Handedness and Musicality in Secondary School Students

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This article investigates the relationship between handedness and abilities in secondary school students, specifically analyzing the effect of handedness on subjective and objective musicality and academic performance. Previous research on the association between handedness and musicality has yielded mixed conclusions. Some studies have documented a positive correlation between musicality and non-right-handedness, but other studies have found no relationship. Here we aim to address some of this uncertainty, using a greater diversity of relevant covariates and a considerably larger sample than previous research. Our dataset of 2,902 participants (age range 10–18) comes from the LongGold project: an international longitudinal study of educational development in secondary school students. Musicality was measured through a self-report questionnaire (Gold-MSI) and perceptual tests; academic ability was determined using a Matrix Reasoning test and school grades. Using regression analyses, our main result is a lack of relationship between musicality and handedness, both for self-reported musicality and objective perceptual ability. In contrast, we found a significant association between right-handedness and higher academic ability. Our results provide a clearer perspective on the nature of handedness and its relationship to abilities, as well as highlighting changing dexterity as an area for future research.

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Most individuals prefer using a particular hand for diverse actions ranging from the basic (grasping, pulling, pushing) to the complex (throwing, writing, drawing). This "consistent use of one hand rather than the other in performing certain tasks" is termed *handedness* (American Psychological Association, n.d.). Based on self-reported writing and throwing hand, approximately 89% of people can be categorized as right-handed; left-handedness is relatively rare at 6.5%, and ambidextrousness even rarer at 4.5% (Gilbert & Wysocki, 1992). Prior research has connected non-right-handedness with various traits, including cognitive deficits, heightened levels of creativity, and higher levels of musical ability. However, the empirical evidence for these phenomena is conflicting, with many studies finding no associations between the key variables.

The present study aims to address the heterogeneity of this prior research, as well as attending to a number of its limitations. We focus in particular on musicality, exploring its relationship with handedness in a large sample of secondary school students tested as part of the international LongGold project (Müllensiefen et al., 2022; Müllensiefen & Harrison, 2020; Müllensiefen et al., 2015). By investigating this association using a large and diverse dataset with established measures of musicality, this study aims to provide more conclusive evidence concerning the abilities of non-right-handers. Before considering our research methods and results, our article will summarize key literature on the measurement and origins of handedness, as well as outlining previous research on the link handedness exhibits with academic and musical abilities. We will contextualize our review of previous studies on handedness and musicality within research on the laterality of music perception in the brain, going on to highlight how the present study addresses limitations of previous work.

Measuring Handedness

The two most prevalent measurements for handedness are hand preference inventories for everyday tasks (e.g., Edinburgh Inventory: Oldfield, 1971) and hand

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efficiency on performative tasks (e.g., peg moving task: Annett, 2002; speed tapping: Peters & Durding, 1978). Performative tasks provide a more objective assessment of handedness but are limited in sample size compared to the ease of distributing an inventory. Both methods create a continuous laterality scale, designating subjects above a defined boundary as right-handed and those below as left-handed. Nevertheless, they provide contrasting conceptualizations of handedness that highlight the inconsistencies in definition found throughout the literature, with research often overlooking the differences between hand preference and performance (Coren, 1992).

Further inconsistencies can be found in the categorization of handedness. Research typically uses categories of left-, mixed-, and right-handed but some studies use alternative classifications (e.g., right- and non-right-handed: Hassler & Birbaumer, 1988; Hassler & Gupta, 1993). It has been argued that handedness should be considered a continuous variable (Annett, 2002). Additionally, self-reported handedness has been found to be highly subjective: Oldfield (1971) suggested that participants often underestimated the extent of their non-right-handedness.

Origins of Handedness

The origins of handedness and the right-handed skew found in the human population remain somewhat elusive. The most prevalent genetic models were proposed by Annett (1972, 1985, 2002) and McManus (1985, 2000). Annett's Right Shift Theory suggests handedness to be determined by two factors: a chance factor resulting from "numerous small accidental differences" between the fetal development of each side of the body (2002, p. 67) and a right shift factor increasing the chance of favoring the right-hand. The right shift factor is hypothesized to develop from left hemisphere specialization for language processing, which is supported by the lack of cerebral asymmetry in species without language capacities (e.g., Marchant & McGrew, 2013).

McManus (1985) proposes a similar theory where handedness is regulated by a combination of two alleles. In their homozygous forms, the dextral allele produces certainty of right-handedness and the chance allele produces an equal probability of right- or left-handedness. However, in their review of the genetic contribution to handedness, Paracchini and Scerri (2017) report a relatively small genetic contribution of around 25% from several twin studies of MZ and DZ concordance rates (e.g., Medland et al., 2009). They argue that this relatively weak link suggests handedness is not determined by one specific gene, but rather is influenced by a combination of many genes with small effects.

An alternative hormonal hypothesis has been suggested by Geschwind and Galaburda (1985). They propose that increased levels of prenatal testosterone in a fetus delay the growth of the left-hemisphere and thus shift towards a more bilateral brain. Drawing on Annett's theory of random dominance (1978), they suggest that these subjects are therefore equally likely to become left- or right-handed. Several pathological theories have also been proposed. One example is the brain damage model proposed by Satz (1972) to explain the correlation between left-handedness and various "clinical populations" (p. 121), with left hemisphere damage forcing right-handed children to switch to using their left hand. In addition to these theories, there is an intuitive influence of the environment and societal norms on handedness, which Annett acknowledges as "culturally imposed enhancements of the dextral bias" (2002, p. 68). Despite the number of potential theories of handedness, of which only a few are highlighted here, no model has yet been sufficiently validated.

Handedness and Academic Ability

One of the relationships to handedness that has resulted in a plethora of conflicting evidence is that of academic ability. On the one hand, many studies have supported the link Geschwind and Galaburda emphasize between left-handedness and cognitive deficits (e.g., Nicholls et al., 2010). On the other hand, several studies have found a correlation between non-right-handedness and elevated levels of cognitive skill, including intelligence (e.g., Ghayas & Adil, 2007) and spatial reasoning (e.g., Tan, 1989). Conversely, some other studies have demonstrated no overall link between handedness and academic ability (e.g., Annett & Turner, 1974). Methodological discrepancies between individual studies might account for some of these inconclusive results. For example, Somers et al. (2015) suggest that the measurement of distinct cognitive abilities might yield contradictory results, with right-handers achieving significantly higher on overall spatial ability, but no difference being found for verbal ability. Recent reviews and meta-analyses by Ntokla and Papadatou-Pastou (2017) and Papadatou-Pastou (2018) conclude from this literature that the relationship between handedness and academic ability is negligible.

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Laterality of Music Perception

Handedness is intricately connected with the cerebral lateralization of the brain. Processing in the brain is highly complex, combining many adaptable functional and structural networks in both hemispheres (Doron et al., 2012). Neuroimaging techniques highlight the dynamic inter- and intra-hemispheric connectivity, but also support the functional asymmetries between the hemispheres that have long been recognized (Hervé et al., 2013). Research suggests speech is primarily processed in the left hemisphere and visuo-spatial stimuli primarily in the right (e.g., Baron-Cohen, 2012; Bryden, 1982). While approximately 96% of right-handers exhibit left-hemisphere dominance for language, the same dominance has been found for only 76% of left-handers (Pujol et al., 1999). Additionally, 10% more left-handed participants have been found to have a bilateral activation (Pujol et al., 1999). Therefore, handedness could be the "best behavioral predictor of cerebral lateralization" (Medland et al., 2009) and link to the cerebral dominance of many other abilities, including processing of music.

The lateralization of music processing in the brain has been significantly debated over the last century. Some studies have used dichotic listening tasks to demonstrate right ear and therefore left hemisphere superiority for music perception (e.g., melody recognition: Bever & Chiarello, 1974; melody discrimination: Gates & Bradshaw, 1977). However, many other studies have found right hemisphere dominance for a range of musical tasks (e.g., Milner, 1958; melody: Kimura, 1964; pitch and loudness: Nachshon, 1978; self-perceived musical ability: Szirony et al., 2008).

The inconclusive nature of the research could be explained by a number of discrepancies between experiments, including the specific musical task, the environment of the study, and the technique of identifying hemispheric dominance. In their review of the literature on the laterality of music perception, Peretz and Zatorre (2005) found pitch and melody to be primarily processed in the right hemisphere and temporal musical processing to be more bilateral. Current evidence demonstrates that the perception of music in the brain is highly complex, involving cortical and subcortical structures across all lobes in both hemispheres (Levitin & Tirovolas, 2009). Unilateral theories have been increasingly rejected in favor of a more holistic "whole-brain" approach (Warren, 2008).

Another potentially confounding variable stems from the choice of participants. A plethora of evidence demonstrates that musicians have a more bilateral representation of music than nonmusicians (e.g., Amunts et al., 1997; Hassler & Birbaumer, 1988; for tonal memory: Gaede et al., 1977; for pitch, chord, timbre, and rhythm tasks: Ono et al., 2011). This research appears consistent with the notion that music may be processed in both hemispheres. Nevertheless, the direction of causality is difficult to ascertain. These studies could imply that people are more likely to become musicians if their processing of music is inherently more bilateral. Alternatively, the findings could suggest that enhancing one's musical skills makes changes in the brain over time, in line with existing research on music-induced brain plasticity (e.g., Olszewska et al., 2021; Hyde et al., 2009).

