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Neurological and developmental approaches to poor pitch perception and production

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Abstract

Whereas much of research in music and neuroscience is aimed at understanding the mechanisms by which the human brain facilitates music, emerging interest in the neuromusic community aims to translate basic music research into clinical and educational applications. In the present workshop, we explore the problems of poor pitch perception and production from both neurological and developmental/educational perspectives. We begin by reviewing previous and novel findings on the neural regulation of pitch perception and production. We then discuss issues in measuring singing accuracy consistently between the laboratory and educational settings. We review the Seattle Singing Accuracy Protocol—a new assessment tool that we hope can be adopted by cognitive psychologists as well as music educators—and we conclude with some suggestions that the present interdisciplinary approach might offer for future research.

Keywords

singing; neuroimaging; measurement; lifespan; development

Production, perception, and their mismatch in pitch

Successful singing requires perceptual skills (pitch matching, interval reproduction, and fine-grained pitch discrimination ability), cognitive abilities (working memory, attention, and learning processes), and motor skills (motor planning, motor selection, and motor execution). Difficulty singing in tune may reflect impairment in any or all of these abilities.

Although up to 15% of the normal population self-identifies as tone deaf,[1] most of these individuals do not exhibit the kind of perceptual difficulties that define amusia.[2,3] Instead, they might be poor pitch singers rather than true amusic individuals.[4] Congenital amusia is frequently described as a disorder of fine-grained pitch discrimination ability.[2] (Although

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Conflicts of interest
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the defining characteristics for amusia, tone deafness, and other musical disorders continue to evolve, in this review we will use the term amusia to refer to all individuals with pitch perception impairments.) Although one might expect that perception and production abilities would be highly correlated in this population, there are multiple reports of amusic individuals whose pitch production abilities do not necessarily reflect their pitch perception abilities, and vice versa.[5,6] In a study investigating the relationship between pitch perception and production abilities, amusic and control participants were played a pair of tones and were asked to first hum them back and then indicate verbally whether the second tone was higher or lower than the first. Although control subjects were able to perceive and produce the correct direction of pitch change, amusic individuals hummed pitches in the correct direction without correctly identifying the direction of pitch change above chance.[5] This behavioral disconnection between perception and production has been reported by others in the field[6] and suggests a neural disconnection between regions of the brain that are important for perception and for production of pitch.

The arcuate fasciculus as an endophenotype

In search of a neural substrate of the perception–production disconnect in pitch, diffusion tensor imaging was used to compare white-matter structures in the brains of amusic and matched control subjects.[7] Results showed a difference between amusic and control subjects in the arcuate fasciculus (AF), which comprises a superior branch (connection between the superior temporal gyrus (STG) and the inferior frontal gyrus (IFG)) and an inferior branch (connection between the middle temporal gyrus (MTG) and the IFG). Both the superior and inferior branches of the AF showed reduced volume in the amusic group. Further brain–behavior comparisons showed that tract volume of the superior AF was correlated with pitch perception threshold, whereas tract volume of the inferior AF was correlated with degree of perception–production mismatch. These findings suggest that amusia is a neural disconnection syndrome in which areas of the brain that are important for pitch production are poorly connected with areas important for conscious access of perceptual information. These results are further supported by magnetoencephalography and voxel-based morphometry studies that report abnormalities in the right frontotemporal pathways of the brains of amusic individuals.[8]

Following up on the association between AF and pitch perception/production abilities, we asked whether AF tract abnormality might qualify as an *endophenotype* for disrupted pitch discrimination ability.[9] In translational medicine, an endophenotype is a biomarker that serves as a stable predictor of a set of symptomatic behaviors by reflecting a large range of individual differences in behavior. Thus, the endophenotype bridges the low-level descriptor of a genotype (biological variable) with the high-level descriptor of a phenotype (behavior). As an example of a neurological endophenotype, dopamine deficiency in the nigrostriatal pathway is now considered to be a biomarker of Parkinson's disease. Positron emission tomography showing dopamine deficiency in this pathway is both predictive of the phenotypic traits of Parkinson's disease such as tremors, gait problems, and other motor deficiencies, and has a pattern of association with genetic mutations and alterations that are known to cause Parkinson's disease. Thus, dopamine deficiency in the nigrostriatal pathway serves as an endophenotype of Parkinson's disease by linking the genetic variability at the lowest level and abnormal motor behavior at the highest level.[10]

