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Enhanced pitch perception in early blind individuals and musicians is due to reduced internal noise

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Abstract

Although it is commonly assumed that early blind individuals have enhanced pitch perception, the literature to date has been contradictory. We measured performance on two tasks known to recruit early versus late stages of auditory frequency tuning in early blind and sighted human adults of both sexes with matched years of musical training. The two groups showed equivalent performance on a tone detection in notched-noise task that assesses cochlear frequency selectivity. In contrast, early blind individuals showed enhanced performance in a pitch discrimination task thought to be mediated by cortical mechanisms. Computational modeling revealed that this enhancement was best explained by reduced internal noise rather than narrower frequency tuning, with both blindness and years of musical training predicting a reduction in internal noise. These findings identify internal noise as a key factor in experience-driven auditory plasticity as a result of both musical experience and early blindness.

Significance Statement

For centuries, early blindness has been associated with superior auditory abilities. Here we find that the enhanced pitch perception in early blind individuals is best explained by reduced internal noise at higher levels of auditory processing, rather than sharper frequency tuning. Years of musical training similarly resulted in lower internal noise, suggesting a shared mechanism through which experience improves auditory perception. These findings identify internal noise reduction as a key component of experience-dependent auditory plasticity.

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Introduction

For centuries, it has been suggested that individuals who become blind early in life develop superior auditory abilities (Diderot, 1749/2011). Indeed, many blind individuals pursue careers as piano tuners and musicians. However, the empirical evidence for enhanced pitch perception in blindness remains mixed (Sabourin et al., 2022). Some studies report superior performance in blind individuals (Gougoux et al., 2004; Voss & Zatorre, 2012; Wan et al., 2010), whereas others find no differences relative to sighted controls (Collignon et al., 2013; Watkins et al., 2013). This inconsistency raises a key question: is pitch perception enhanced in early blind individuals, and if so, by what mechanism?

Pitch perception relies on multiple stages of auditory processing. At early stages, including the cochlea and brainstem, frequency selectivity is determined largely by the sharpness of cochlear filters (Glasberg & Moore, 1990; Patterson, 1976; Shera et al., 2002), providing the sensory information from which pitch representations are subsequently constructed. This frequency filtering, although peripheral, is not entirely fixed. Corticofugal feedback can modulate cochlear responses (Terreros & Delano, 2015), and microstimulation of the auditory cortex alters the otoacoustic emissions recorded at the auditory periphery in humans (Perrot et al., 2006). Some evidence suggests that experience might also shape this selectivity: trained musicians, another population with extensive auditory experience, show sharper cochlear frequency tuning, correlated with years of musical training (Bidelman et al., 2014, 2016).

At later stages, cortical circuits integrate spectral and temporal information to construct the percept of pitch and support comparisons between pitch representations (Bendor & Wang, 2005; Johnsrude et al., 2000; Oxenham, 2012). Enhancement at this stage could arise through multiple mechanisms. One possibility is sharpened frequency tuning. Early experience shapes cortical frequency selectivity in animals, with the elimination of patterned input extending the critical period (Chang et al., 2005; Chang & Merzenich, 2003), and extensive exposure to a single frequency resulting in an expansion of the representation of that frequency (De Villers-Sidani et al., 2007; Zhang et al., 2001). In line with this, in early blind individuals, a very small narrowing of auditory frequency tuning has been observed in the primary and secondary auditory cortices using fMRI-based population receptive field mapping (Huber et al., 2019).

A second possibility is reduced internal noise. Internal noise manifests as trial-to-trial variability in neural responses (Arazi et al., 2017; Carandini, 2004; Churchland et al., 2010). Lower internal noise can improve perceptual precision through more reliable and consistent neural representations across trials, even without changes in tuning width. Indeed, perceptual learning studies show that improved discrimination often results from more efficient readout of sensory information rather than sharper tuning per se (Bejjanki et al., 2011; Dosher & Lu, 1998).

To determine where and how auditory enhancements arise following early blindness, we measured performance on two psychoacoustic tasks that are thought to probe different stages of auditory processing (see Methods). The first was tone detection in notched noise (Figure 1A), primarily associated with cochlear frequency selectivity. Our second task, pitch discrimination (Figure 1B), measures the ability to compare perceived pitches and is thought to rely more heavily on cortical processing. Participants were early blind and sighted individuals who were matched based on age and years of musical experience (Table 1), allowing us to separately examine the effects of blindness and musical training.

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Early blind and sighted individuals performed comparably on the notched-noise task, providing no evidence for enhanced cochlear frequency selectivity. In contrast, early blind individuals showed significantly better pitch discrimination. Computational modeling further revealed that this enhancement, observed in both early blind individuals and those with extensive musical training, was best explained by reduced internal noise rather than narrower frequency tuning. Critically, the effect of blindness on internal noise could not be accounted for by musical experience alone, indicating that early blindness independently contributes to reduced internal noise at higher levels of the auditory system.