The aforementioned research on the laterality of music perception could provide a potential explanation for linking handedness with musicality. Several studies have demonstrated that left-handed participants have greater hemispheric interaction and bilateral representation of processes relating to music (e.g., Torrance creativity test: Stewart & Clayson, 1980; pitch and loudness identification: Nachshon, 1978). As music perception requires significant interhemispheric communication, this could imply that non-right-handed people will have a greater innate proclivity for music due to their inherently more bilateral brains. This could make them less likely to drop out of music education, increasing the proportion of non-right-handed subjects in musician populations, and also make them more likely to reach a higher level of musical ability. The following section will review the research on both these areas of interest and highlight the importance of the present study in reaching firmer conclusions about these speculations.

Handedness and Musicality

Previous research on the relationship between musicianship and handedness falls broadly into two categories. Prior research investigating the relative proportions of handedness in musician populations compared to the general population is reviewed in Table 1. Papers specifically investigating how handedness correlates to musical abilities are summarized in Table 2. Papers were identified through searches on Google Scholar, Science Direct, and Semantic Scholar for relevant keywords, combining "handedness"/"left-handed" with "musicality"/"music"/"musical ability." Citations of these papers were scanned to find additional research suitable for inclusion.

The previous literature presented in Table 1 implies a potential association between handedness and musicality. Several studies have shown an increased

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TABLE 1. *Previous Literature on the Proportion of Non-right-handedness in Musician Populations Compared to the General Population*

	Participant group	Musician sample size	Measure of handedness	Main finding	Statistics	Effect Size	
						Phi coefficient	Cohen's d
Aggleton et al. (1994)	Professional instrumentalists, composers and choir members	1,538	Edinburgh Handedness Inventory (10-item version)	Greater proportion of LH and relative loss of strongly handed in musician population	Interaction between handedness and being a musician: $X^2 = 23.10$, $p < .005$	$\Phi = -0.08$ [-0.11, -0.04]	$d = -0.16$ [-0.23, -0.09]
Byrne (1974)	Staff and students from a music conservatory	242	Edinburgh Handedness Inventory (10-item version)	More mixed-handers among instrumentalists versus unselected students	$X^2 = 4.08$, $p < .05$	$\Phi = -0.02$ [-0.08, 0.04]	$d = -0.04$ [-0.16, 0.08]
Götestam (1990)*	University music students	88	Hand preference of four activities	No differences found between the musician and control groups		$\Phi = 0.03$ [-0.12, 0.17]	$d = 0.06$ [-0.24, 0.36]
Hassler & Birbaumer (1988)	9-14 year olds from elementary and high schools	80	Hand preference of four activities	Among the male LH group, there were more musicians than non-musicians	78.9% of the left-handed children had musical talent	$\Phi = -0.11$ [-0.28, 0.054]	$d = -0.22$ [-0.58, 0.14]
Kopiez et al. (2006)	University music student pianists	52	Speed tapping	No significant difference between handedness of controls and musicians	Musician: 86.5% RH, 13.5% NRH Non-musician: 84.4% RH, 15.6% NRH	$\Phi = 0.01$ [-0.04, 0.06]	$d = 0.02$ [-0.09, 0.13]
Kopiez et al. (2010)	University music students (pianists, strings)	128	Tapping speed regularity and fatigue	Incidence of designated NRH in musicians higher than non-musicians	Musician: 69.2% RH, 30.8% NRH Non-musician: 78.3% RH, 21.7% NRH	$\Phi = -0.06$ [-0.12, 0.00]	$d = -0.12$ [-0.23, -0.01]
Oldfield (1969)	Students/staff from two schools of music	129	Hand choice for inventory of activities	No evidence of handedness difference among musicians and undergraduates	$X^2 = 0.083$	$\Phi = -0.01$ [-0.06, 0.05]	$d = -0.02$ [-0.13, 0.09]
Quinan (1922)	Professional male musicians	100	Peg board test	Higher proportion of NRH in musician population	Machinists: 4% LH, 4% dextral Musicians: 4% LH, 24% dextral	$\Phi = -0.26$ [-0.40, -0.12]	$d = -0.54$ [-0.83, -0.25]

Note: RH = right-handed, LH = left-handed and NRH = non-right-handed. Statistics refer to the main finding of that specific study. Effect sizes were calculated using an online calculator (Wilson, 2017) as the relative proportions of right- and non-right-handedness in the musician and nonmusician populations of each study. A negative coefficient suggests a positive relationship between non-right-handedness and musicianship. The Phi coefficient measures the association between the two binary variables (handedness, musicianship), with 0 denoting no association and .20–.29 suggesting a weak relationship. Cohen's d effect size denotes the standardized difference between two means. Typically, 0.2–0.3 is interpreted as a small effect, 0.5 as a medium effect and 0.8 as a large effect. *This paper did not include any relevant inferential statistics, but the effect size could be calculated from the descriptive statistics.

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TABLE 2. *Previous Literature on the Relationship Between Handedness and Music-related Perceptual and Performative Skills*

	Participant group	Sample size	Measure of handedness	Measure of musical ability	Main finding	Statistics	Effect size
Byrne (1974)*	Staff/students from a music conservatory	71	Edinburgh Handedness Inventory	Timbre and tonal memory subtests of Seashore battery	No significant differences between right- and mixed-handers		–
Craig (1980)	University students	36	Self-report	Dichotic rhythm pattern memory	Left-handed participants accurately reported more signals	$t = 4.05$, $df = 142$, $p < .001$	$d = -1.47$ [-2.25, -0.68]
Deutsch (1980)	University undergraduates	Exp 1: 129 Exp 2: 104	Edinburgh Handedness Inventory (10-item version)	Pitch memory	LH subjects had a significantly lower error rate (mixed LH had highest performance)	Exp 1: $X^2 = 8.03$, $df = 1$, $p < .01$ Exp 2: $X^2 = 4.08$, $df = 1$, $p < .05$	$d = -0.52$ [-0.87, -0.16] $d = -0.40$ [-0.80, -0.01]
Farnsworth (1938)*	Children in grades 1-4	1,169	Teacher ratings	Teacher ratings	Students rated highly for musical abilities had a non-significant tendency to be more RH		$d = 0.18$ [0.07, 0.30]
Good et al. (1997)	School children aged 7-8	897	Hand preference exhibited by four activities	Bentley Measures of Musical Ability (BMMA)	No effect of handedness on any of the BMMA subtests	Overall: $F(2,869) = 0.01$	$d = 0.01$ [-0.19, 0.21]
Hassler & Birbaumer (1988)	9-14 year olds from elementary and high schools	120	Hand preference of four activities	Ratings of ability to compose/improvise, Wing's Standardized Tests of Musical Intelligence	Creative musicality related to LH in boys, male left-handers had higher ability	$r = -.59$, $p = .017$	$d = -0.44$ [-0.80, -0.08]
Hassler & Gupta (1993)	Young adults from Hassler & Birbaumer (1988)	93	Hand preference for four activities	Tests 1-3 of Wing's Standardized Tests of Musical Ability	Significant handedness effect (left-handers surpassed right-handers)	$F = 4.92$, $p = .031$	–
Kopiez et al. (2006)	University music student pianists	52	Speed tapping	Sight reading alongside a pre-recorded melody	Superior performance by NRH pianists	22.0% advantage, $p = .03$	$d = -0.95$ [-1.76, -0.13]
Kopiez et al. (2012)	Professional pianists	19	Edinburgh Handedness Inventory	Temporal unevenness in scale playing	No significant difference between groups	$z = -1.38$, $p = 0.16$	–
Laguitton et al. (1998)	Adults	58	Edinburgh Handedness Inventory	Identifying the pitch content of complex tones	Left-handers significantly more sensitive to spectral changes of tones	$F(1, 52) = 5.3$, $p = .025$	$d = -0.65$ [-1.22, -0.08]
Piro & Ortiz (2010)	School children in grades 3-6	178	Edinburgh Handedness Inventory (10-item version)	Music Ability Screening Test (MAST)	Effect of handedness on musical ability was not significant	$F(1, 174) = 0.605$, $p = .438$	$d = -0.19$ [-0.51, 0.12]
Schleuter (1978)*	Instrumental music students in grades 4-6	104	Hand preference exhibited by six activities	Four rating scales measured musical achievement	No significant effect of handedness		–

Note: RH = right-handed, LH = left-handed and NRH = non-right-handed. It was not possible to compute effect sizes for several studies in this table, as the original papers are missing the necessary descriptive statistics. Effect sizes were calculated using an online calculator (Wilson, 2017). A negative coefficient suggests a positive relationship between non-right-handedness and musicianship. Cohen's *d* effect size denotes the standardized difference between two means. Typically, 0.2–0.3 is interpreted as a small effect, 0.5 as a medium effect, and 0.8 as a large effect. *These papers did not include any relevant inferential statistics.

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proportion of non-right-handedness in populations of musicians compared to non-musician control groups. They provide evidence to support theories regarding the enhanced proclivity non-right-handed people have for music. The conflicting papers reporting negligible effect sizes are in the minority (Götestam, 1990; Kopiez et al., 2006; Oldfield, 1969).