Applying the concept of an endophenotype to our understanding of poor pitch perception and production, we hypothesized that abnormality in the AF could serve as an endophenotype for amusia. Establishing AF abnormality as an endophenotype would be useful not only for understanding the causes of poor pitch perception/production but also for translating basic human neuroscience research into clinical applications. Support for this hypothesis would include (1) showing that the AF is related to the behavioral manifestations of amusia; and (2) demonstrating that no other tract in the brain is associated with amusia. The AF is one of many white-matter tracts in the brain; it is part of the superior longitudinal fasciculus (SLF), which is a large, bidirectional bundle of white-matter fibers that yokes the frontal and temporal lobes via the parietal lobe. Other white-matter pathways in the central nervous system include the corticospinal tract (important for motor functions), the corpus callosum (enables communication between the right and left hemispheres of the brain), and the uncinate fasciculus (connects anterior temporal lobe and medial prefrontal cortex). No white-matter tracts aside from the AF had previously been tested for their association with amusia. In ongoing efforts[9] diffusion tensor imaging was used to assess white-matter connectivity across the whole brain and its correlation with behavior. The study involved tract-based spatial statistics:[11] deriving a voxel-based analysis of white-matter fractional anisotropy (FA) from a sample of 60 subjects, who reflected a large range of individual differences in pitch perception and production abilities. Each voxel was probabilistically labeled with the names of the tracts to which it belonged. Subsequently, behavioral variables (including pitch-production threshold, pitch-perception threshold, and average of scores on the three melodic tests of the Montreal Battery of Evaluation of Amusia: scale, contour, and interval[3]), were applied as regressors to test for an association between these measures and FA value in voxels across the whole brain. Results indicated that pitch-perception threshold was significantly correlated with FA in the right SLF and no other white-matter tract in the brain (significant at the 0.05 level after correcting for multiple comparisons across the whole brain threshold-free cluster enhancement[12]). This finding supports the hypothesis that abnormal AF integrity is an endophenotype for poor pitch-perception ability.

The role of the arcuate fasciculus and pitch perception in language processing

The AF is associated not only with pitch perception and production, but also with language disturbances. Since the 19th century, neurologists have reported cases of stroke and brain trauma victims who present with lesioned arcuate fasciculi and are often unable to repeat sentences that are spoken to them; this condition is known as *conduction aphasia* and has in recent work been localized to the AF.[13,14] Other work on the AF/SLF has associated these pathways with dyslexia. In a diffusion tensor imaging study investigating phonological awareness in pre-reading children, Saygin *et al*. found that scores on the Blending Words portion of the Comprehensive Test of Phonological Processing (CTOPP) were significantly correlated with both volume and FA of the left AF.[15] This suggests that AF integrity can predict dyslexia even before a child learns to read. Findings also extend to the right hemisphere: a recent study on tonal language learning showed that volume and FA of the right SLF was associated with success in Mandarin Chinese learning.[16] Given that tonal languages use pitch information to convey semantics, this association provides further support for the hypothesis that right hemisphere frontotemporal networks subserve pitch perception and production.

Tonal languages use pitch information to convey meaning, but nontonal languages (e.g., English, French) also use pitch information to convey emotion via prosody. Amusic individuals are worse than controls at using prosodic cues to interpret emotion in speech.[17] To test for a possible correlation between pitch perception and emotional identification from speech, we applied a low-pass filter to speech samples in the Macquarie Battery of Emotional Prosody (MBEP).[17] Preliminary results suggest that accuracy in emotion identification from low-pass-filtered speech is significantly correlated with pitch perception threshold. Thus, individual differences in right frontotemporal white-matter pathways, particularly in the AF/SLF, may lead to differences in pitch-perception ability that affect not only music processing but also language processing.

