

Article

Twin Data Support a Sensitive Period for Singing Ability

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Abstract

As with many other musical traits, the social environment is a key influence on the development of singing ability. While the familial singing environment is likely to be formative, its role relative to other environmental influences such as training is unclear. We used structural equation modeling to test relationships among demographic characteristics, familial environmental variables (early and current singing with family), vocal training, and singing ability in a large, previously documented sample of Australian twins ($N = 1163$). Notably, early singing with family, and to a lesser extent vocal training, predicted singing ability, whereas current singing with family did not. Early familial singing also mediated the relationship between sex and singing ability, with men who sang less with family during childhood showing poorer ability. Bivariate twin models between early familial singing and singing ability showed the phenotypic correlation was largely explained by shared environmental influences. This raises the possibility of a sensitive period for singing ability, with sociocultural expectations around singing potentially differentiating the developmental trajectories of this skill for men and women.

Keywords: Singing ability; Twins; Sensitive period; Childhood family singing

(Received 20 March 2024; revise received 11 June 2024; accepted 11 June 2024)

As one of only a few potentially universal musical behaviors, singing represents a major form of engagement with music (Singh & Mehr, 2023). Singing is unique as a musical production behavior as it exists widely in the general population, does not require a physical instrument, and develops alongside language production ability (Dalla Bella et al., 2007). Singing also has several neurocognitive and health benefits across the lifespan. Singing competency has been associated with greater feelings of social inclusion and connectedness in children, which are important for psychological wellbeing (Papageorgi et al., 2022). Regular singing may confer protective benefits against neurodegeneration in older adulthood (Särkamo, 2018), with recent longitudinal evidence suggesting that it may maintain or even improve specific cognitive functions, such as verbal fluency (Pentikäinen et al., 2023). It may also protect against age-related physiological declines in vocal quality, such as loss of control over the vocal folds (Lortie et al., 2017; McHenry & Evans, 2022). Thus, singing can have positive impacts across the lifespan, and understanding the mechanisms that influence its development can inform how it increases and shapes our mental and physical wellbeing.

While aesthetic evaluations of singing ability often vary, a primary component of accurate singing is intonation, or the ability to sing in tune (Watts, Barnes-Burroughs et al., 2003). Attesting to this, under most conditions even nonmusicians in the general population can reproduce familiar tunes with a reasonable

level of accuracy. However, wide individual differences are evident (Dalla Bella & Berkowska, 2009; Dalla Bella et al., 2007; Pfordresher, 2022) and we still have limited understanding of what predicts the ability to sing accurately.

Genetic factors likely play a crucial role in the development of singing, although the exact mechanisms involved remain unknown (Park et al., 2012; Yeom et al., 2022). Two studies have shown that engaging in singing activities is partially heritable (20–71%), potentially reflecting predispositions for singing engagement (Coon & Carey, 1989; Gustavson et al., 2021). A more recent twin study has shown that objective singing performance is also moderately heritable (~41%), with similar estimates to what has been observed for singing engagement (Yeom et al., 2022). Likewise, Park et al. (2012) found that vocal pitch-matching ability is partially heritable (40%), and identified genetic loci in large families related to this skill. Notably, studies investigating the genetic bases of other musical traits in humans have identified loci that are also known to regulate song-learning and cognition in songbirds (Nair et al., 2019; Nair et al., 2020). This provides tentative evidence for a potential shared evolutionary basis of musical traits (Savage et al., 2020; Singh & Mehr, 2023). These genetic factors may influence the maturation and development of both physiological and neurological processes underlying the song system of the human brain, including control of vocal articulatory systems (Harris et al., 2023) and networks involved in sensorimotor integration (Tsang et al., 2011).

Formal musical training and practice have also been shown to improve singing ability (Pfordresher, 2022; Pfordresher & Demorest, 2021), but training is not a sufficient explanatory factor on its own

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Cite this article: Yeom D, Haslam N, Tan YT, McPherson GE, Wilson SJ. Twin Data Support a Sensitive Period for Singing Ability. *Twin Research and Human Genetics* <https://doi.org/10.1017/thg.2024.30>

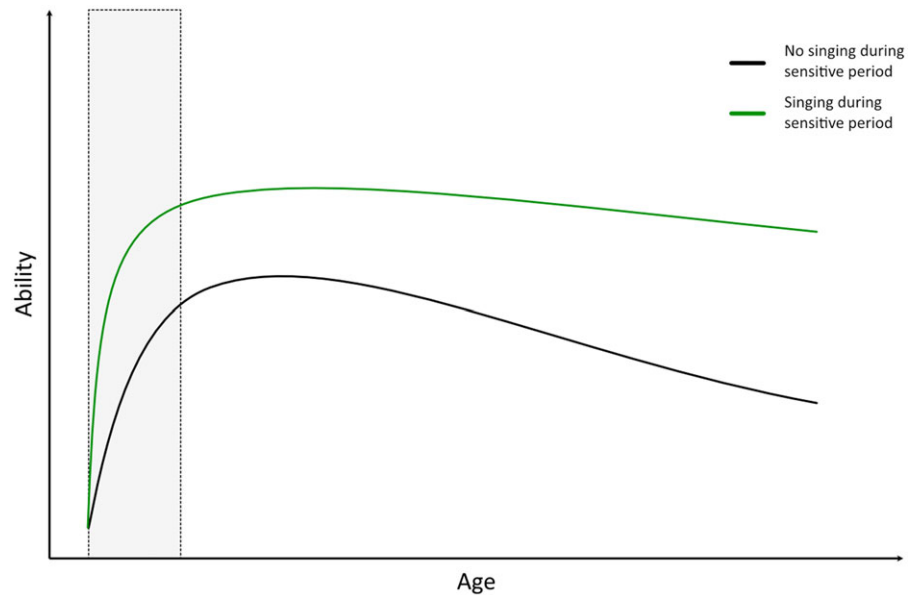


Figure 1. Schematic of hypothesized trajectories for singing development, based on exposure to singing in early life. The grey shaded box represents a possible sensitive period for singing, where exposure and/or engagement during this time has the most optimal impact on skill development.

(Ullen *et al.*, 2016; Watts *et al.*, 2006; Watts, Murphy *et al.*, 2003). Prior research points to several other environmental influences that shape singing, such as socioeconomic status (McPherson *et al.*, 2015), peer influence (Demorest, Kelley *et al.*, 2017; Hall, 2005), classroom-based instruction (Demorest, Nichols *et al.*, 2017) and musical enrichment during childhood (Demorest, Kelley *et al.*, 2017; Persellin, 2006; Theorell *et al.*, 2015). Although the relative importance of these different environmental influences remains unknown, in general, richer musical and singing environments are considered to foster greater singing participation and ability. While group singing is prevalent in most cultures (Shilton *et al.*, 2023), children raised in cultures where singing is a normative social behavior generally learn to sing at a faster rate (Kreuntzer, 2001). Similarly, sociocultural beliefs such as stereotypes around singing may influence how likely individuals are to take up singing (Harrison, 2007). Within Western contexts, men are often discouraged from singing at a young age on account that it has been culturally identified as a feminine endeavour (Hall, 2005; Harrison, 2007; Powell, 2014). Since these differences in singing engagement can influence how singing ability develops over time, this may partly explain previously observed differences between male and female singing skills (Welch *et al.*, 2012).

Broadly, interactions between genetic and environmental factors are now considered to shape the development of singing ability (Yeom *et al.*, 2022). In the general population singing ability has been found to follow a maturational trajectory of development across the lifespan. As shown in Figure 1, singing ability rapidly increases in the early years of life and plateaus in early adulthood (Pfordresher, 2022), with pitch and interval accuracy showing a small decrease with age after this point, potentially due to weakened control of vocal muscles (Pfordresher, 2022; Pfordresher & Demorest, 2021; Yeom *et al.*, 2022). However, the specific influence of genetic and environmental factors at different points of this trajectory has not been explored in detail, nor has the relative importance of different developmental periods for singing. Based on a large body of prior research (Ismail *et al.*, 2017), we might expect that childhood is an especially important time when neuroplasticity is greatest, potentially providing a sensitive period for singing development. Were this the case, enriched singing experiences early in life, such as regular singing in the home,

classroom singing or formal training, would have the greatest impact on brain maturation, and in turn, on the developmental trajectory of singing (Figure 1). This might also account for the observation that formal training is neither sufficient, nor even necessary, to become a proficient singer (Pfordresher & Demorest, 2021; Watts, Murphy *et al.*, 2003).