The causal direction of this potential correlation between non-right-handedness and musicianship is difficult to determine. One possibility is that non-right-handedness causally precedes musicality. Non-right-handers would then be more likely to pursue formal music training, and less likely to drop out over time, resulting in a higher proportion of non-right-handedness among the musician population.

However, a contrasting idea suggests that musicians gradually become more non-right-handed as they increase their musical skills, reversing the direction of causality. Jäncke et al. (1997) concluded that the increased left-hand skill they identified in musicians could be explained by the performance requirements of instrumental playing in interaction with childhood cerebral maturation. Additionally, Christman (1993) found bimanual instrumentalists to be more mixed-handed than unimanual instrumentalists. This suggests a potential effect of music training on handedness that could affect the dextrality proportions of musician populations, despite conflicting evidence regarding the direction of adaptation (e.g., Kopiez et al., 2010).

A typical characteristic of the musician populations from Table 1 is their high level of training in performative skills, which may influence handedness specifically through motor-aspects of music training. Therefore, an alternative approach is to explore the degree of perceptual music abilities, which may demonstrate different associations with handedness. The research summarized in Table 2 takes this alternative approach, exploring how handedness measures correlate with these musical abilities. This body of evidence contains a mixture of effect sizes, with a trend towards associating non-right-handedness with higher musical skills.

Figure 1 summarizes this review of previous literature, plotting the computed effect sizes for studies outlined in Tables 1 and 2. This plot visualizes the

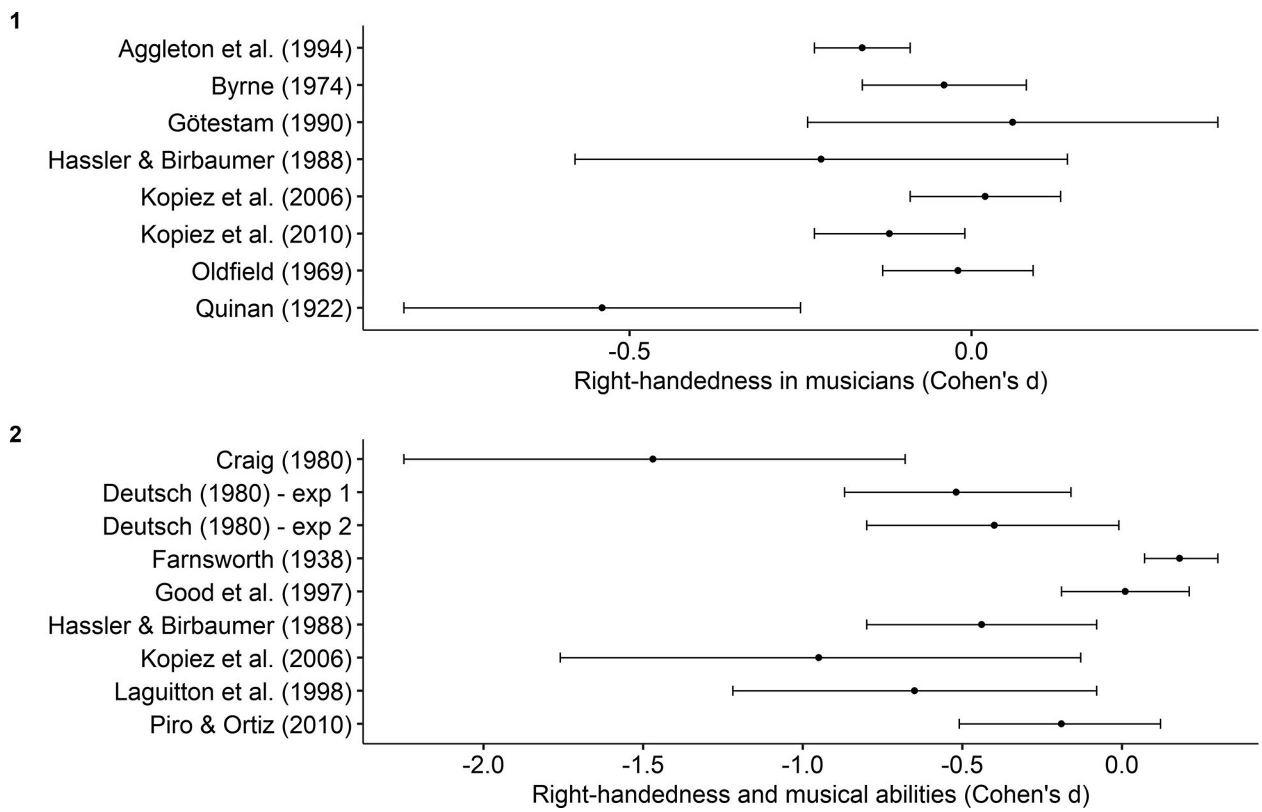

FIGURE 1. Effect sizes of prior research on the relationship between handedness and musicality. Calculated effect sizes are Cohen's *d* and error bars correspond to 95% confidence intervals.

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conflicting nature of prior research with diverse effect sizes from -1.47 to 0.18. It further indicates the sense in which large effect sizes often go hand in hand with very large confidence intervals, suggesting low reliability of individual estimates. The calculated effect sizes from Table 1 indicate small or very small effects, with the exception of the large effect found by Quinan (1922). The confidence intervals of several of the studies include 0, which could suggest that their true effects are non-significant. Many studies from Table 2 demonstrate larger effect sizes and fewer confidence intervals include 0; however, several effect sizes from this table could not be calculated.

Power analyses indicate that, due to the unbalanced nature of handedness, most studies do not include sufficiently many participants to detect the relatively small effects that we might expect handedness to have in the population. Supplementary Figure S1 (accompanying the online version of this paper at mp.ucpress.edu) shows the minimum effect size that can be detected with 80% power for a given number of participants, accounting for the fact that right-handers tend to outnumber non-right-handers approximately 9:1. For example, in order to detect a "small" effect size of $d = 0.2$, one would need 2,184 participants. We address this necessity in the current study, where we test 2,902 participants.

It should be noted that this approach of plotting solely the association between right- or non-right-handedness and musicality to allow comparison between research can hide effects that are specific to certain population subgroups. For example, Hassler and Birbaumer (1988) only found an effect for male left-handers, Byrne (1974) only found an effect for mixed-handers, and Deutsch (1980) found a specific performance advantage for mixed left-handers. Despite the advantages of more nuanced results, such analyses are only practical with relatively large sample sizes.

The chosen assessment method for handedness classification has been previously shown to impact reported prevalence levels (e.g., Papadatou-Pastou et al., 2020), so could help to elucidate the heterogeneity of findings in Tables 1 and 2. The most frequently used measure was the Edinburgh Handedness Inventory, but a range of other less established inventories have also been used. Analyses of the construct validity of the Edinburgh Handedness Inventory found some items did not fulfill the best psychometric function model and suggested writing and drawing items to have low discriminatory power (Büsch et al., 2010). Performance criteria are significantly more precise, being able to distinguish true right-handers from right-preferring non-right-handers (e.g., Kopiez et al., 2010), but only a small minority of studies used this method. Therefore, inconsistencies in the conceptualization of the handedness variable could have a significant impact on conclusions.

The samples used in the papers from Table 2 could suggest a potential explanation for the inconclusiveness of this previous research. Of the six studies assessing children as participants, only Hassler and colleagues (1988, 1993) found a significant relationship between musicality and handedness. Furthermore, this relationship was dependent on gender for Hassler and Birbaumer (1988). Contrastingly, three of the five studies on student or adult populations found associations. This provides one speculative explanation for the discrepancies between studies, with samples from older age groups being more likely to implicate an association. Comparison between these prior studies is difficult due to the varying nature of the populations and musical ability tests, so future research would be required to investigate this speculation and its potential implications for changes in dexterity.

Overall, this literature review demonstrates the highly conflicting nature of previous studies investigating the relationship between musicianship and handedness. While there is a slight majority of studies demonstrating a positive relationship with non-right-handedness, the significant number of null results casts doubt on this association. Our article aims to resolve some of this uncertainty between studies, while also addressing some of the limitations of this previous research.

Limitations of Previous Work

There are several limitations of the papers outlined above that may further contribute to their inconsistency in findings, including sample representativity and variety of musicality measurements. Several studies from Table 1 reach large sample sizes through the high number of nonmusicians tested, but only two papers studied more than 200 musician participants (Aggleton et al., 1994; Byrne, 1974). The sample sizes in Table 2 are even smaller due to the more time-consuming procedures, with only Good et al. (1997) and Farnsworth (1938) studying a total sample size over 200. Considering the relative rarity of non-right-handed people in the general population, the sample sizes of this previous research have a detrimental effect on their generalizability and therefore lack the statistical power to provide strong support for a relationship. Additionally, although a range of demographics have been tested overall, individual samples often contain very specific participant groups. The vast majority of the studies are confined to either young children or university students, with

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very few studies on secondary school students or adult populations.

Another discrepancy between studies is their subjective categorization of musicianship. For example, Hassler and Birbaumer (1988) classified musicians as those who had played an instrument for several years and achieved a high score in Wing's (1968) Standardized Tests of Musical Intelligence. This contrasts significantly to the highly musically experienced samples of professional musicians used in other studies from Table 1 (Aggleton et al., 1994; Byrne, 1974; Oldfield, 1969; Quinan, 1922). Additionally, research has often tested very different, and often specific, musical abilities. On the one hand, some studies have used musical test batteries, including the well-established Bentley Measures of Musical Ability in Good et al. (1997) and the Seashore battery in Byrne (1974). On the other hand, other studies tested specific abilities, such as pitch memory (Deutsch, 1980) or rhythm memory (Craig, 1980). This significantly reduces the comparison that can be made between studies and the generalizability of specific musical abilities to a broader conception of musicality. These discrepancies could explain the differences in findings, with certain musical abilities correlating more with handedness than others.