Understanding both the structural and functional organizations of pathways in the brain and how they enable music perception and production will be critical for identifying not only the neurological underpinnings of musical impairments such as poor pitch singing but also the patterns of connectivity that are necessary for normal musical development. To that end, it could be fruitful to examine the strength of AF connectivity in children of different ages and whether it correlates with musical and linguistic development involving pitch perception and production. If such a connection exists, then AF connectivity changes could be used as a measure to evaluate the success of certain educational interventions. Although it is essential that we interpret findings from cognitive neuroscience/psychology in the context of research on music education and development in order to design effective interventions, both synergies and challenges may arise from the divergent disciplinary approaches toward the study of individual differences in musical ability.

Cognitive and educational perspectives on singing development

Researchers in both cognitive psychology and music education are interested in how singing skills develop. For cognitive psychology the interest stems from examining disorders of singing production to identify the different manifestations and root causes of those disorders and how other auditory and motor systems might be affected by those impairments. The recent research in poor pitch singing has added a great deal to our understanding of the different variables that can affect accurate singing as well as the different aspects of singing that might be measured.[18,19]

Music education research has long been interested in singing development because singing is one of the earliest developing productive musical skills.[20] The U.S. National Standards for Music Education list “Singing alone and with others” as the first standard. The focus of much early childhood and primary music instruction is on activities that combine singing and movement. There is also some evidence that singing difficulties can lead to poor musical self-image and decreased participation in any musical activity.[21,22] For these reasons, music educators in both research and practice have focused attention on poor pitch singing but often with the primary goal of remediating problems and identifying the most effective instructional methods.[23]

Although these two disciplines study poor pitch singing for different reasons, their interests converge on several key issues. Research in both areas has been hampered by the following gaps or conflicts in the knowledge base: (1) a consistent approach to the measurement of accurate singing; (2) A consistent definition of accurate singing; and (3) sampling from a broad range of age and experience. These issues can create challenges within each discipline, but are exacerbated by the fact that the two disciplines do not always consult the research being done by the other.[a]

Measuring singing accuracy

Research within and between music education and cognitive psychology has been hampered by the lack of standard procedures for measuring poor pitch singing. It sometimes seems, when one reads the literature, as if each study "reinvents the wheel" regarding measurement. One study measures only single-pitch matching to a piano timbre, whereas another has participants sing a song from memory, and still a third has participants match pitch patterns while being doubled on piano; and each study features a different means of recording and analyzing the resulting data. Although these changes are sometimes due to perceived deficits in previous attempts, measurement tasks and analysis choices are not always tied to a clear rationale. For any researcher interested in singing, the challenge is always what to include and what to leave out. The following variables have at least a hypothetical relationship to how accurately one sings: perceptual skills, musical experience, singing range, stimulus timbre, stimulus complexity, stimulus familiarity, memory capacity, feedback, and absolute versus relative pitch demands.

A single study might explore two or three of these variables or very carefully explore one variable, but because the tasks and measurement procedures are different from those of other studies, the results can be hard to generalize to a comprehensive view of singing development. Thus, when researchers discuss the prevalence of singing accuracy in the general population only by age or by training, the view is incomplete. Researchers in this area have begun to examine how different singing tasks reveal different aspects of singing accuracy and which offer the most information about the nature of a person's singing problem. [4,19,24,25,26,27] Recently several groups have developed batteries of singing tasks for use by any interested researchers.[19,28] The challenge in creating such a battery is to be comprehensive enough to be useful to researchers exploring a variety of phenomena while being short enough to be used in conjunction with other measures that might be specific to a particular study.

At a symposium in October 2013[b] a group of researchers from music education and cognitive psychology who were interested in poor pitch singing proposed a battery of tasks,

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[a] For some notable exceptions from recent reviews in psychology, see Refs. 18 and 36.