Both sensitive and critical periods have been observed for some musical traits and for language development. Here we use the accepted definition of sensitive periods as time windows where relevant environmental experience has the most impact on the development of a skill. In contrast, critical periods are windows where experience is *necessary* for development of a skill. Songbirds have critical periods early in life where species-specific songs must be learnt, which serves analogous social and communicative functions to language in humans (Bolhuis *et al.*, 2010; Doupe & Kuhl, 1998). Notably, the neurocognitive networks subserving singing and language in humans have been shown to be proximally located, with their overlap partly influenced by the perceptual or productive nature of the task and the individual's level of speech proficiency or singing expertise (Brown *et al.*, 2006; Ozdemir *et al.*, 2006; Pitkäniemi *et al.*, 2023; Whitehead & Armony, 2018; Wilson *et al.*, 2011).

There is consensus that language acquisition in humans has a critical period (Friedmann & Rusou, 2015; Mayberry & Kluender, 2018; Werker & Hensch, 2015), as does the acquisition of pitch-verbal label associations necessary for the expression of absolute pitch (Bairnsfather *et al.*, 2022; Levitin & Zatorre, 2003; Wilson *et al.*, 2012). Otherwise, critical periods in music have mainly been observed for basic sensory processes, like pitch perception (Lynch & Eilers, 1992; Lynch *et al.*, 1990) and rhythm perception (Hannon & Trehub, 2005a, 2005b). Both demonstrate perceptual narrowing in early life, where enculturation processes reduce infants' sensitivity to unfamiliar tonal or metric systems (Penhune & De Villers-Sidani, 2014; Zhao *et al.*, 2022). For other, more complex musical traits, recent reviews point to the importance of sensitive periods in childhood when neuroplasticity is greatest (Habib & Besson, 2009; Penhune, 2020). For instance, benefits associated with early onset of music training have been reported for rhythmic synchronisation and melody discrimination (Bailey & Penhune, 2012; Ireland *et al.*, 2019), as well as closely

related cognitive functions such as executive skills and motor learning (Chen et al., 2021; Watanabe et al., 2007).

The effects of music training are also typically associated with greater changes in neural structure and function during childhood due to heightened neuroplasticity (Bailey & Penhune, 2012; Penhune, 2020). These changes are most evident in regions activated during music perception and production tasks, such as the auditory and motor networks (Zatorre et al., 2007). However, Wesseldijk et al. (2021) recently reported that age of onset did not predict rhythmic or melodic perception after controlling for lifetime practice and familial confounding. Ireland et al. (2019) also found no relationship between age of onset and discrimination of complex melodies or rhythms. As such, sensitive periods may not be evident for all forms of musical behaviour, highlighting that a sensitive period for singing warrants empirical investigation.

Several lines of evidence indicate a possible sensitive period for singing. First, while singing engages many regions of the brain, both structural and functional differences related to the amount of singing training have been observed (Zarate et al., 2010; Zarate & Zatorre, 2008), particularly in regions supporting sensorimotor integration of auditory and motor representations (Kleber et al., 2013; Zamorano et al., 2023). Sensorimotor integration is a crucial neurocognitive process for accurate singing (Hutchins & Peretz, 2012; Pfordresher et al., 2015; Tsang et al., 2011), with recent evidence suggesting that sensorimotor integration has a sensitive period for development (Penhune, 2020; Steele et al., 2013; Vaquero et al., 2016). Second, in a recent twin study we noted that the familial environment in early childhood may have a crucial role to play (Yeom et al., 2022). Specifically, we found that singing with family in childhood and being surrounded by music were important predictors of singing ability, after controlling for current singing with family. Combining these lines of evidence points to the possibility of a sensitive period for singing development early in life, where genetic and environmental factors interact and drive neuroplastic changes that maximise the development of this skill (Figure 1).

Intuitively, a sensitive period for singing would manifest in childhood alongside sensitive periods for other musical behaviors when neuroplasticity is greatest (Bailey & Penhune, 2012). However, to our knowledge, the existence of a sensitive period for singing ability in humans has not been empirically tested. In addition, studies that examine sensitive periods for music generally focus solely on music training and do not account for other environmental factors (Penhune, 2011, 2020), such as the familial environment. Thus, examining how early and current familial singing influence singing ability relative to vocal training is valuable for understanding how this skill is shaped throughout the lifespan.

Given previous findings point to an early sensitive period for singing ability, we would expect that early shared familial singing predicts greater singing accuracy than current engagement in familial singing. Familial environments, however, are not all equal. Parents who sing accurately may be more likely to create enriched singing environments for their children. Likewise, current familial environments will vary according to an individual's age, living arrangements and other factors that impact opportunity like socioeconomic status. Since all of these factors may influence how frequently people sing with their families, here we adopted a broad view of early and current familial singing across environments and contexts to provide an initial estimate of the general influence of familial singing.

In particular, in a large, previously described sample of Australian twins we used structural equation modelling (SEM)

to explore the relative contributions of early and current singing with family and vocal training to singing ability, while also accounting for sex and age. We then explored observed effects further using bivariate twin modeling. Our analyses were based on a previously validated psychometric tool, the 'Melbourne Singing Tool', which produces a phenotypic index that reliably captures everyday singing ability (Tan et al., 2021; Yeom et al., 2022). We used SEM as it provides a powerful method of exploring hypothesised multivariate relationships (e.g., see Senn et al., 2023, for a recent example on musical groove). Using SEM, the current study expands on our previous findings by testing explicit hypotheses about the relative roles of vocal training, early and current familial singing on singing ability while accounting for their influence on each other. We hypothesised that:

- H1: Early singing with family would predict singing ability in adulthood.
- H2: Vocal training would predict singing ability in adulthood.
- H3: Early familial singing would be a stronger predictor of singing ability than current familial singing.

Materials and Methods

Participants

Data from 1189 Australian twins from a previous study (Yeom et al., 2022), collected between 2012–2019, were analysed in this study. For the SEM, the twins were treated as a general cross-sectional sample and thus, to rule out twin-specific effects we also ran our main structural model on two subsamples of statistically independent singletons. Both subsamples showed the same pattern of results as the full sample (see Supplemental Results), so we have reported results from the full sample here. Ethical approval was given by the University of Melbourne Office of Research Ethics and Integrity (ID: 1750061).

Participants were recruited with the assistance of Twins Research Australia, a national database of twins, as well as social media and print advertisements. Participants were provided with information through the Melbourne Singing Tool's webpage and were informed that by completing the activity, they were providing informed consent to participate. Participants self-reported their age and biological sex in the first part of the tool. Based on this self-report, irrespective of age, we refer to males and females as men and women respectively from this point onwards. After removing participants with missing data on at least one variable, 1163 participants (855 self-reported female) were included in the final analyses. The mean age of the current sample was 43.5 years ($SD = 16.5$), with a range of 15–90 years. We used the R Shiny app *pwrSEM* (with 1,000 simulations; Wang & Rhemtulla, 2021) for a priori power analysis, and estimated that a minimum of 268 participants was needed for at least 80% power to detect a minimum effect size of $\beta = .20$ for all three paths of interest, as described in further detail below (cf. Figure 2).

Materials and Procedure

Participants completed the Melbourne Singing Tool, which is an online tool designed for widescale singing research previously described by Tan et al. (2021). In brief, the tool includes three singing tasks that capture everyday singing ability. The first asks participants to sing the familiar song 'Happy Birthday' on the syllable 'dah'. The second is a vocal pitch-matching task where participants listen to individual notes and sing them back.