Furthermore, there have been no empirical contributions to these research questions in the last decade and very few studies have been undertaken since the turn of the century. Updating the research in this field is especially important when considering that the proportion of non-right-handers in the general population is increasing with more recent birth cohorts (Gilbert & Wysocki, 1992). This intuitively follows the changing societal perceptions of handedness over the last century: negative stereotypes perceiving left-handers as "wrong" and "inferior" are increasingly being discredited and the attempted societal repression of left-handed tendencies is gradually easing (Coren, 1992, p. 4).

The Present Study

The various limitations of previous work are addressed in the current study through the analysis of a newly collected international longitudinal dataset generated by the LongGold project (Müllensiefen et al., 2022; Müllensiefen & Harrison, 2020; Müllensiefen et al., 2015). The LongGold project focuses on tracing the development of a range of musical and academic abilities, as well as various personality traits, across the teenage years. Beginning in 2015, the project aims to annually test students from a range of schools in the UK and Germany. The resulting dataset has three primary advantages over previous work: the sample size, the rich set of covariates, and the longitudinal aspect.

The LongGold dataset provides a significantly larger sample size than any of the prior studies reviewed above and is international, sampling across the secondary school age range from thirteen different German and British schools. This enhances the generalizability of conclusions compared to previous smaller-scale studies. Additionally, the secondary school age range has very rarely been tested by previous work but presents a crucial period in the development of abilities and their connection to handedness.

The rich set of covariates included in the LongGold battery of music perception tests could additionally help to address some of the conflicting previous evidence. Participants were tested on their self-perception of various aspects of their musicality and were given three perceptual musical abilities tests measuring melody discrimination, mistuning perception, and beat perception. In our study, we use the term musicality to encompass the overall measures of self-reported musical sophistication (subjective musicality) and perceptual listening abilities (objective musicality), as well as their individual tests and subscales. Although the LongGold battery does not measure musical performance, this dataset nonetheless helps to draw together the research on different aspects of musicality by exploring a plethora of relevant variables with the same participants. Additionally, many other relevant variables relating to academic performance and personality were measured, expanding the range of analyses to comparisons with non-musical variables.

Furthermore, the covariates used within the dataset have been shown to exhibit strong validity and reliability across a variety of samples. The test battery contains specifically formulated and well-established measures of musicality. The Goldsmiths Musical Sophistication Index (Fiedler & Müllensiefen, 2015; Müllensiefen et al., 2014) captures a multifaceted, valid, and reliable conception of musicality in a short time frame, independent of music preferences and sensitive to any level of musical ability. Additionally, the beat perception, melody discrimination, and mistuning perception tests are adaptive to cater for all ability levels and have been thoroughly tested with diverse samples, establishing reliability and validity (Harrison et al., 2017; Harrison & Müllensiefen, 2018; Larrouy-Maestri et al., 2019).

Finally, the longitudinal nature of the LongGold data collection allows for an exploratory analysis into developmental aspects of handedness. Although this analysis is necessarily limited by the small number of participants changing their handedness over the four-year

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time span of the dataset, it could implicate potential evidence for the direction of causality of any relationships between musicality and handedness. This exploratory analysis could provide a foundation for future research investigating these questions of causality more concretely in a dataset spanning a longer time frame.

Expanding the prior research detailed above, this study aims to investigate the relationship between handedness and abilities in secondary school students using the LongGold dataset. Specifically, the present research analyses the effect of being right-handed or non-right-handed on subjective and objective musicality. In addition, we explore the relationship between handedness and academic school performance and intelligence measures. Our use of mixed effects regression allows us to adjust for potential confounds, including gender, which adds to the robustness of the results. In addition, we will perform an exploratory analysis utilizing the longitudinal nature of the dataset to explore why a small percentage of students changed their handedness over time.

Method

PROCEDURE

The present study analyses the data of 2,902 secondary school students from thirteen schools in the UK and Germany. Participants' ages ranged from 10 to 18, with a mean age of 12.85 years (*SD* = 2.00). All participant data was taken from the LongGold project (Müllensiefen et al., 2022; Müllensiefen & Harrison, 2020; Müllensiefen et al., 2015). The LongGold project is an international longitudinal study of educational development in adolescents, which began in 2015. Through a repeated measures design, the project aims to capture the development of a range of musical, academic, and personality skills by testing the same participants annually over their secondary school years. The test battery used to assess students each year comprises several cognitive and musical tests and a number of short self-report questionnaires through an online interface. Pupils were assessed individually in their school computer rooms or using tablets and headphones during a double lesson in their classroom, both in the presence of a test supervisor and one of their teachers.

MEASURES

The LongGold test battery collects data for a wide variety of variables, including objective tests, self-report measures, and data from school assessments. Demographic data, including gender, age, school, country, and socio-economic status, were additionally collected and used in the analysis. The measurement and conceptualization of handedness within the present study is detailed below. Following this are descriptions of the battery measures analyzed specifically in this study: objective measures of musicality, self-reported musicality, general cognitive measures, and academic abilities.

Before any analysis was carried out, scores across all the relevant variables were standardized through *z*-scoring. Therefore, data points represent the number of standard deviations from the mean for that ability, allowing comparison between measures. Most variables are standardized across the entire dataset, with the exception of the academic measures, which are standardized within groups of school and year group as the scores are not comparable between different year groups or schools.

Handedness

Self-reported handedness was measured using two questions of hand preference as part of the LongGold test battery:

1. Are you . . . left-handed / right-handed / ambidextrous (use both hands equally)?
2. Which hand do you normally use for writing? The right hand / the left hand / both hands equally

Handedness is treated as a dichotomous variable in this study. Two categories were created from the two hand preference questions: right-handed (RH) for participants who answered "right-handed" on both questions and non-right-handed (NRH) for participants who answered "left" or "ambidextrous/both hands" for at least one of the two questions. Therefore, all participants who gave inconsistent answers between the two questions were categorized as non-right-handed. This takes a similar approach to Hassler and colleagues (1988, 1993), who classified their right-handed group of participants as those who answered "right" to two or more of their four inventory questions and "either hand" to the remainder, and classified all other participants as non-right-handed. More recently, the same handedness categories were used by Kopiez et al. (2006, 2012), although they used a tapping paradigm for classification. While splitting the sample into smaller groups, such as separating the mixed- and left-handers, could provide more nuanced results, the sample size of these groups would have been too small to achieve sufficient statistical power to detect small effect sizes. Additionally, our measurement method is not precise enough to make these distinctions with sufficient validity.

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Objective Measures of Musicality

Objective musicality was measured using three tests as part of the LongGold test battery. The three tests are adaptive, meaning that the difficulty of each successive trial depends on the participant ability estimated over previous trials using Bayes modal estimation. This adaptive nature helps the tests to produce reliable ability estimates in a short amount of time, while catering to a wide range of possible ability levels. Weighted maximum-likelihood estimation was used to determine ability at the end of each test.

The Computerized Adaptive Beat Alignment Test (Harrison & Müllensiefen, 2018) assesses participants' ability to process the beat of musical examples. The test requires participants to discriminate between pure tones presented on the beat and displaced off the beat by a constant proportion. Excerpts of jazz, rock, and orchestral pop were used to create a representative sample of music genres over 25 trials. The Melodic Discrimination Test (Harrison et al., 2017) measures the ability of pupils to differentiate between similar, but slightly altered melodies in a three-alternative forced-choice paradigm. Each melody is played three times in different keys, with one note changed in one of the three iterations. Participants are asked to identify the altered melody in 20 trials of this test. The Mistuning Perception Test (Larrouy-Maestri et al., 2019) measures participants' ability to recognize mistuning in accompanied vocal singing over the course of 25 trials. Each trial comprises a single musical extract drawn from the "MedleyDB" multitrack audio dataset played twice: once without any alteration, and once with the vocal line pitch-shifted slightly sharp or flat. Participants are required to identify which one of the two versions has been pitch-shifted.

In the present study, scores for each test were analyzed separately and factor analyzed to produce an overall general factor of objective musicality. An initial inspection indicated that scores from the three tests were significantly correlated (Pearson's r values from .35 to .38, all p values < .001), suggesting the aggregation of scores by factor analysis. All three tests showed high loadings (range of loadings: .58 to .63; range of communalities: .34 to .39) on the single factor of the minimum residual factor analysis model. The factor model explained 37% of the variance of the raw scores and the multiple R^2 between estimated factor scores and factors was .64. Subsequently, students' test scores were extracted by regression from the latent factor and termed objective musicality. The resulting scores correlate highly with a straight average of the three variables. A rerun of our main analysis using this alternative averaging method is reported in Supplementary Table S2 and Figure S2 (accompanying the online version of this paper at mp.ucpress.edu).