[b] The Seattle International Singing Research Symposium was held October 17–19 in Seattle, Washington. Participants were Simone Dalla Bella, Steven Demorest, Sean Hutchins, Psyche Loui, Peter Pfordresher, Joanne Rutkowski and Graham Welch.

standardized in both administration and scoring, that could be used by both disciplines. Table 1 gives a brief overview of the Seattle Singing Accuracy Protocol (SSAP).[29] The protocol, once implemented, would allow us to combine and compare core data from a variety of studies to begin to flesh out our picture of the variables that influence singing development. The brief perceptual task allows researchers to flag possible perceptual problems, such as amusia. The range finding tasks ensure that the stimuli will be presented in the participant's comfortable range and with the appropriate vocal stimulus. The pitch matching tasks cover variations in timbre (piano v voice) and complexity (single v pattern) that have been significant in previous work. The two song-singing tasks test singing from memory as well as the influence of text on accuracy. (For a detailed explanation of the components of the battery and why they were chosen for inclusion please see Demorest, *et al.*, in press)

Defining accurate singing

Having a standard set of tasks across multiple studies would help us to better understand the nature of various singing difficulties and their development. A related issue is how to define accurate singing consistently. Without a consistent definition of accuracy, our ability to identify different causes of or solutions for poor pitch singing is limited. The different definitions of "accurate" in the literature appear to stem from a combination of different goals and different scoring criteria. Whereas music educators seek to examine typical singing development and bring children up to a functional standard of singing, psychologists are more often interested in "outliers" that are more likely to have a singing deficit. Unfortunately, both groups use similar terminology but in very different ways, which can add to the confusion. A second issue has to do with the ways in which singing performance is analyzed and scored. Both disciplines have used a combination of acoustic measures and human judgment, but with varying criteria for what constitutes accuracy. Figure 1 compares the results of four studies within psychology that measured singing performance acoustically but with different criteria for accuracy and the resulting view of what percentage of adults are "accurate."[c]

Depending on one's definition, then, somewhere between 38% and 87% of the adult population are accurate singers. If the researcher's goal is to identify poor pitch singers whose performance is well outside the norm for the population, then some combination of the ± 100 cent window (a semitone on either side of the target) and distance from the mean error rate is a good strategy. If the goal is to describe general singing competency (i.e., everyone inside the threshold is "accurate"), then there is evidence that the ± 50 cent criterion more closely models human perception.[25,30] Music education research has used a combination of human ratings and acoustic measures to identify inaccurate singing.[31] If both disciplines agreed on an acoustic measure using an error rate based on the ± 50 cent criterion for describing general singing accuracy, it would be easier to compare results between disciplines. The ±50 cent boundary also has the advantage of better matching the category

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[c] It is important to note that there were differences in other aspects of the tasks and analyses. With respect to tasks, studies differ with respect to the use of tasks that vary in pitch complexity,[4,19] timbre,[25] or focus on a single task.[37] With respect to measures, studies differ in using signed pitch deviation scores,[4] absolute deviation scores[19,25] or pitch interval error rates.[37]

boundary for pitch perception and seems to correspond better to self-report and expert judgments of accuracy. If we agree that the ±50 cent boundary defines accurate singing, then we are confronted with the problem that the majority of the population may be defined as inaccurate singers. There may be a disconnect between “normal” singing performance (that acquired spontaneously) and “accurate” singing performance (that acquired through more formal or at least intensive engagement). Such a disconnect might explain some peoples’ tendency within our culture to assess their own signing ability rather negatively.

Sampling across the lifespan

Another challenge in tracking the development of singing skills has been the lack of large sample studies that span a wide range of ages. We know that young children typically are not accurate when they first begin to vocalize.[32] A number of studies in music education have sampled across the primary grades to track singing development.[20] The picture of development that emerges from these cross-sectional studies suggests that, in general, singing accuracy increases with age. However, in almost all of these studies the children being measured were also receiving regular music instruction. Although some studies have accounted for outside musical training, they frequently treat school training as a given. Consequently, it is difficult to know the relative influence of maturation over experience in the improvement demonstrated by these younger singers.