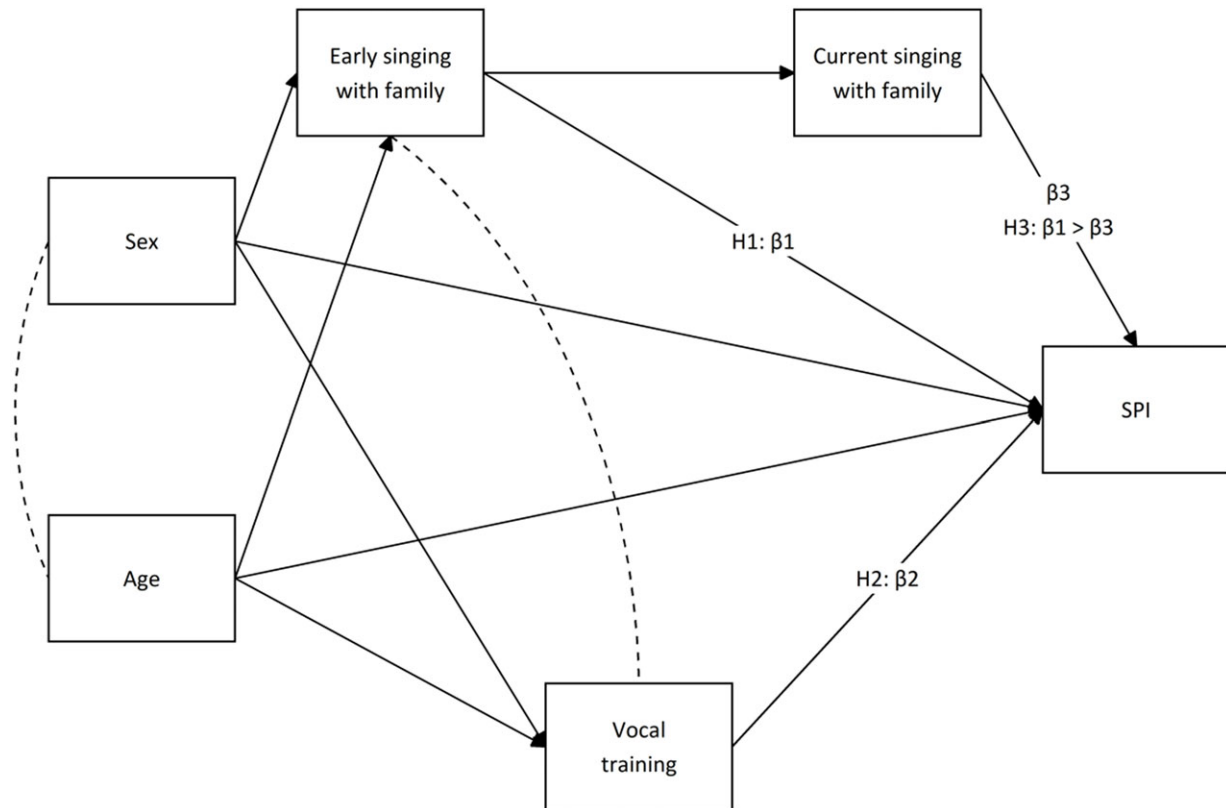


Figure 2. Conceptual structural equation model.

Note: β , path coefficients; SPI, Singing Phenotypic Index. H1, H2 and H3 are the key hypotheses tested by the model. Note that the dotted line depicts the covariance pathway between early familial singing and vocal training.

The third is an unfamiliar tune task where participants listen to a series of 7-note tonal melodies and sing them back as accurately as they can (see Tan et al., 2021 for more details). To account for range, participants were presented stimuli in different octaves depending on their reported sex for the pitch-matching and unfamiliar tune tasks, with men presented stimuli an octave lower than women. Participants were able to start on any note for the Happy Birthday task.

From these tasks, five measures of singing performance were extracted, including three pitch accuracy measures (one for each task) and two interval accuracy measures (for the melodic tasks) (Tan et al., 2021). Pitch accuracy in this context refers to the absolute difference, or deviation, between each sung note and target note, measured in cents. Interval accuracy, on the other hand, describes the absolute difference between a sung interval (the difference between two adjacent notes) and the target interval. The five measures were extracted using the open-source program 'TONY', which uses the pYIN algorithm to automatically segment notes in audio and identify each note's fundamental frequency (Mauch et al., 2015). Each participant's audio was aurally and visually inspected for any misidentified or missing notes, and manually corrected where needed. TONY's automated pitch segmentation method correlates very highly with manual segmentation (Tan et al., 2021). Pitch and interval accuracy measures were calculated for each note/interval in each trial (Tan et al., 2021; see Supplemental Methods for formulae), and then averaged over the task to provide a single accuracy value for each participant on the five measures described above. In previous work we showed that these five measures all load strongly onto one

latent factor, which we termed the 'Singing Phenotypic Index' (SPI; Yeom et al., 2022). Higher scores on the SPI represent better performance on the tasks. Tan et al. (2021) showed high test–retest reliability for the SPI over a period of 4.5 years ($r = .65-.80$). Further details on how these measures are extracted and calculated are available in Tan et al. (2021) and Yeom et al. (2022).

Participants were asked whether they had done any musical training ('Have you ever had lessons on a musical instrument or voice?'). If they responded 'yes', they were then asked what their primary instrument was (i.e., the instrument they had the most engagement and experience with), as well as how many years of training they had on that instrument and what age they were when they began training. 109 (9.4%) participants reported voice as their primary instrument, 744 (64.0%) reported a nonvocal instrument, and 310 (26.7%) reported no instrumental training. We winsorized years of training to a maximum of 20 years to account for implausible training values. To create a measure of vocal training, we recoded the years of training variable for participants who reported voice as their primary instrument. Ten of the 109 participants (9.2%) had their years of training winsorized to 20 years. Participants who reported other instruments or no training were assigned a value of zero on this vocal training measure. We note that this is a relatively conservative measure of vocal training and would not include individuals who may have had vocal training but did not report voice as their primary instrument. For the familial variables, participants were asked to rate how often they sang with family in their childhood (early singing) and now (current singing) on a 5-point scale (1 = *Not at all*, 5 = *A great deal*). These two variables were selected as measures

of familial environmental influence in twins, as they represented singing behaviors that twins reared in the same households would have likely experienced together (Yeom et al., 2022).

Statistical Analyses

All analyses were conducted in R version 4.3.1 (R Core Team, 2023). SEM was performed using the *lavaan* package in R (version 0.6-17; Rosseel, 2012). A maximum likelihood estimator was used, with robust standard errors and Satorra-Bentler corrections (MLR in *lavaan*) to account for potential multivariate non-normality in the twin data. We evaluated model fit using the robust comparative fit index (CFI), robust Tucker-Lewis Index (TLI), the robust root mean square error of approximation (RMSEA) and the standardized root mean square residual (SRMR).

Figure 2 summarises the model that was tested in this analysis. To test H1, we specified a direct path between early familial singing and the SPI. We also specified a path from early familial singing to current familial singing, and then from current singing to the SPI to test H3. To test H2, we included a path from vocal training to the SPI. We included age and sex to account for demographic effects in our model. We specified paths between the two demographic variables and both early familial singing and vocal training, as well as direct paths from them to the SPI. On average, participants who reported vocal training started at 13.8 years of age (median = 11; $SD = 10.5$). We therefore specified a covariance pathway between early singing with family to vocal training, to assess whether these variables shared a relationship.

Transparency and Openness

This study was not preregistered. The data for this study cannot be shared publicly, as ethical approval to openly share data was not sought at the time the study began. Therefore, the data are subject to restrictions by both our institutional review board and Twins Research Australia. Requests for the data should be directed to the corresponding author. The code used to run the analyses and create the figures is available on Figshare at the following link: <https://doi.org/10.26188/23694378>.

Results

Table 1 shows descriptive statistics for the variables used in the study. Table 2 shows Pearson's correlations between all the variables in the SEM. Given the significant correlation between sex and age, we specified a covariation term between these two variables in the SEM to control for this relationship.

Structural Equation Model

Model fit indices suggested adequate to good fit (robust CFI = .964, robust TLI = .821, robust RMSEA = .096, SRMR = .033). This model explained 24.3% of the variance in the SPI, and is shown with standardized coefficients in Figure 3. Sex ($\beta = -.399, p < .001, 95\% \text{ CI } [-.553, -.245]$) and age ($\beta = -.009, p < .001, 95\% \text{ CI } [-.013, -.005]$) were significant predictors of early singing with family. Men sang less with their family in childhood, and participants who were older also tended to have sung less in early childhood. Age was a significant predictor of years of training, in that older participants also tended to have less vocal training ($\beta = -.014, p = .002, 95\% \text{ CI } [-.023, -.005]$). Sex remained a nonsignificant predictor of years of vocal training ($\beta = .043, p = .821, 95\% \text{ CI } [-.333, .419]$). Early singing with family significantly covaried with vocal training ($\beta = .519, p < .001, 95\% \text{ CI } [.302, .737]$), whereby

Table 1. Descriptive statistics for the continuous variables in the structural equation model

	<i>N</i>	<i>M</i>	<i>SD</i>	Median	Range
Age	1163	43.54	16.49	43	15–90
Early singing with family ^a	1163	2.91	1.17	3	1–5
Current singing with family ^a	1163	2.46	1.15	2	1–5
Singing Phenotypic Index (SPI)	1163	−0.01	0.98	0.14	−2.59–2.12
Years of vocal training ^b	109	6.83	6.10	5	0–20

Note: ^aRated on a 5-point scale, where 1 = *Never*, 2 = *Rarely*, 3 = *Sometimes*, 4 = *Often*, 5 = *Always*.