Self-reported Musicality

Self-reported musicality was measured using the Goldsmiths Musical Sophistication Index (Gold-MSI). The Gold-MSI is a self-report inventory of 39 items using seven-point rating scales assessing five subscales of musical sophistication (Müllensiefen et al., 2014): active engagement, emotions, music training, perceptual abilities, and singing abilities, as well as one general factor. Both the five individual subscales and an overarching general factor drawing on all the subscales were used for analysis in this study. The Gold-MSI has good internal reliability and a high correlation to actual musical skill levels (Müllensiefen et al., 2014).

General Cognitive Measures

General intelligence was assessed using a Matrix Reasoning Test. This assesses fluid intelligence, non-verbal reasoning, and problem solving through asking subjects to complete visual puzzles similar in style to Raven's Matrices (Chan & Kosinski, 2015). Additionally, visuo-spatial working memory was measured using a Working Memory Test which required participants to remember the positions of colored balls in the hands of two cartoon characters (Tsigeman et al., 2022).

Academic Measures

Academic ability was assessed using the school grades of participants, categorized on a scale from 0 to 100. Some schools provided subject scores for some year groups already on a 0–100 scale. Other schools and year groups provided grades using an ordered system with a small number of categories, such as 1–5 or A–E. In these cases, we partitioned the 0–100 range into a number of bins corresponding to the number of grade categories given. Each student's grade was then mapped to the numeric value corresponding to the midpoint of the respective bin. Therefore, academic ability scores are comparable within combinations of year group and school but are not comparable between year groups or different schools. We computed overall academic achievement as an average of each student's school grades; we also computed grades differentiated into six categories referring to different school subject groups (applied; languages; maths and sciences; music; aesthetic and non-music; social and cultural).

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Results

DESCRIPTIVE STATISTICS

Every data point where handedness was not measured was immediately excluded, including all data from 2015 to 2016 when handedness was not yet part of the test battery. Due to data collection errors, a small proportion of participants duplicated the identification number of another participant, so were additionally excluded due to the difficulty distinguishing between them.

The participants used in this study were 2,902 secondary school students from thirteen schools in the UK and Germany. The participants were aged 10 to 18, with an average age of 12 years and 10 months old (12.85 years, *SD* = 2.00). Table 3 demonstrates the main descriptive characteristics of the sample and variables, separated by handedness category. A more detailed descriptive statistics table split by school is presented in Supplementary Table S3 (accompanying the online version of this paper at mp.ucpress.edu).

84.25% of the sample were classified as right-handed (RH, *n* = 2445) and 13.16% were classified as non-right-handed (NRH, *n* = 382). From the subsample of participants that answered questions on their socio-economic status (SES, *n* = 349), the average SES class was 1.49 (*SD* = 0.90). Following the NS-SEC (Rose & Pevalin, 2001), class 1 describes managerial and professional occupations and class 2 represents intermediate occupations. This suggests that the participants typically came from relatively affluent backgrounds.

The sample contains significantly more participants that identify as female (*n* = 1778, 61.27%) than male (*n* = 951, 32.77%), other (*n* = 42, 1.45%), or preferred not to reveal their gender (*n* = 68, 2.34%). A small subsample of participants changed their gender identification over the years they were tested (*n* = 63, 2.17%).

TABLE 3. *Descriptive Statistics and Mean Scores for the Dataset of Participants, Split by Category of Handedness*

Measure		RH	NRH	Changing handedness
Total number		2445	382	75
Gender	Female	1556 (87.5%)	195 (11.0%)	27 (1.5%)
	Male	767 (80.7%)	152 (16.0%)	32 (3.4%)
	Other	122 (70.5%)	35 (20.2%)	16 (9.2%)
Mean SES class*		1.51 (0.89)	1.40 (0.82)	
Mean age (years)		12.88 (2.00)	12.82 (2.11)	12.04 (1.84)
Academic	Overall	0.02 (0.96)	-0.15 (1.06)	-0.22 (0.80)
	Applied	0.02 (0.92)	-0.08 (1.01)	-0.12 (0.90)
	Languages	0.02 (0.96)	-0.13 (1.01)	-0.29 (0.76)
	Maths/sciences	0.01 (0.96)	-0.16 (1.04)	-0.19 (0.82)
	Music	0.01 (0.94)	-0.18 (0.98)	-0.21 (0.78)
	Non-music aesthetic	0.04 (0.92)	-0.18 (1.03)	-0.07 (0.85)
	Social/cultural	0.01 (0.94)	-0.11 (1.05)	-0.04 (0.76)
Intelligence/memory	General intelligence	0.07 (0.96)	-0.07 (1.01)	-0.31 (0.79)
	Visuospatial memory*	0.01 (1.02)	-0.06 (1.05)	
Self-reported musicality	General	-0.01 (0.98)	-0.01 (1.01)	0.27 (0.87)
	Active engagement	0.02 (0.96)	-0.02 (0.99)	0.19 (0.82)
	Emotions	0.03 (0.97)	0.02 (0.96)	-0.12 (0.83)
	Music training	-0.01 (0.96)	-0.00 (1.01)	0.21 (0.95)
	Perceptual abilities	-0.00 (0.98)	-0.01 (0.91)	0.04 (0.82)
	Singing abilities	0.01 (0.97)	-0.05 (0.97)	0.25 (0.84)
Objective musicality	Overall	0.06 (0.97)	0.04 (1.01)	-0.33 (0.86)
	Beat perception	0.05 (0.93)	0.03 (0.98)	-0.31 (0.81)
	Melody discrimination	0.03 (0.97)	0.09 (1.00)	-0.22 (0.78)
	Mistuning perception	0.06 (0.93)	-0.05 (0.98)	-0.21 (0.87)

Note: Each measure aside from age has been *z*-scored, so is expressed in terms of the number of standard deviations from the mean; standard deviations are given in brackets. Changing handedness refers to those who have been categorized as both RH and NRH during different rounds of measurement. *Participants who changed their handedness were missing data for these measures.

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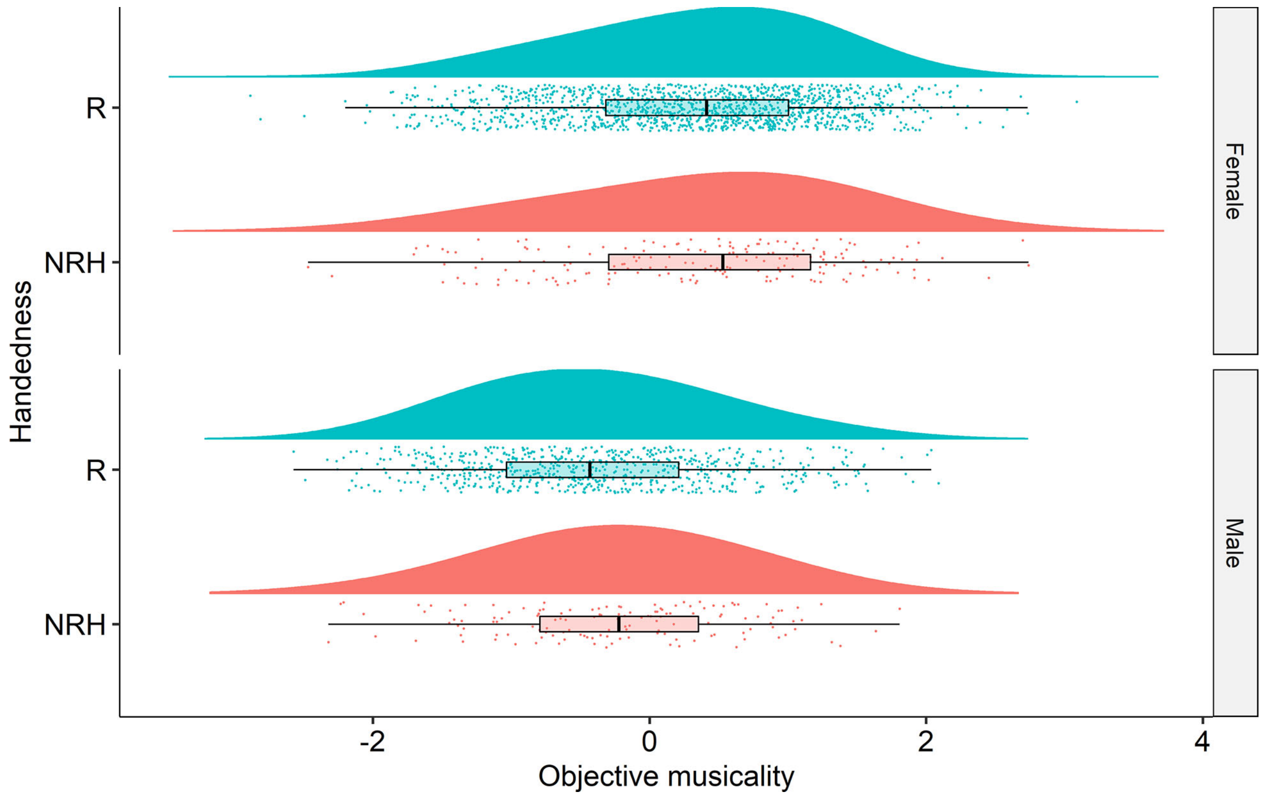

FIGURE 2. A raincloud plot comparing the standardized general factor of three musical ability tests (objective musicality) of female and male participants, split into right-handed and non-right-handed. After Allen et al. (v2, 2021).