Studies in psychology, on the other hand, deal almost exclusively with adult samples. Figure 2 shows the range of ages represented in singing accuracy studies from music education, music cognition, and other disciplines. These studies were drawn from the singing research literature as represented by the ERIC, Psycinfo, and Medline databases and represent research from 1963 to the present. Studies involving special populations such as tinnitus or cochlear implant patients were excluded, although amusic participants were included. This is not meant to be an exhaustive analysis, but it gives one a snapshot of the most frequently studied age groups by discipline.

We can see clearly that there is a gap in who studies what age group, with psychology working almost exclusively with adults and music education almost exclusively with primary-grade children (4–12 years old). Our ability to draw inferences about age-related development in singing and the influence of age versus experience is limited by these gaps in our knowledge base. We need research that samples more broadly across age groups and includes children, adolescents, and adults in the same sample. Such research must also look carefully at each participant’s music biography so that the relative influence of different types of musical experiences on singing skill development may be taken into account.

In addition, adolescents aged 13 to 17 years old are underrepresented in the work of all disciplines. There are two primary reasons why this age group is significant in singing development research, one developmental and one experiential. Developmentally, children in this age group undergo vocal mutation or “change.” The changes to the laryngeal mechanism that occur during vocal mutation make singing more challenging for both males and females, but the shift is much more drastic for males Although there is no clear evidence that accuracy is compromised during vocal mutation,[33,34] the corresponding register limitations and timbre changes may discourage some children from singing.

From an experience standpoint, 11–12 years old is the age when mandatory music instruction ceases for the majority of children in the United States. Data from a U.S. survey suggest that only 34% of children continue any elective music participation after primary school, and only 17% of them choose singing.[35] Consequently, most children do not continue to receive singing training in any systematic way after age 12 years. Thus, it is difficult to know how accurate an adult might have been when s/he were singing regularly as a child, versus how accurate s/he is after years of not singing regularly. We need to study a broader range of ages, both cross-sectionally and longitudinally, in order to better understand how maturation and experience interact in singing development across the life span.

The power of collaboration

In a first attempt to address both the lack of direct comparisons of children and adults and the lack of communication between researchers in music education and psychology, data from three previous studies of participants aged 5–6 years, 11–12 years, and adult that used a similar methodology for gathering singing performance data were compared.[30] Data analysis incorporated the same acoustic procedure across studies to see what picture of singing development might emerge. Figure 3 shows the percentage of singing errors by age group from this comparison study (redrawn to emphasize the role of age). The expected age-related reduction in errors from age 5 to age 12 emerged, but the performance of the adult sample suggested a regression in singing skill that opened up a number of questions about the role of maturation and experience in development across the life span. We include the graph here mainly to demonstrate the potential benefits of broader sampling and communication strategies between music education and psychology.

Conclusion

Taken together, results from cognitive psychology, neuroimaging, and music educational perspectives converge to show that neurological approaches have clear implications for the conceptualization, identification, and treatment of poor pitch perception and production. Congenital amusia, characterized by poor pitch perception, involves the AF as an identifiable endophenotype that has consequences for language learning as well as emotional identification in speech. Together, the disciplines of neuroscience, psychology, and education have the potential to create a much richer description of the process of singing development in both typically developing and disordered populations and to identify strategies to help those who experience difficulties. Future work could examine the strength of AF connectivity in children of different ages and relate it to the development of musical and linguistic processes involving pitch perception and production. Accurate characterization of the developmental trajectory of singing skills is necessary for identifying poor pitch singers in order to develop neurologically informed, age-appropriate interventions that may improve both musical and extramusical behavior within and outside the classroom.