^bYears of vocal training is winsorized to 20 years.

participants who sang more with their family in childhood also had more years of vocal training.

Likewise, more early familial singing predicted more current familial singing ($\beta = .543, p < .001, 95\% \text{ CI } [.497, .590]$); however, current singing with family now showed a much smaller effect compared to early singing and no longer predicted the SPI, supporting H3 ($\beta = .011, p = .677, 95\% \text{ CI } [-.040, .062]$). Early singing with family directly predicted the SPI, in line with H1 ($\beta = .345, p < .001, 95\% \text{ CI } [.293, .397]$). To a lesser extent, years of vocal training also significantly predicted the SPI ($\beta = .043, p < .001, 95\% \text{ CI } [.029, .058]$), supporting H2. Sex also no longer predicted the SPI ($\beta = -.072, p = .192, 95\% \text{ CI } [-.181, .036]$) but age was a significant predictor, indicating a slight decline in singing ability with age ($\beta = -.006, p < .001, 95\% \text{ CI } [-.009, -.003]$). This pattern of results did not change when variables were mean-centered and scaled prior to running the model. As noted above, to rule out the possibility that twin-specific effects were driving these results we split the sample by randomized twin order and re-ran the model on each subsample. Both subsamples showed the same patterns of results (Figures S1–S2, Supplementary Material). Finally, when considering years of training on any instrument instead of vocal training only, the three hypothesised effects remained the same (Figure S3, Supplementary Material).

Exploratory Mediation Analyses

While bivariate correlations between sex and the SPI suggested a significant correlation (Table 2), the SEM indicated that this association disappeared when other paths involving these variables were taken into account. We performed an exploratory mediation analysis to formally test whether early singing with family mediated the sex difference in singing ability ($N = 1163$, Figure 4). Percentile-based bootstrapping of standard errors was used. Early singing significantly mediated the relationship between sex and the SPI (indirect effect = $-.174$, bootstrapped $z = -5.589, p < .001, 95\% \text{ CI } [-.236, -.113]$). In line with the SEM shown in Figure 3, men sang less with family during childhood than women, and this difference in early singing was associated with poorer performance on the SPI by men. The direct effect of sex on the SPI was now negligible after accounting for this indirect effect ($\beta = -.102$, bootstrapped $z = -1.898, p = .06, 95\% \text{ CI } [-.209, .005]$).

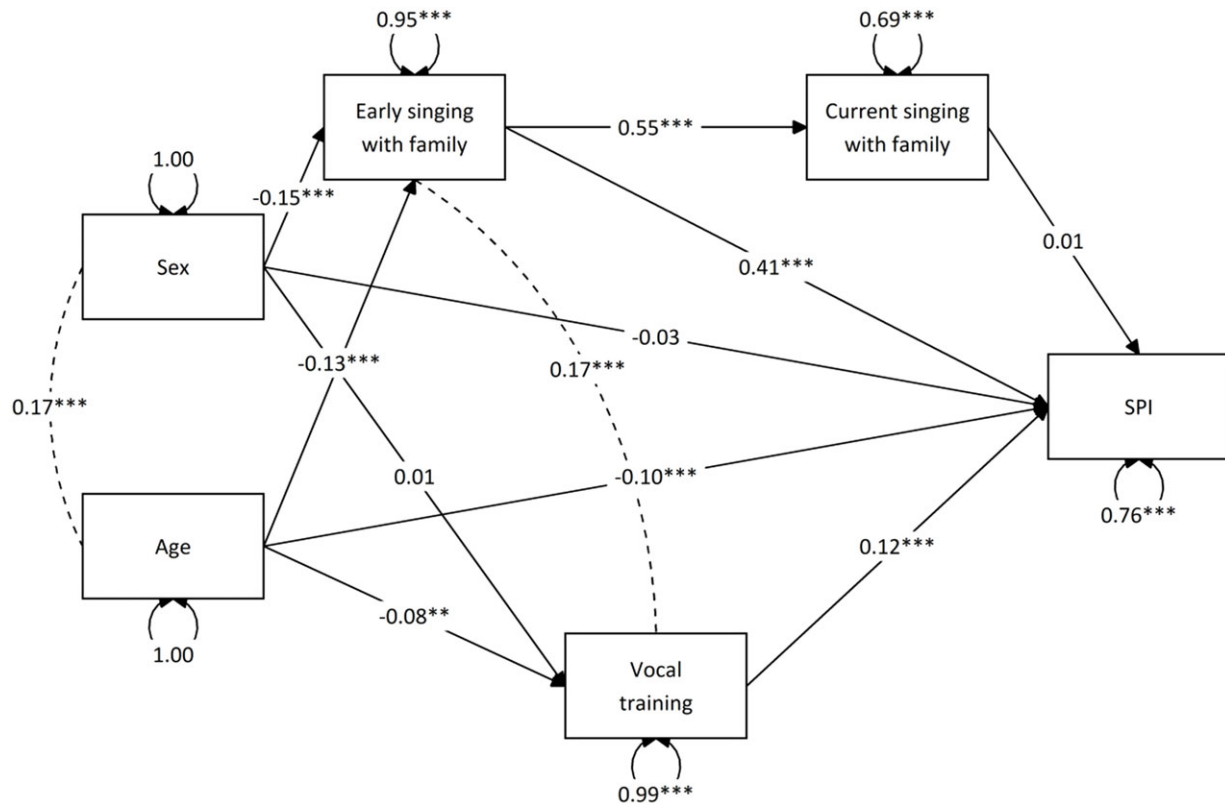
Bivariate Modeling of Early Familial Singing

To examine whether genetic and/or environmental factors were driving the relationship between early familial singing and objective

Table 2. Bivariate Pearson correlations between all variables in the model ($n = 1163$)

	Age	Early singing with family	Current singing with family	Vocal training	SPI
Sex (Male)	.17*	-.17**	-.16**	-.01	-.13**
Age		-.16**	-.22**	-.08*	-.19**
Early singing with family ^a			.55**	.17**	.46**
Current singing with family ^a				.13**	.29**
Years of vocal training ^b					.20**

Note: SPI, Singing Phenotypic Index. $p < .01$; ** $p < .001$. ^aRated on a 5-point scale, where 1 = *Not at all*, 5 = *A great deal*. ^bYears of vocal training is winsorized to 20 years.

**Figure 3.** Structural equation model labelled with standardized coefficients ($N = 1163$).

Note: SPI, Singing Phenotypic Index. Asterisks denote significant paths (** $p < .01$; *** $p < .001$).

performance, we fit an exploratory bivariate twin model with a Cholesky decomposition adjusted for age and sex. Bivariate twin models allow for the estimation of genetic and environmental influences on the covariation between two variables, which can unpack the factors that shape their association (de Vries et al., 2021). Thus, applying a bivariate twin model to the relationship between early familial singing and objective ability allowed us to examine whether the observed effect from the SEM model likely reflected genuine environmental influence, or whether genetic effects were instead driving the correlation. Twin modeling was conducted using the *OpenMx* package (version 2.21.8; Neale et al., 2016).

Cross-twin cross-trait correlations were $r = .47$ (95% CI: [.41, .52]) for MZ twins and $r = .43$ (95% CI: [.34, .50]) for DZ twins, indicating that a bivariate ACE model was suitable for the data. The phenotypic (within-pair) correlation between early familial singing and the SPI was $r = .47$. The contributions of A, C and E to this phenotypic correlation were 16%, 83.3% and 0.7% respectively,

suggesting that the relationship was largely explained by common shared environmental influences. The genetic correlation ($r_G = .34$, 95% CI: [.34, 1]) and unshared environmental correlation ($r_E = .01$, 95% CI: [-.09, .11]) between early familial singing and ability were low. In contrast, the shared environmental correlation was high ($r_C = .88$, 95% CI: [.88, 1]), suggesting that shared environmental influences between early familial singing and subsequent ability were both highly shared and explained most of the phenotypic relationship.

