Flöel, Buyx, Breitenstein, Lohmann, and Knecht (2005) investigated the correlation between handedness and attention and language lateralization. Except for a few cases, authors could confirm Annett's fundamental assumption of a relationship between handedness and brain organization as measured by language processing. Annett's assumption was also confirmed through the studies by Knecht et al. (2000, 2001).

4.2. Theoretical explanations of non-right-superiority for musical achievement

There are currently two theoretical approaches to explain a possible superior achievement of NRH: the inhibition theory and the theory of interhemispheric communication. The inhibition theory was proposed by Kilshaw and Annett (1983), and the authors assume that the "typical human bias towards the left hemisphere and right-hand might be due to a right hemisphere handicap rather than to a left hemisphere advantage" (p. 269). This means that a weaker right-hand laterality (and stronger tendency to non-right-handedness) could result in better motor performance. Evidence for a reduced interhemispheric inhibition was also found by Ridding, Brouwer, & Nordstrom, 2000. The authors observed that transcallosal interhemispheric inhibitory circuits are less effective in bimanually trained musicians than in controls.

The second theory, the assumption of an improved interhemispheric communication, is supported by the studies of Schlaug, Jäncke, Huang, Staiger, and Steinmetz (1995) and Schlaug (2001). The authors showed that due to task-specific neural plasticity, the brain of professional musicians is characterized by a stronger connection between hemispheres in the corpus callosum. This theory explains improved communication between hemispheres through a faster or more complete data transfer caused by a stronger connection between hemispheres. Further evidence for this theory was found by Hécaen, Agostini, and Monzon-Montes (1981). They analyzed the verbal and spatial performances of left-handed and right-handed patients with a family history of sinistrality who had suffered unilateral hemispheric lesions. Results confirmed a relationship between sinistrality on the one hand, and the ambilaterality of the functional representations of language and the lesser intrahemispheric focalization on the other. In a morphometric analysis of the interhemispheric asymmetry deep within the central sulcus in the region of cortical hand representation, Amunts, Jäncke Mohlberg, Steinmetz, and Zilles (2000) found that anatomical asymmetries decreased significantly from the male consistent right-handers group over the mixed-handers group to the consistent left-handers group. However, interhemispheric asymmetry was found in females, suggesting gender differences in the cortical organization of hand movements. This provides evidence for the hypothesis that achievement is not primarily determined by the size of a brain area but by the size of the difference between areas in both hemispheres, with smaller differences resulting in higher achievement.

To conclude, our study gives a new perspective on the structure and acquisition of exceptional musical skills. The concept of the expertise theory should be extended, and for a sufficient explanation of peak performances, accumulated practice must be complemented by consideration of selection processes through neurobiological factors, such as mental capacity and laterality (McPherson, 2005). It remains open as to whether other underlying neurobiological factors could also be of importance for exceptional musical achievement (Pitts, Davidson, & McPherson, 2000). For some musical activities, weaker laterality could be the 'egg' and practice the 'chicken'. From this perspective, laterality would be one facet of musical ability.

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