Female participants achieved higher than males on both self-reported and objective musicality measures—self-reported: $t(1740.5) = 8.94$, $p < .001$, $d = 0.36$, 95% CI [0.28, 0.44]; objective: $t(1819.1) = 17.99$, $p < .001$, $d = 0.72$, 95% CI [0.62, 0.77]—as well as the academic variables—general intelligence: $t(2075.6) = 9.96$, $p < .001$, $d = 0.40$, 95% CI [0.30, 0.45]. This is illustrated in Figure 2, which compares the overall objective musicality score for male and female participants split by handedness.

A higher proportion of female participants are right-handed (87.51%) than male participants (80.65%). Synthesizing these gendered characteristics of the dataset implies a potential gender confound: as females are more likely to be right-handed and also performed better on the test battery, this could skew the results in the direction of a correlation between right-handedness and enhanced abilities. A regression-based analysis was therefore used to account for this gender confound alongside other potentially confounding variables.

A varied proportion of participants are missing data for each of the relevant variables. Table 4 compares the overall percentage missingness for the main response variables with percentage missingness split by handedness. Similar percentages of right- and non-right-handed participants were missing data for these four main measurements, so we continued without any data imputation.

TABLE 4. *Percentage of Missing Data for Each of the Four Main Response Variables*

Measure	Overall missingness (%)	RH missingness (%)	NRH missingness (%)
Overall academic performance	11.92	11.74	14.40
General intelligence (IQ)	3.14	3.19	3.40
Overall objective musicality	10.79	10.76	9.42
Overall self-reported musicality	8.14	7.98	8.12

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ANALYSIS

Our primary analyses are cross-sectional, with each participant contributing a single data point to a given regression model. Given that the LongGold dataset is longitudinal in nature, we had to make a decision about how to summarize data from participants who contributed multiple rounds of measurement. We considered several approaches:

a. Taking scores from a particular year of testing (e.g., 2017, 2018, 2019, or 2020);
b. Taking each student's first year of participating in the battery;
c. Taking each student's most recent year of participating in the battery;
d. Averaging each student's scores over all years that they took part in the study.

We preferred the final strategy as it makes the most use of the available data, hence maximizing statistical power. However, we also repeated our main analyses with alternative approaches b) and c) mentioned above to verify that they were not materially affected by this analysis decision (see Supplementary Tables and Figures S4 and S5 accompanying the online version of this paper at mp.ucpress.edu).

When averaging the scores of participants who took part more than once, a small group of participants (n = 75) were found to have changed their handedness over time. These participants were excluded from the main analyses but used in an exploratory longitudinal analysis investigating changing dexterity.

All analysis was carried out using R 4.1.1 (R Core Team, 2021). We used mixed-effects linear regression as opposed to simple correlation analyses so that we could adjust for potential confounding variables. We address three main confounds alongside handedness as explanatory variables in our regressions: gender, age and school. Handedness, gender, and age were specified as fixed effects, and school as a random intercept, reflecting the fact that different schools might have different baseline ability levels. An alternative analysis specifying all four variables as fixed effects is presented in Supplementary Table S6 and Figure S6 (accompanying the online version of this paper at mp.ucpress.edu).

REGRESSION ANALYSIS

Separate mixed-effects linear regression models were run for each relevant measure of musical and academic ability as the response variable, using right-handedness, gender, age, and school as predictor variables. Table 5 represents the predictive accuracy of the models for the four overarching abilities measures. The marginal R^2 represents the variance explained by the three fixed effects (handedness, gender, and age), whereas the conditional R^2 represents the total variance explained by all four predictor variables (including school). Comparing the two statistics indicates that school is an important predictor of intelligence and objective musicality, but a weak predictor of academic performance and self-reported musicality. The overall predictive accuracy of the models (conditional R^2) significantly varies between variables, but suggests that the combination of handedness with gender, age, and school can be a significant predictor of ability.

TABLE 5. *Predictive Accuracy of Regression Models for the Four Overarching Response Variables*

Measure	Marginal R^2	Conditional R^2
Overall academic performance	0.02	0.02
General intelligence (IQ)	0.02	0.22
Overall objective musicality	0.04	0.26
Overall self-reported musicality	0.03	0.06

Note: The R^2 statistics were calculated using the MuMIn package (v1.47.1, Bartoń, 2022).

Figure 3 plots the resulting standardized regression coefficients for right-handedness in these regression models. Each point represents the amount that the response variable would change if someone was changed from being non-right-handed to right-handed while keeping all other variables constant. A positive coefficient demonstrates that right-handedness predicts higher ability levels and a negative coefficient demonstrates that right-handedness predicts lower ability levels. The error bars plot 95% confidence intervals for these regression coefficients.

This plot visualizes a contrast between the relationships that handedness has with academic ability versus musicality. On the one hand, right-handedness seems reliably associated with higher academic ability (academic variables and intelligence); on the other hand, right-handedness seems to have no reliable association with musicality (objective or self-reported).

Table 6 lists the standardized regression coefficient for right-handedness (β), confidence interval (CI), and p value for each of the four overarching abilities measurements.

No statistically significant relationships were found between handedness and either objective or self-reported musicality. None of the individual Gold-MSI subscales of self-reported musicality or individual tests of musical ability demonstrate a significant association with handedness.

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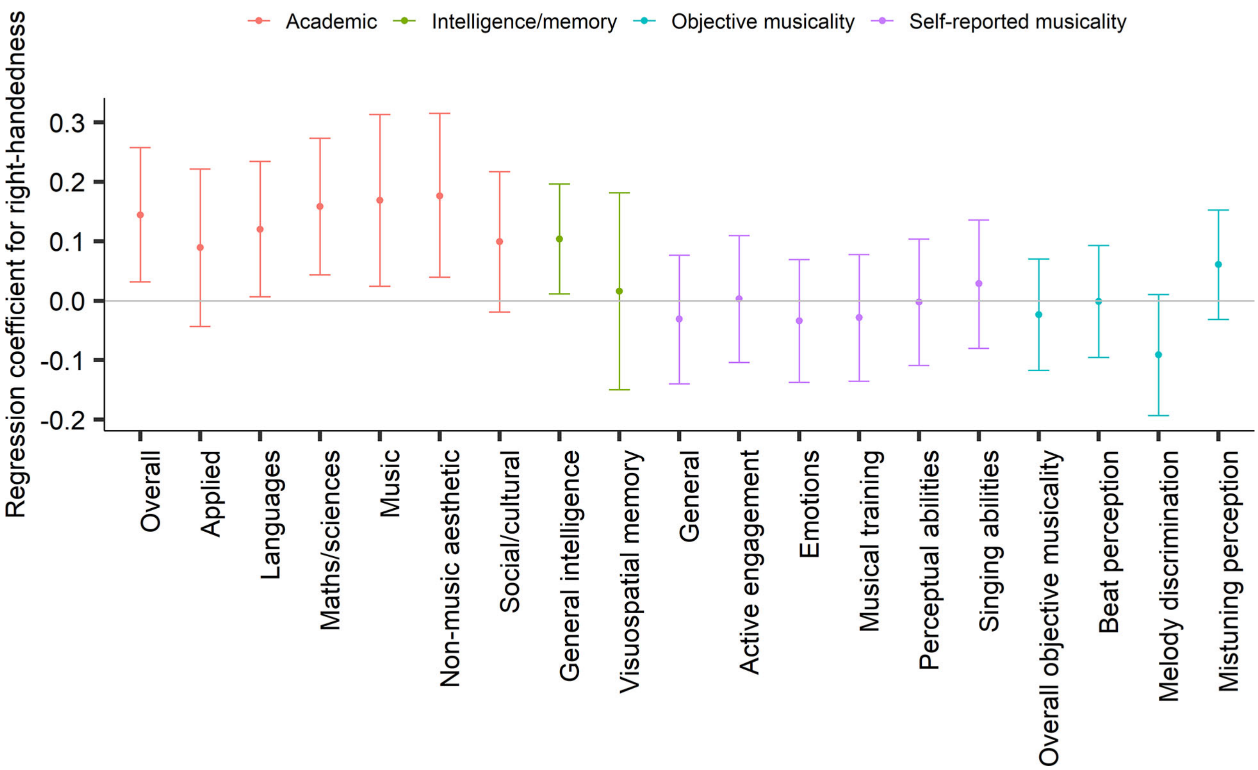

FIGURE 3. A graph demonstrating the standardized regression coefficient for handedness of each response variable. Errors bars plot 95% confidence intervals.

TABLE 6. *Standardized Regression Coefficients for Right-handedness for the Four Overarching Response Variables*

Measure	β	95% CI	*p*	*d*	95% CI
Overall academic performance	0.14	[0.03, 0.26]	.01	0.15	[0.03, 0.27]
General intelligence (IQ)	0.10	[0.01, 0.20]	.03	0.12	[0.00, 0.25]
Overall objective musicality	−0.02	[-0.12, 0.07]	.62	−0.03	[-0.15, 0.10]
Overall self-reported musicality	−0.03	[-0.14, 0.08]	.57	−0.03	[-0.15, 0.09]

Note: Regression coefficients and *p* values were computed using the lmerTest package (v3.1-3, Kuznetsova et al., 2017). The regression confidence intervals were computed through the lme4 package (v1.1-30, Bates et al., 2015). Cohen's *d* effect sizes and their confidence intervals were calculated using the emmeans package (v1.8.5, Lenth, 2023).