Nested models that constrained the A, C and E components of the phenotypic correlation to zero were then fit to test whether each covariance component was significant. Each nested model was compared to the full bivariate model using likelihood ratio tests. The contributions of A ($p = .301$) and E ($p = .821$) to the phenotypic correlation were not significant and thus could be safely dropped without worse model fit. However, the contribution of C was significant ($p < .001$). Nested bivariate AE and CE models

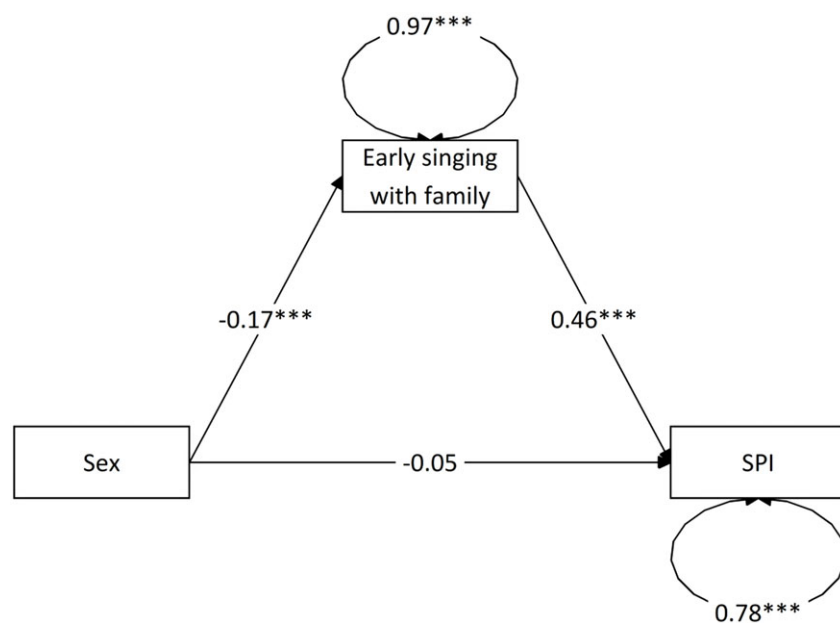


Figure 4. Mediation model between sex, early singing with family and the singing phenotypic index (SPI; $N = 1163$). Note: Standardised coefficients are shown on the paths.

also led to significantly worse model fit (both $p < .001$), indicating that while both early familial singing and objective singing ability had univariate genetic and environmental influences, only shared environmental effects influenced the relationship between them.

Discussion

This study showed that regular singing with family in childhood is an important predictor of objective singing ability. Using SEM, we tested the contributions of early and current singing with family on singing ability while also accounting for vocal training, age and sex. Our hypotheses that both early singing with family and vocal training would predict objective singing performance were supported, with early familial singing showing the stronger effect. Crucially, while we initially observed a significant relationship between current familial singing and objective performance, this was entirely explained by early familial singing in our structural model. This relationship remained constant when factoring in vocal-specific music training. Moreover, using an exploratory mediation analysis we showed that sex differences in objective singing performance were mediated by early familial singing. Finally, using exploratory bivariate twin modeling we showed that the effect of early familial singing on objective ability was driven mainly by common shared environmental influences.

These findings lend support to the possibility of a sensitive period of singing development. Penhune (2020) argued that engagement with music during sensitive periods early in life may heighten the receptiveness of neural networks to musical experience, thereby shaping the long-term development of musical skills. Consequently, engaging in singing during a sensitive period may accelerate the development of singing, in line with evidence for other music-related behaviors (Bailey & Penhune, 2012; Penhune, 2020). If a sensitive period for singing does exist, a key question will be determining when the period opens and closes. The exact time windows of sensitive periods for other musical skills have not been precisely mapped, in part because sensitive periods are subject to individual differences (Penhune, 2020). However, both prior evidence from other musical skills and the role of early familial singing observed in our data suggest that on average, this

period lies in early childhood. People who sing frequently in childhood, particularly with their family, may experience important benefits for the development of their singing voice, perhaps via enhanced learning of melody and prosody (Greenspon & Montanaro, 2023). Prosody and singing both rely on sensorimotor integration mechanisms underlying the vocal motor system (Greenspon & Montanaro, 2023). Thus, these shared vocal mechanisms may be enhanced by early exposure to regular singing. In contrast, engagement after this sensitive period may still improve singing ability, albeit at a slower rate and to a lesser degree.

The significant covariance between early familial singing and vocal training suggests that children in early pro-singing environments are also more likely to have vocal training, which may further amplify the development of singing ability. Familial environments serve as a unique source of environmental enrichment (Demorest, Kelley et al., 2017; Theorell et al., 2015), particularly in situations where a child is exposed to singing with family members from a very young age (Yan et al., 2021). Strikingly, our exploratory twin modeling showed that the relationship between early familial singing and objective ability was largely explained by shared environmental rather than genetic influences, and that these environmental influences were common to both variables. These results indicate that the effect of early familial singing on subsequent ability is truly environmental in nature, with family environments that encourage singing together in childhood also encouraging the development of singing ability.

Notably, early non-familial singing (e.g., in church choirs, school) may also be important sources of enrichment, which we were not able to analyse here. Similarly, the early familial environment may simultaneously influence the development of other musical skills relevant to singing, such as absolute pitch. Early environments that emphasise fixed pitch-label associations have been implicated in the development of absolute pitch (Wilson et al., 2012), which may subsequently alter the development of singing ability (Dohn et al., 2014). Importantly, a robust longitudinal design with individuals who start singing both early and later in life would provide a confirmatory test of the existence of a sensitive period by comparing the rate of singing development between early- and late-onset singers. Such a design would also

allow careful examination of the influence of other factors, such as non-familial environments, self-reported singing ability, other musical skills, and demographic characteristics like socioeconomic status and parental musicality.

Our data also showed sex effects. On average, men performed worse on the singing tasks than women; however, this discrepancy disappeared when controlling for childhood singing with family. We interpret this in light of broader findings of gendered participation in music (Harrison, 2007; Powell, 2014). It is well documented that men in Australia face several sociocultural barriers to participation in singing (Harrison, 2007; Powell, 2014). Within an Australian context, sport is tightly associated with masculinity while singing is not (Powell, 2014). Similar social pressures have been documented in other Western societies, such as Europe (Freer, 2015). As a corollary, because singing is seen as a stereotypically 'feminine' endeavour (Freer, 2015; Hall, 2005), women may be encouraged to engage in it, both with family members and through vocal training, with resulting benefits for their ability. Men, on the other hand, may only be encouraged to take up singing if they already show a predisposition for it (Wesseldijk et al., 2019), otherwise social expectations around masculinity may discourage them from doing so. If men do not take up singing early in life this will likely limit their engagement beyond this sensitive period. Therefore, the developmental trajectory of singing ability may diverge for men and women (at least within an Australian/Western context), in part due to sociocultural factors relating to gender and singing. Our results, however, may not generalise to societies where singing is not subject to similar gendered stereotypes, and thus where we may expect familial singing to be taken up equally by men and women from childhood.

There are limitations in our study. First, our sample had more women than men. We have previously noted that Twins Research Australia, who helped facilitate recruitment, have a higher proportion of women than men in their database (Murphy et al., 2019; Yeom et al., 2022). In keeping with the constraints on generality noted above, the higher proportion of women is also likely to be symptomatic of a lack of men who are willing to participate in music; notably, men may have been less likely to participate in a singing study. Nevertheless, with 308 men in the sample our analyses of sex effects are not underpowered. Second, our early familial singing measure is subject to retrospective bias, and the data in this study are cross-sectional. The observed sex differences may also partially influence the accuracy of our self-report items, in that men who sang less with their family may also be less inclined to recall doing so. A prospective longitudinal study beginning in childhood would allow more precise estimates of early environmental singing effects. Moreover, longitudinal designs would allow more detailed examination of how familial environments change with age, in turn impacting how often people sing in these contexts and the relative importance of other non-familial environmental effects. Equally important, asking adult participants about their familial singing at multiple timepoints would provide data on the reliability of this measure. Third, our measure of vocal training was derived from participants who reported voice as their primary instrument but does not account for participants who may have had training on multiple instruments. In particular, participants who may have received vocal training but did not report voice as their primary instrument were not captured by our measure. Separate questions exploring training on more than one instrument would address this issue.