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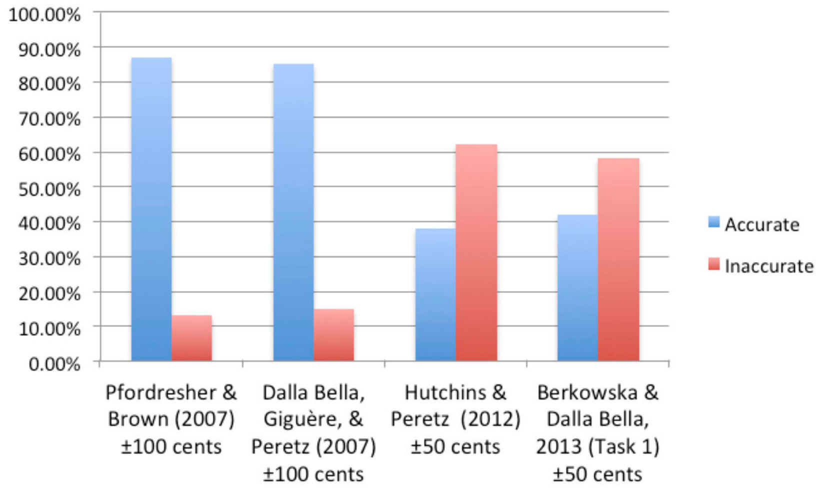

Figure 1.

Accuracy percentages based on different scoring criteria across studies.