On the other hand, the data indicates a statistically significant association between general intelligence and right-handedness, as well as between overall academic performance and right-handedness. The languages, maths/sciences, music and non-music aesthetic subscales of academic ability demonstrate a significant relationship. No reliable association was found for visuospatial memory.

COMPARISON ANALYSIS INVESTIGATING AGE

For comparison, Figure 4 plots semi-standardized regression coefficients for age against a representative selection of these response variables (note that, due to the data normalization process, it does not make sense to analyze several omitted variables as a function of age). Each point represents the number of standard deviations the response variable would increase if age was increased by one year. This plot demonstrates the increase in intelligence, memory and objective musicality with age. The strongest positive association is between that of general intelligence and age, which is borne out by the statistical data in Table 7.

This allows us to interpret handedness effects in terms of the corresponding age effects. For example, the analyses indicate that the difference in general intelligence between being right- and non-right-handed corresponds to an age advantage of 1.7 years (95% CI [0.1, 6.7]).

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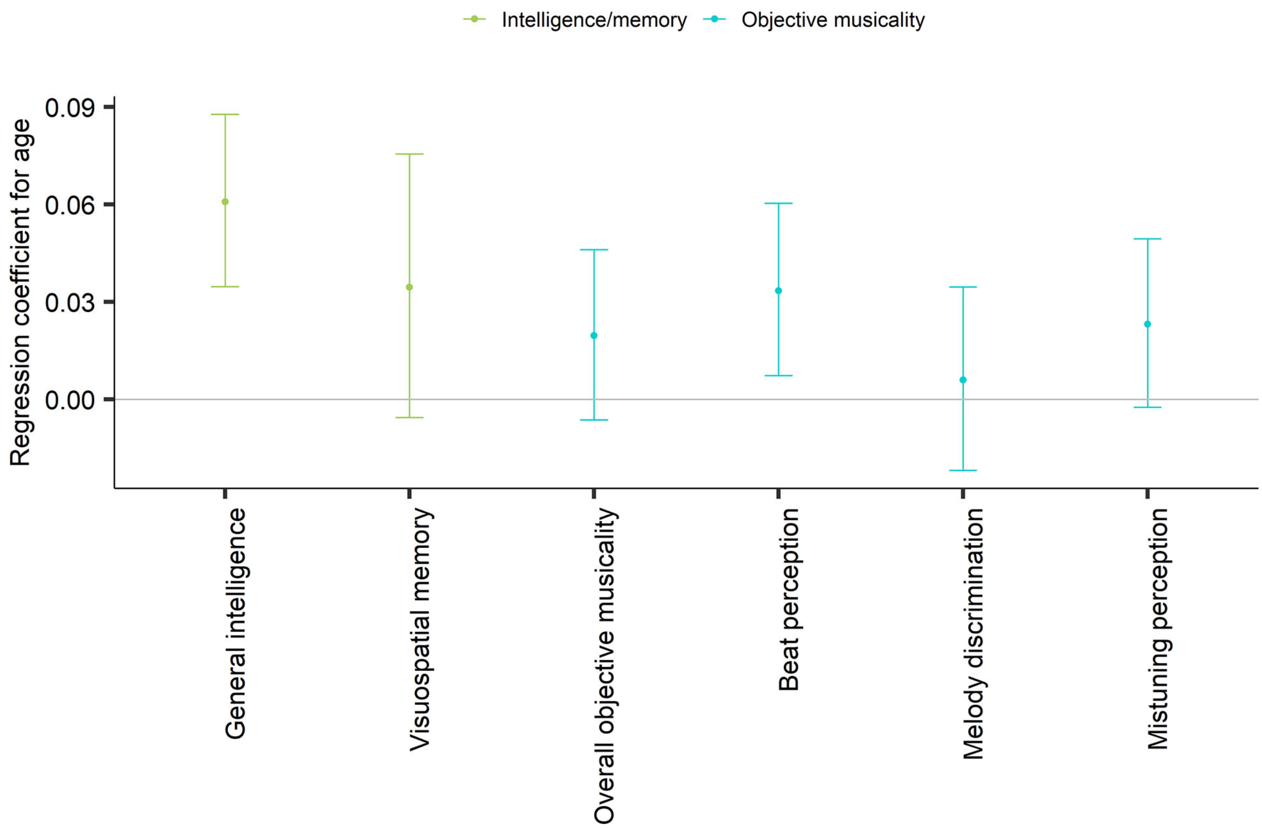

FIGURE 4. A graph demonstrating the age regression coefficient for a subset of response variables. Error bars plot 95% confidence intervals.

TABLE 7. *Semi-standardized Regression Coefficients for Age for Three Overarching Response Variables*

Measure	β	95% CI	p	η_p^2	95% CI
General intelligence (IQ)	0.06	[0.03, 0.09]	< .001	0.0081	[0.0026, 0.0164]
Visuospatial memory	0.04	[-0.01, 0.08]	.10	0.0071	[0.0000, 0.0326]
Overall objective musicality	0.02	[-0.01, 0.05]	.14	0.0009	[0.0000, 0.0049]

Note: Type III partial eta-squared effect sizes and their confidence intervals were computed using the effectsize package (v0.8.3, Ben-Shachar et al., 2020).

SUBSAMPLE ANALYSES

We performed a small number of subgroup analyses to explore any interaction effects handedness exhibited with gender, age, or country of data collection. An interaction term was added to our regression models between the main effect of handedness and either gender, age, or country. These interaction terms were all non-significant for objective musicality, subjective musicality, and general intelligence (see Supplementary Table S7 accompanying the online version of this paper at mp.ucpress.edu for full statistics). This highlights that our results remain consistent for all subsamples of gender, age and country.

EXPLORATORY ANALYSIS INVESTIGATING CHANGING HANDEDNESS

We additionally constructed a logistic regression model to compare participants with stable handedness to those who exhibited changing handedness patterns. We acknowledge the lack of precision and validity in the assumption of changing handedness and merely provide this exploration as a suggestion to be expanded in future work. Following previous literature that has identified musicians to demonstrate increasing non-right-hand skill, this exploratory analysis was confined to comparing the ability of participants who changed from right-handed to non-right-handed (n = 56) with participants who remained right-handed throughout

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TABLE 8. *Standardized Regression Coefficients for a Logistic Regression Model Classifying Students as Changing-handed Versus Right-handed (Baseline)*

Measure	β	95% CI	*p*	*OR*	95% CI
Overall academic performance	−0.14	[-0.56, 0.29]	.52	0.88	[0.59, 1.32]
General intelligence (IQ)	−0.33	[-0.83, 0.16]	.20	0.74	[0.46, 1.17]
Overall objective musicality	0.01	[-0.47, 0.50]	.97	1.01	[0.63, 1.62]
Overall self-reported musicality	0.15	[-0.29, 0.60]	.50	1.16	[0.76, 1.77]

Note: Odds ratio (OR) effect sizes and their confidence intervals were computed using the effect size package (v0.8.3, Ben-Shachar et al., 2020). ORs > 1 indicate that this variable was positively associated with changing handedness, whereas ORs < 1 indicate a negative association.

(n = 2,445). The logistic regression model tested the extent to which each of the four overarching abilities variables could predict whether a participant changed from right- to non-right-handed versus staying right-handed. However, the overall model had a low predictive power (McFadden's pseudo R^2 = .01; after Jackman, 2020, v1.5.5), and none of the four variables were statistically significant predictors (see Table 8).

Discussion

The purpose of this study was to investigate the relationship between handedness and musical/academic abilities, using the LongGold dataset of secondary school students. We assessed musicality and academic ability using a variety of measures, including three music perception tests, a self-report musicality questionnaire, assessment of school test scores, and short tests of intelligence and visuo-spatial memory. Our main result is a lack of relationship between musicality and handedness, both for self-reported musicality and objective musicality. However, we found a statistically significant relationship between right-handedness and academic ability, including general intelligence and school grades.

The lack of association found between musicality and handedness is interesting in the context of the two categories of literature discussed previously (Table 1, Table 2). First, previous literature has generally found that musician populations tend to be more non-right-handed than nonmusician populations (Table 1). In contrast, we found no association between music training scores and handedness. Second, some previous literature has found that non-right-handedness tends to be associated with stronger musical abilities (Table 2). However, we found no association between handedness and either objective or self-reported measures of musicality once gender, age, and school were taken into account, contrasting with previous literature.

This key finding of our article helps to resolve the inconclusiveness of previous research in this field. Several limitations of previous work are addressed in the current study, which includes a significantly larger and more generalizable international sample. The rich set of covariates and the reliability and validity of the established LongGold test battery measures additionally extend beyond the scope of previous research. Our findings show that relationships between handedness and musicality do not remain once we address these limitations and control for the right variables.

Previous research has provided a speculative explanation for the association between non-right-handedness and musical ability found in prior studies: processing of music in the brain is increasingly perceived to be bilateral (e.g., Warren, 2008) and non-right-handed people have been found to have greater interhemispheric interaction for music perception than right-handed people (e.g., Nachshon, 1978; Stewart & Clayson, 1980). However, we found no such association between handedness and musicality in the present study. One possible explanation for this could be that handedness remains a relatively low predictor of cerebral lateralization and the vast majority (76%) of left-handed people still have the left hemisphere language dominance typical of almost all right-handed people (Pujol et al., 1999).