Lastly, we cannot draw strong causal inferences from our current structural model, and there might be unmeasured variables outside of the current model, such as socioeconomic status, that may alter the interpretation of the findings.

Despite these limitations, the current study provides an initial test of the magnitude of the relationships between early and current familial singing, vocal training and objective singing performance. In particular, we show that early singing with family is an important predictor of singing ability, more powerful than current singing and vocal training. Moreover, the relationship between early singing and objective ability is largely shaped by the shared environment. Thus, our findings point to a sensitive period for the development of singing ability and may partly account for previously reported sex differences, with men who described less early familial singing showing poorer singing ability. In other words, malleable environmental factors can influence both people's ability to sing and their propensity to do so, bringing new insights into how genetic and environmental factors may interact to develop this uniquely human and sociocultural skill. Future studies using more rigorous longitudinal designs will be crucial for confirming the existence of a sensitive period and identifying its opening and closing points.

Supplementary material. To view supplementary material for this article, please visit <https://doi.org/10.1017/thg.2024.30>.

Acknowledgments. We first thank the twins for their participation in the original study. We also thank Trisnasari Fraser for her assistance in recruiting the twins and processing the data, and Dr. Valerie Yap for her assistance with preparing the dataset.

Author contributions. Y. T. T., G. E. M. and S. J. W. designed the research. Y. T. T. performed the research and processed the data. D. Y., N. H. and S. J. W. analysed the data. D. Y., N. H., G. E. M., and S. J. W. wrote the article.

Financial support. This work was supported through two Australian Research Council Discovery Project Grants (DP170102479, DP200100961) and an Australian Government Research Training Program Scholarship. This research was facilitated through access to Twins Research Australia, a national resource supported by a Centre of Research Excellence Grant (ID: 1079102), from the National Health and Medical Research Council.

Competing interests. None.

References

- Bailey, J., & Penhune, V. B. (2012). A sensitive period for musical training: Contributions of age of onset and cognitive abilities. *Annals of the New York Academy of Sciences*, 1252, 163–170. <https://doi.org/10.1111/j.1749-6632.2011.06434.x>
- Bairnsfather, J. E., Ullen, F., Osborne, M. S., Wilson, S. J., & Mosing, M. A. (2022). Investigating the relationship between childhood music practice and pitch-naming ability in professional musicians and a population-based twin sample. *Twin Research and Human Genetics*, 25, 140–148. <https://doi.org/10.1017/thg.2022.29>
- Bolhuis, J. J., Okanoya, K., & Scharff, C. (2010). Twitter evolution: Converging mechanisms in birdsong and human speech. *Nature Reviews Neuroscience*, 11, 747–759. <https://doi.org/10.1038/nrn2931>
- Brown, S., Martinez, M. J., & Parsons, L. M. (2006). Music and language side by side in the brain: a PET study of the generation of melodies and sentences. *European Journal of Neuroscience*, 23, 2791–2803. <https://doi.org/10.1111/j.1460-9568.2006.04785.x>
- Chen, J., Scheller, M., Wu, C., Hu, B., Peng, R., Liu, C., Liu, S., Zhu, L., & Chen, J. (2021). The relationship between early musical training and executive functions: Validation of effects of the sensitive period. *Psychology of Music*, 50, 86–99. <https://doi.org/10.1177/0305735620978690>