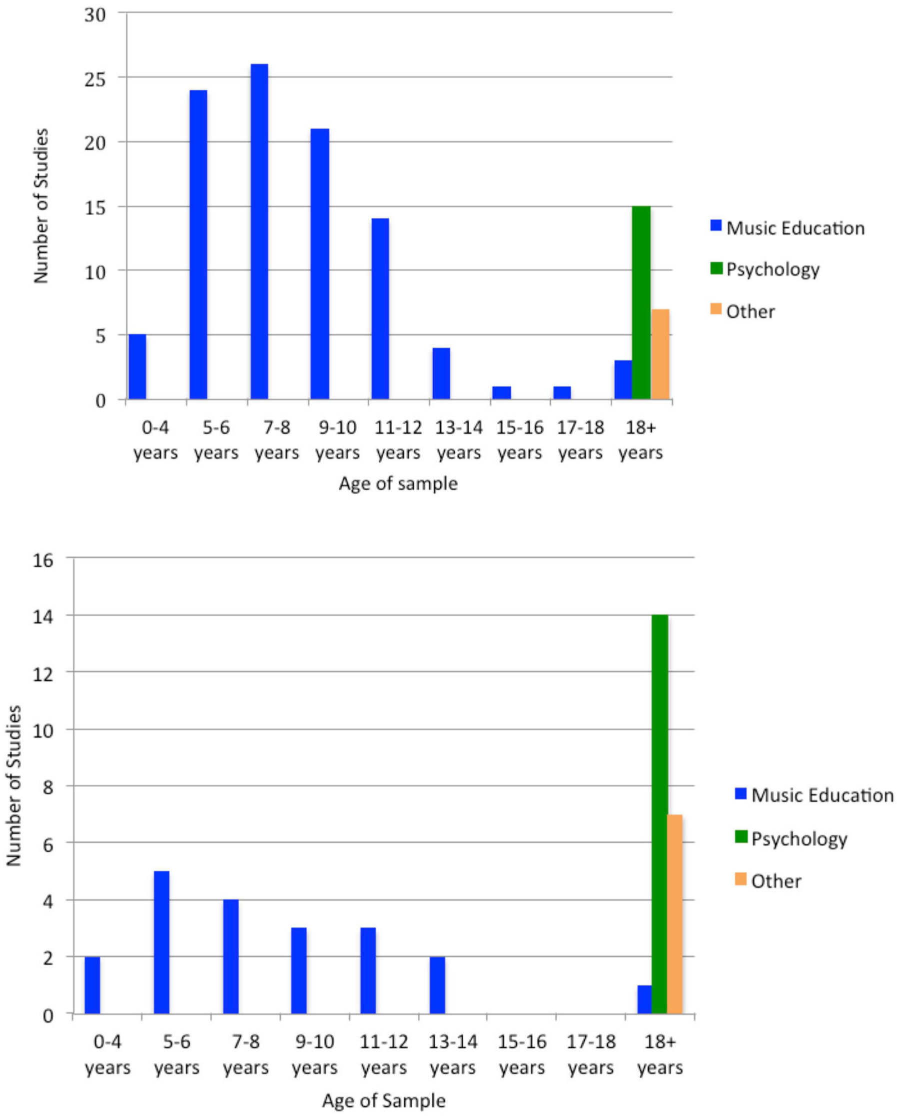

Figure 2.

Populations sampled for singing studies by discipline from 1963 to the present.

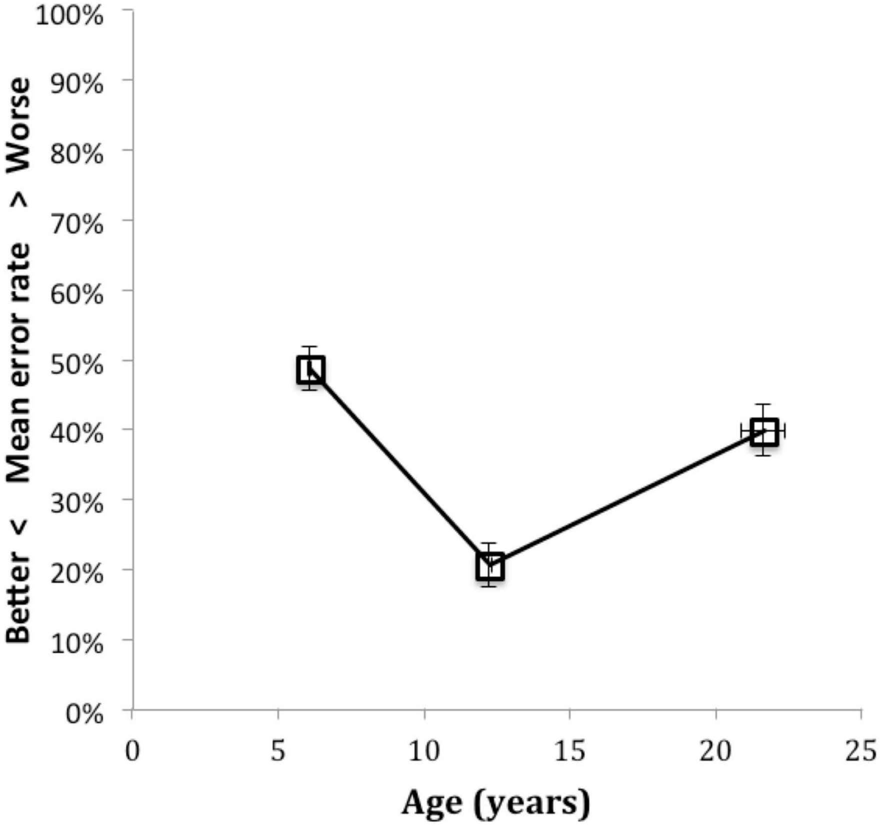

Figure 3.

Error rates compared across the age groups using a ± 50 cent criterion pitch by pitch.

Table 1

The components of the Seattle Singing Accuracy Protocol

Procedures

- **1** Adaptive pitch discrimination task
- **2** Acoustic range-finding measures
- **3** Echo-singing tasks
    - **a.** Task 1: Single pitch echo human voice
    - **b.** Task 2: Single pitch echo piano timbre
    - **c.** Task 3: Four-pitch pattern echo human voice task
- **4** Two song-singing tasks
    - **a.** Task 1: Sing a familiar song on text *a cappella*
    - **b.** Task 2: Sing the same song on a neutral syllable (e.g., “doo”)

Note: From Demorest *et al.*[29]