However, the reverse causal explanation discussed previously—that musicians may change their handedness over time—cannot be discounted from the present data analysis, and future research would be required to investigate this theory. The longitudinal nature of the current study tested students over a maximum of four years, which provides only a relatively short time span over which to measure changes in handedness that could take many years to develop. More detailed and precise measurements of handedness using performance criterion would be required to precisely and validly measure any changes. Additionally, the average age of the sample was only 12.85 years, so the majority of participants were still relatively early in their musical education and any effect of music training on handedness would be very small. Our exploratory analysis was merely provided as a suggestion for future work due to

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our small sample size and imprecise assumption of changing handedness, but we found no correlation between increasing non-right-handedness and musicality.

This reverse causal explanation does support the pattern in Table 2 that relationships between non-right-handedness and musical ability were less likely to be found in children than adults and could be underpinned by research finding musicians to have more bilateral representations of music in the brain (e.g., Ono et al., 2011). This could suggest the plasticity of dexterity in the case of musicians completing intense bimanual training and the plasticity of brain lateralization in the case of anyone undergoing musical learning, including our sample of school students. Nevertheless, this speculation is complicated by Kopiez et al. (2012), who identified a reverse adaptive response where the temporal sensorimotor precision of left-handed pianists was superior in their right hand, so left-handed musicians had become more right-handed. This highlights the complexity of these ideas and the necessity for future work specifically focusing on changing handedness in musicians.

The lack of association between handedness and musicality additionally provides further support to falsify claims surrounding innate differences for left-handed people. For example, the idea that left-handers are "right-brained" and use the right hemisphere or artistic side of the brain for the majority of their thinking remains a popular misconception (Macdonald et al., 2017; McManus, 2019), despite having very little support (Beaumont et al., 1984). This highlights the importance of the present study in further dispelling this "neuromyth" of brainedness and other claims about the artistic nature of left-handers.

One interesting inconsistency in this key finding is the effects of the different music perception tests, with melody discrimination being associated with slightly higher performance for non-right-handers and mistuning perception associated with slightly higher performance for right-handers. Although these effects are statistically not significant, these small differences between tests could suggest that different musical skills present contrasting relationships with handedness. Peretz and Zatorre (2005) found pitch and melody to primarily be processed in the right hemisphere, but temporal musical processing to be more bilateral. This could explain why non-right-handers performed better in a melody test, but equally to right-handers in a beat perception test. The effect of the mistuning perception test is most difficult to rationalize, as no prior research on the relationship between handedness and musicality has found a significant positive association with right-handedness. Furthermore, our statistically significant association between right-handedness and academic school grades for music contrasts with our null associations between handedness and other aspects of musicality. These discrepancies could suggest that handedness presents different relationships with different aspects of musicality. This could also point towards another area for future work, comparing the specific effects of a range of musical measures on handedness.

The second finding pertaining to the relationship between handedness and academic ability could have important implications for the education of non-right-handed children. The tendency found for non-right-handed students to be academically outperformed by right-handers is supported by several of the models for the origins of left-handedness cited previously, including the neuropathological explanation by Geschwind and Galaburda (1985), the brain damage model by Satz (1972), and cultural factors that disadvantage left-handed people.

The higher prevalence of non-right-handedness in males (16.0%) compared to females (11.0%) could suggest further support for Geschwind and Galaburda's (1985) hypothesis, with increased levels of prenatal testosterone that delay left-hemisphere growth potentially being more likely to occur in males. The difference in prevalence of non-right-handedness in males and females in our dataset is even more significant than prior research, with Papadatou-Pastou et al. (2020) finding 16.20% for females and 19.80% for males. These numeric discrepancies in prevalence may simply reflect the different handedness measures used.

The present study suggests a stronger association between handedness and academic ability than the negligible link found in previous meta-analyses (e.g., Ntokla & Papadatou-Pastou, 2017; Papadatou-Pastou, 2018). Our findings suggest the importance of providing adequate educational support for non-right-handers, but more research on less affluent samples is required to support our conclusions.

LIMITATIONS AND FUTURE WORK

Despite the ways the present study builds upon previous research, there remain some limitations to the design and implementation that could be improved with future work, especially regarding handedness classification. Although a dichotomous categorization of handedness has been utilized in previous research (e.g., Gilbert & Wysocki, 1992; Hassler & Birbaumer, 1988; Hassler & Gupta, 1993; Kopiez et al., 2006, 2011), it is arguably overly reductive. More recent research suggests that

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degree of handedness could be a more appropriate measure (e.g., Papadatou-Pastou, 2018; Prichard et al., 2013), as highlighted by the importance of more detailed categorization in some prior findings (e.g., Deutsch, 1980). This supports Annett's (2002) proposition that valid handedness measures should consider the variable to be continuous. Splitting the non-right-handed participants in the LongGold dataset into left- and mixed-handed would have resulted in a lack of construct validity for these categories due to our simplistic and imprecise measurement of handedness and reduced the statistical power of the findings due to small group sizes.

Therefore, our measurement of handedness is the most significant limitation of this study. Due to space constraints we only asked two basic questions regarding hand preference, but previous research has often used a more thorough assessment of handedness, such as the prevalent ten-item Edinburgh Inventory (Oldfield, 1971). Using such a handedness tool may improve the strength of the conclusions. Furthermore, the subjective self-report design of the handedness measurement could decrease its validity. Kopiez et al. (2006) found female participants to significantly overestimate the extent of their non-right-handedness and Oldfield (1971) found participants to underestimate the extent of their deviation from right-handedness, suggesting societal and cultural perceptions of handedness could impact self-reporting. Tested and self-reported handedness have been frequently shown to exhibit relatively high correlations of over .90 (e.g., Corey et al., 2001; Kuderer et al., 2022), but other research highlights discrepancies in correspondence of the measures (Ruck & Schoenemann, 2021). Inventories cannot separate right-handers from right-preferring non-right-handers, resulting in misclassifications compared with hand performance measurement (Kopiez et al., 2010).

Future research could address this fundamental limitation using a more robust measurement of handedness allowing further nuance in classification parameters. Hand performance tasks provide a more objective and precise measure than self-report inventories but can be difficult to administer on such a large scale. Using an accurate measure of handedness is arguably more important than the scale of the implementation but recent advances have developed economic and easy to administer manual preference tasks. One example is the Handedness Index Practical Task (Kuderer et al., 2022), which could be used in future research to enable more fine-grained examinations of handedness. A further suggestion could be to add a speed tapping paradigm to the LongGold test battery in the future.

Furthermore, the academic variables used are limited as a valid measure of academic achievement, as they were based on subjective school grades and tests that could significantly vary in difficulty between year groups and schools. We addressed this by scaling scores within year groups and schools, and by incorporating additional standardized intelligence tests in our battery; however, future research could address this limitation through incorporating standardized academic performance assessments completed by all students. Future work could additionally extend the musicality variables beyond perceptual ability and self-report measures to include performative skill, which could exhibit a different association with handedness due to the effect of motor training.

While the sample used in this study is a significant strength, some aspects lack representativity. Although socio-economic status was only measured in a minority of participants (n = 349), the recorded data indicated a relatively high average SES class of 1.49 (SD = 0.90), which is not representative of the SES of the general population. This could have a significant impact on academic and musical ability, with the greater encouragement and access to support of more affluent areas putting these students at a significant advantage. For example, classroom musical experience is three times more likely to be described as "non-existent" or "virtually non-existent" in disadvantaged areas compared to more affluent areas (Moscardini et al., 2021). Additionally, the present study aimed at investigating secondary school students but future work could expand this to explore whether the same results would be found within adult populations. It could be argued that relationships between handedness and musicality may be more likely to be found in older participants, as they have been involved with music for a larger number of years. Recent fMRI research has identified differences in certain brain areas of professional musicians that could predispose them to musicality and atypical language lateralization (Villar-Rodríguez et al., 2020).

It could be of particular interest for future research to compare samples of adults and children on identical tasks to explore the effect of age. While previous work sampling adults has been more likely to find an association between musicality and handedness, which could explain the lack of association with the present adolescent sample, comparison between different studies is limited due to methodological inconsistencies. Although potentially impractical to design and implement, a longitudinal study spanning a significantly longer time frame, measuring participants from childhood through adulthood, could be the most ideal study design

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to explore questions of causality with more certainty. This research could directly investigate whether dextrality does change over time and the relationship this presents with musicality. A test of hand performance, such as a speed tapping paradigm, could reveal more detailed findings, as it could measure small changes in handedness. Additionally, it could be speculated that investigating the strength of handedness, such as how mixed-handed participants are, or hemispheric dominance directly, which is only somewhat linked to handedness, could provide interesting insights into why the previous literature on handedness and musicality is so divided.

Overall, the present study makes a significant contribution to the body of literature on handedness and musicality, helping to resolve some of the inconclusiveness by addressing some of the limitations of previous work. The overall conclusion that there is no relationship between musicality and handedness can help to falsify some of the claims about the innate differences of non-right-handed people. This study additionally provides important implications for future work in the field, suggesting that research should explore changes in dexterity over time instead of the focus on a non-right-handed invariant innate proclivity for music processing found in previous research.

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