- Coon, H., & Carey, G. (1989). Genetic and environmental determinants of musical ability in twins. *Behaviour Genetics*, 19, 183–193. <https://doi.org/10.1007/bf01065903>
- Dalla Bella, S., & Berkowska, M. (2009). Singing proficiency in the majority: Normality and ‘phenotypes’ of poor singing. *Annals of the New York Academy of Sciences*, 1169, 99–107. <https://doi.org/10.1111/j.1749-6632.2009.04558.x>
- Dalla Bella, S., Giguère, J.-F., & Peretz, I. (2007). Singing proficiency in the general population. *The Journal of the Acoustical Society of America*, 121, 1182–1189.
- de Vries, L. P., Van Beijsterveldt, T. C. E. M., Maes, H., Colodro-Conde, L., & Bartels, M. (2021). Genetic influences on the covariance and genetic correlations in a bivariate twin model: An application to well-being. *Behavior Genetics*, 51, 191–203. <https://doi.org/10.1007/s10519-021-10046-y>
- Demorest, S. M., Kelley, J., & Pfordresher, P. Q. (2017). Singing ability, musical self-concept, and future music participation. *Journal of Research in Music Education*, 64, 405–420. <https://doi.org/10.1177/0022429416680096>
- Demorest, S. M., Nichols, B., & Pfordresher, P. Q. (2017). The effect of focused instruction on young children’s singing accuracy. *Psychology of Music*, 46, 488–499. <https://doi.org/10.1177/0305735617713120>
- Dohn, A., Garza-Villarreal, E. A., Ribe, L. R., Wallentin, M., & Vuust, P. (2014). Musical activity tunes up absolute pitch ability. *Music Perception*, 31, 359–371. <https://doi.org/10.1525/mp.2014.31.4.359>
- Doupe, A. J., & Kuhl, P. K. (1998). Birdsong and human speech: Common themes and mechanisms. *Annual Review of Neuroscience*, 22, 567–631. <https://doi.org/10.1146/annurev.neuro.22.1.567>
- Freer, P. K. (2015). Perspectives of European boys about their voice change and school choral singing: Developing the possible selves of adolescent male singers. *British Journal of Music Education*, 32, 87–106. <https://doi.org/10.1017/S026505171400031X>
- Friedmann, N., & Rusou, D. (2015). Critical period for first language: The crucial role of language input during the first year of life. *Current Opinion in Neurobiology*, 35, 27–34. <https://doi.org/10.1016/j.conb.2015.06.003>
- Greenspon, E. B., & Montanaro, V. (2023). Singing ability is related to vocal emotion recognition: Evidence for shared sensorimotor processing across speech and music. *Attention, Perception, & Psychophysics*, 85, 234–243. <https://doi.org/10.3758/s13414-022-02613-0>
- Gustavson, D. E., Friedman, N. P., Stallings, M. C., Reynolds, C. A., Coon, H., Corley, R. P., Hewitt, J. K., & Gordon, R. L. (2021). Musical instrument engagement in adolescence predicts verbal ability 4 years later: A twin and adoption study. *Developmental Psychology*, 57, 1943–1957. <https://doi.org/10.1037/dev0001245>
- Habib, M., & Besson, M. (2009). What do music training and musical experience teach us about brain plasticity? *Music Perception*, 26, 279–285. <https://doi.org/10.1525/mp.2009.26.3.279>
- Hall, C. (2005). Gender and boys’ singing in early childhood. *British Journal of Music Education*, 22, 5–20. <https://doi.org/10.1017/s0265051704005960>
- Hannon, E. E., & Trehub, S. E. (2005a). Metrical categories in infancy and adulthood. *Psychological Science*, 16, 48–55. <https://doi.org/10.1111/j.0956-7976.2005.00779.x>
- Hannon, E. E., & Trehub, S. E. (2005b). Tuning in to musical rhythms: Infants learn more readily than adults. *Proceedings of the National Academy of Sciences*, 102, 12639–12643. <https://doi.org/10.1073/pnas.0504254102>
- Harris, I., Niven, E. C., Griffin, A., & Scott, S. K. (2023). Is song processing distinct and special in the auditory cortex? *Nature Reviews Neuroscience*, 24, 711–722. <https://doi.org/10.1038/s41583-023-00743-4>
- Harrison, S. D. (2007). A perennial problem in gendered participation in music: What’s happening to the boys? *British Journal of Music Education*, 24, 267–280. <https://doi.org/10.1017/s0265051707007577>
- Hutchins, S., & Peretz, I. (2012). A frog in your throat or in your ear? Searching for the causes of poor singing. *Journal of Experimental Psychology: General*, 141, 76–97. <https://doi.org/10.1037/a0025064>
- Ireland, K., Iyer, T. A., & Penhune, V. B. (2019). Contributions of age of start, cognitive abilities and practice to musical task performance in childhood. *PLoS One*, 14, e0216119. <https://doi.org/10.1371/journal.pone.0216119>
- Ismail, F. Y., Fatemi, A., & Johnston, M. V. (2017). Cerebral plasticity: Windows of opportunity in the developing brain. *European Journal of Paediatric Neurology*, 21, 23–48. <https://doi.org/10.1016/j.ejpn.2016.07.007>
- Kleber, B., Zeitouni, A. G., Friberg, A., & Zatorre, R. J. (2013). Experience-dependent modulation of feedback integration during singing: Role of the right anterior insula. *The Journal of Neuroscience*, 33, 6070–6080. <https://doi.org/10.1523/jneurosci.4418-12.2013>
- Kreuntzer, N. J. (2001). Song acquisition among rural Shona-speaking Zimbabwean children from birth to 7 years. *Journal of Research in Music Education*, 49, 198–211. <https://doi.org/10.2307/3345706>
- Levitin, D. J., & Zatorre, R. J. (2003). On the nature of early music training and absolute pitch: A reply to Brown, Sachs, Cammuso, and Folstein. *Music Perception*, 21, 105–110. <https://doi.org/10.1525/mp.2003.21.1.105>
- Lortie, C. L., Rivard, J., Thibeault, M., & Tremblay, P. (2017). The moderating effect of frequent singing on voice aging. *Journal of Voice*, 31, 112.e1–112.e12. <https://doi.org/10.1016/j.jvoice.2016.02.015>
- Lynch, M. P., & Eilers, R. E. (1992). A study of perceptual development for musical tuning. *Perception & Psychophysics*, 52, 599–608. <https://doi.org/10.3758/bf03211696>
- Lynch, M. P., Eilers, R. E., Oller, D. K., & Urbano, R. C. (1990). Innateness, experience, and music perception. *Psychological Science*, 1, 272–276. <https://doi.org/10.1111/j.1467-9280.1990.tb00213.x>
- Mauch, M., Cannam, C., Bittner, R., Fazekas, G., Salamon, J., Dai, J., Bello, J., & Dixon, S. (2015). *Computer-aided melody note transcription using the TONY software: Accuracy and efficiency* [Paper presentation]. Proceedings of the First International Conference on Technologies for Music Notation and Representation, Paris.
- Mayberry, R. I., & Kluender, R. (2018). Rethinking the critical period for language: New insights into an old question from American Sign Language. *Bilingualism: Language and Cognition*, 21, 938–944. <https://doi.org/10.1017/S1366728918000585>
- McHenry, M. A., & Evans, J. (2022). Maintaining professional performance viability with age. *Journal of Voice*, 36, 668–672. <https://doi.org/10.1016/j.jvoice.2020.08.012>
- McPherson, G. E., Osborne, M. S., Barrett, M. S., Davidson, J. W., & Faulkner, R. (2015). Motivation to study music in Australian schools: The impact of music learning, gender, and socio-economic status. *Research Studies in Music Education*, 37, 141–160. <https://doi.org/10.1177/1321103X156009>
- Murphy, K., Lam, J., Cutler, T., Tyler, J., Calais-Ferreira, L., Li, S., Little, C., Ferreira, P., Craig, J. M., Scurrah, K. J., & Hopper, J. L. (2019). Twins Research Australia: A new paradigm for driving twin research. *Twin Research and Human Genetics*, 22, 438–445. <https://doi.org/10.1017/thg.2019.101>
- Nair, P. S., Kuusi, T., Ahvenainen, M., Philips, A. K., & Järvelä, I. (2019). Music-performance regulates microRNAs in professional musicians. *PeerJ*, 7, e6660. <https://doi.org/10.7717/peerj.6660>
- Nair, P. S., Raijas, P., Ahvenainen, M., Philips, A. K., Ukkola-Vuoti, L., & Järvelä, I. (2020). Music-listening regulates human microRNA expression. *Epigenetics*, 16, 554–566. <https://doi.org/10.1080/15592294.2020.1809853>
- Neale, M. C., Hunter, M. D., Pritikin, J. N., Zahery, M., Brick, T. R., Kirkpatrick, R. M., Estabrook, R., Bates, T. C., Maes, H. H., & Boker, S. M. (2016). OpenMx 2.0: Extended structural equation and statistical modeling. *Psychometrika*, 81, 535–549. <https://doi.org/10.1007/s11336-014-9435-8>
- Ozdemir, E., Norton, A., & Schlaug, G. (2006). Shared and distinct neural correlates of singing and speaking. *Neuroimage*, 33, 628–635. <https://doi.org/10.1016/j.neuroimage.2006.07.013>
- Papageorgi, I., Saunders, J., Himonides, E., & Welch, G. F. (2022). Singing and social identity in young children. *Frontiers in Psychology*, 13. <https://doi.org/10.3389/fpsyg.2022.823229>
- Park, H., Lee, S., Kim, H. J., Ju, Y. S., Shin, J. Y., Hong, D., von Grothuss, M., Lee, D. S., Park, C., Kim, J. H., Kim, B., Yoo, Y. J., Cho, S. I., Sung, J., Lee, C., Kim, J. I., & Seo, J. S. (2012). Comprehensive genomic analyses associate UGT8 variants with musical ability in a Mongolian population. *Journal of Medical Genetics*, 49, 747–752. <https://doi.org/10.1136/jmedgenet-2012-101209>

- Penhune, V., & De Villers-Sidani, E. (2014). Time for new thinking about sensitive periods. *Frontiers in Systems Neuroscience*, 8. <https://doi.org/10.3389/fnsys.2014.00055>
- Penhune, V. B. (2011). Sensitive periods in human development: Evidence from musical training. *Cortex*, 47, 1126–1137. <https://doi.org/10.1016/j.cortex.2011.05.010>
- Penhune, V. B. (2020). A gene-maturation-environment model for understanding sensitive period effects in musical training. *Current Opinion in Behavioral Sciences*, 36, 13–22. <https://doi.org/10.1016/j.cobeha.2020.05.011>
- Pentikäinen, E., Kimppa, L., Pitkäniemi, A., Lahti, O., & Särkämö, T. (2023). Longitudinal effects of choir singing on aging cognition and wellbeing: a two-year follow-up study. *Frontiers in Human Neuroscience*, 17. <https://doi.org/10.3389/fnhum.2023.1174574>
- Persellin, D. C. (2006). The effects of vocal modelling, musical aptitude, and home environment on pitch accuracy of young children. *Bulletin of the Council for Research in Music Education* (169), 39–50.
- Pfordresher, P. Q. (2022). Singing accuracy across the lifespan. *Annals of the New York Academy of Sciences*, 1515, 120–128. <https://doi.org/10.1111/nyas.14815>
- Pfordresher, P. Q., & Demorest, S. M. (2021). The prevalence and correlates of accurate singing. *Journal of Research in Music Education*, 69, 5–23. <https://doi.org/10.1177/020022429420951630>
- Pfordresher, P. Q., Halpern, A. R., & Greenspon, E. B. (2015). A mechanism for sensorimotor translation in singing. *Music Perception*, 32, 242–253. <https://doi.org/10.1525/mp.2015.32.3.242>
- Pitkäniemi, A., Särkämö, T., Siponkoski, S.-T., Brownsett, S. L. E., Copland, D. A., Sairanen, V., & Sihvonen, A. J. (2023). Hodological organization of spoken language production and singing in the human brain. *Communications Biology*, 6, Article number 779. <https://doi.org/10.1038/s42003-023-05152-y>
- Powell, S. J. (2014). Masculinity and choral singing: An Australian perspective. *International Journal of Music Education*, 33, 233–243. <https://doi.org/10.1177/0255761414533307>
- R Core Team. (2023). *R: A language environment for statistical computing*. In R Foundation for Statistical Computing (Version 4.2.0). <https://www.R-project.org/>
- Rosseeel, Y. (2012). lavaan: An R Package for structural equation modelling. *Journal of Statistical Software*, 48, 1–36. <https://doi.org/10.18637/jss.v048.i02>
- Särkämö, T. (2018). Cognitive, emotional, and neural benefits of musical leisure activities in aging and neurological rehabilitation: A critical review. *Annals of Physical and Rehabilitation Medicine*, 61, 414–418. <https://doi.org/10.1016/j.rehab.2017.03.006>
- Savage, P. E., Loui, P., Tarr, B., Schachner, A., Glowacki, L., Mithen, S., & Fitch, W. T. (2020). Music as a coevolved system for social bonding. *Behavioral and Brain Sciences*, 44, e59. <https://doi.org/10.1017/S0140525X20000333>
- Senn, O., Bechtold, T., Hoels, F., Jerjen, R., Kilchenmann, L., Rose, D., Baldassarre, A., Sigrist, C., & Alessandri, E. (2023). An SEM approach to validating the psychological model of musical groove. *Journal of Experimental Psychology: Human Perception and Performance*, 49, 290–305. <https://doi.org/10.1037/xhp0001087>
- Shilton, D., Passmore, S., & Savage, P. E. (2023). Group singing is globally dominant and associated with social context. *Royal Society Open Science*, 10. <https://doi.org/10.1098/rsos.230562>
- Singh, M., & Mehr, S. A. (2023). Universality, domain-specificity and development of psychological responses to music. *Nature Reviews Psychology*, 2, 333–346. <https://doi.org/10.1038/s44159-023-00182-z>
- Steele, C. J., Bailey, J. A., Zatorre, R. J., & Penhune, V. B. (2013). Early musical training and white-matter plasticity in the corpus callosum: Evidence for a sensitive period. *Journal of Neuroscience*, 33, 1282–1290. <https://doi.org/10.1523/JNEUROSCI.3578-12.2013>
- Tan, Y. T., Peretz, I., McPherson, G. E., & Wilson, S. J. (2021). Establishing the reliability and validity of web-based singing research. *Music Perception*, 38, 386–405. <https://doi.org/10.1525/mp.2021.38.4.386>
- Theorell, T., Lennartsson, A. K., Madison, G., Mosing, M. A., & Ullén, F. (2015). Predictors of continued playing or singing – From childhood and adolescence to adult years. *Acta Paediatrica*, 104, 274–284. <https://doi.org/10.1111/apa.12870>
- Tsang, C. D., Friendly, R. H., & Trainor, L. J. (2011). Singing development as a sensorimotor interaction problem. *Psychomusicology: Music, Mind & Brain*, 21, 31–44. <https://doi.org/10.1037/h0094002>
- Ullen, F., Hambrick, D. Z., & Mosing, M. A. (2016). Rethinking expertise: A multifactorial gene-environment interaction model of expert performance. *Psychological Bulletin*, 142, 427–446. <https://doi.org/10.1037/bul0000033>
- Vaquero, L., Hartmann, K., Ripolles, P., Rojo, N., Sierpowska, J., Francois, C., Camara, E., van Vugt, F. T., Mohammadi, B., Samii, A., Munte, T. F., Rodriguez-Fornells, A., & Altenmüller, E. (2016). Structural neuroplasticity in expert pianists depends on the age of musical training onset. *NeuroImage*, 126, 106–119. <https://doi.org/10.1016/j.neuroimage.2015.11.008>
- Wang, Y. A., & Rhemtulla, M. (2021). Power analysis for parameter estimation in structural equation modeling: A discussion and tutorial. *Advances in Methods and Practices in Psychological Science*, 4. <https://doi.org/10.1177/2515245920918253>
- Watanabe, D., Savion-Lemieux, T., & Penhune, V. B. (2007). The effect of early musical training on adult motor performance: Evidence for a sensitive period in motor learning. *Experimental Brain Research*, 176, 332–340. <https://doi.org/10.1007/s00221-006-0619-z>
- Watts, C., Barnes-Burroughs, K., Andrianopoulos, M., & Carr, M. (2003). Potential factors related to untrained singing talent: A survey of singing pedagogues. *Journal of Voice*, 17, 298–307. [https://doi.org/10.1067/s0892-1997\(03\)00068-7](https://doi.org/10.1067/s0892-1997(03)00068-7)
- Watts, C., Barnes-Burroughs, K., Estis, J., & Blanton, D. (2006). The singing power ratio as an objective measure of singing voice quality in untrained talented and nontalented singers. *Journal of Voice*, 20, 82–88. <https://doi.org/10.1016/j.jvoice.2004.12.003>
- Watts, C., Murphy, J., & Barnes-Burroughs, K. (2003). Pitch matching accuracy of trained singers, untrained subjects with talented singing voices, and untrained subjects with nontalented singing voices in conditions of varying feedback. *Journal of Voice*, 17, 185–194. [https://doi.org/10.1016/s0892-1997\(03\)00023-7](https://doi.org/10.1016/s0892-1997(03)00023-7)
- Welch, G. F., Saunders, J., Papageorgi, I., & Himonides, E. (2012). Sex, gender and singing development: Making a positive difference to boys' singing through a national programme in England. In S. D. Harrison, G. F. Welch, & A. Adler (Eds.), *Perspectives on males and singing* (pp. 27–43). Springer Netherlands. https://doi.org/10.1007/978-94-007-2660-4_3
- Werker, J. F., & Hensch, T. K. (2015). Critical periods in speech perception: New directions. *Annual Review of Psychology*, 66, 173–196. <https://doi.org/10.1146/annurev-psych-010814-015104>
- Wesseldijk, L. W., Mosing, M. A., & Ullén, F. (2021). Why is an early start of training related to musical skills in adulthood? A genetically informative study. *Psychological Science*, 32, 3–13. <https://doi.org/10.1177/0956797620959014>
- Wesseldijk, L. W., Mosing, M. A., & Ullén, F. (2019). Gene-environment interaction in expertise: The importance of childhood environment for musical achievement. *Developmental Psychology*, 55, 1473–1479. <https://doi.org/10.1037/dev0000726>
- Whitehead, J. C., & Armony, J. L. (2018). Singing in the brain: Neural representation of music and voice as revealed by fMRI. *Human Brain Mapping*, 39, 4913–4924. <https://doi.org/10.1002/hbm.24333>
- Wilson, S. J., Abbott, D. F., Lusher, D., Gentle, E. C., & Jackson, G. D. (2011). Finding your voice: a singing lesson from functional imaging. *Human Brain Mapping*, 32, 2115–2130. <https://doi.org/10.1002/hbm.21173>
- Wilson, S. J., Lusher, D., Martin, C. L., Rayner, G., & McLachlan, N. (2012). Intersecting factors lead to absolute pitch acquisition that is maintained in a 'fixed do' environment. *Music Perception*, 29, 285–296. <https://doi.org/10.1525/mp.2012.29.3.285>
- Yan, R., Jessani, G., Spelke, E. S., De Villiers, P., De Villiers, J., & Mehr, S. A. (2021). Across demographics and recent history, most parents sing to their

- infants and toddlers daily. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*, 376. <https://doi.org/10.1098/rstb.2021.0089>
- Yeom, D., Tan, Y. T., Haslam, N., Mosing, M. A., Yap, V. M. Z., Fraser, T., Hildebrand, M. S., Berkovic, S. F., McPherson, G. E., Peretz, I., & Wilson, S. J.** (2022). Genetic factors and shared environment contribute equally to objective singing ability. *iScience*, 25, 104360. <https://doi.org/10.1016/j.isci.2022.104360>
- Zamorano, A. M., Zatorre, R. J., Vuust, P., Friberg, A., Birbaumer, N., & Kleber, B.** (2023). Singing training predicts increased insula connectivity with speech and respiratory sensorimotor areas at rest. *Brain Research*, 1813, 148418. <https://doi.org/10.1016/j.brainres.2023.148418>
- Zarate, J. M., Wood, S., & Zatorre, R. J.** (2010). Neural networks involved in voluntary and involuntary vocal pitch regulation in experienced singers. *Neuropsychologia*, 48, 607–618. <https://doi.org/10.1016/j.neuropsychologia.2009.10.025>
- Zarate, J. M., & Zatorre, R. J.** (2008). Experience-dependent neural substrates involved in vocal pitch regulation during singing. *Neuroimage*, 40, 1871–1887. <https://doi.org/10.1016/j.neuroimage.2008.01.026>
- Zatorre, R. J., Chen, J. L., & Penhune, V. B.** (2007). When the brain plays music: Auditory-motor interactions in music perception and production. *Nature Reviews Neuroscience*, 8, 547–558. <https://doi.org/10.1038/nrn2152>
- Zhao, T. C., Llanos, F., Chandrasekaran, B., & Kuhl, P. K.** (2022). Language experience during the sensitive period narrows infants' sensory encoding of lexical tones—Music intervention reverses it. *Frontiers in Human Neuroscience*, 16. <https://doi.org/10.3389/fnhum.2022.941853>