Methods

This study was approved by the University of Washington's Institutional Review Board and conducted in accordance with the Code of Ethics of the Declaration of Helsinki. Informed written consent was obtained from all participants prior to conducting the experiments.

Participants

Participants included 9 early blind individuals (5 male, 4 female) and 18 sighted controls (8 male, 10 female). Blindness onset was categorized as congenital (present at birth) or acquired (onset after birth but within the first two years of life). Causes of blindness across the early blind group included Leber's congenital amaurosis (n = 2), retinopathy of prematurity (n = 2), congenital glaucoma (n = 2), retinoblastoma (n = 2), and optic atrophy (n = 1). Seven early blind participants self-reported no light perception, and two reported low light perception.

Two sighted individuals were matched to each early blind participant based on their age (within 10 years) and music experience (determined based on the self-reported number of years in musical training, within 15 years). Being in training was defined as 1-2 hours of regular practice per week. In practice, matching was considerably closer than these nominal criteria: the mean absolute age difference between matched early blind and sighted participants was 4.7 years (SD = 2.4, range = 0-9), and the mean absolute difference in years of musical training was 4.3 years (SD = 3.3, range = 0-10), with no matched pair differing by more than 10 years on either measure. Matching was not systematically skewed in either direction: the signed mean difference (early blind minus sighted control) was −0.72 years (SD = 5.36) for age and −0.33 years (SD = 5.51) for musical training.

All participants reported no history of hearing impairment. Hearing was further assessed for each ear at 300, 1200, and 4800 Hz, which encompassed the frequencies used in the experimental tasks. To test their hearing sensitivity, detection thresholds were estimated at these frequencies using an adaptive staircase procedure. Thresholds were converted to dB HL relative to ANSI S3.6-2010 reference values. Participants were excluded if hearing screening indicated thresholds outside the normal range (>20 dB HL) in both ears. While the hearing screening was completed for all participants, the data analyzed for reporting included 24 participants (8 early blind and 16 sighted controls). Thresholds were entered into a linear mixed-effects model with group, ear, and frequency as fixed effects (including all interactions) and a random intercept for participant. There was no significant main effect of group ($F(1, 22) = 1.80$, $p = .193$, partial $\eta^2 = .08$, 95% CI [.00, 1.00], $BF_{01} = 4.64$), nor were there significant interactions

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involving group (group × ear: $F(1, 110) = 1.22$, $p = .27$, partial $\eta^2 = .01$, 95% CI = [.00, 1.00], $BF_{01} = 9.93$; group × frequency: $F(2, 110) = 1.06$, $p = .35$, partial $\eta^2 = .02$, 95% CI [.00, 1.00], $BF_{01} = 24.71$; group × ear × frequency: $F(2, 110) = 0.35$, $p = .71$, partial $\eta^2 <. 001$, 95% CI = [.00, 1.00], $BF_{01} = 1162.80$), indicating comparable hearing thresholds between groups regardless of ear or frequency tested.

Apparatus

The experiment was conducted on an Apple iMac (7th generation) using the computer's integrated onboard audio hardware. Auditory stimuli were delivered through Etymotic ER-2 insert earphones at a sampling rate of 44,100 Hz. The stimuli were generated and presented using MATLAB and Psychophysics Toolbox (Brainard, 1997).

Tone detection in notched-noise task

To estimate cochlear frequency selectivity, we used a tone detection in notched-noise paradigm. Behavioral performance measured with this paradigm is widely regarded as providing an estimate of cochlear frequency filtering (Glasberg & Moore, 2000; Moore & Glasberg, 1987; Oxenham & Shera, 2003; Patterson, 1976), the mechanical basis of frequency selectivity throughout the auditory pathway. Estimates derived using this behavioral paradigm converge closely with tuning measured directly at the auditory nerve and via otoacoustic emissions in the same ears (Sumner et al., 2018), supporting the interpretation that notched-noise thresholds primarily reflect peripheral cochlear frequency filtering.

Stimulus and Task

The stimuli consisted of a target signal and a noise mask. The signal was a pure tone presented at 1200 Hz for 300 ms. The noise mask was created by band-pass filtering broadband noise (300 – 4800 Hz, 40 dB) in the frequency domain. The 'notch' in this noise was centered on the signal tone, and the notch width ranged from 0 to 1.6 times the signal frequency. The noise mask was presented for 600 ms, with the target beginning 150 ms after mask onset and thus centered temporally within the mask. Both the signal and noise mask had 100 ms linear ramps at onset and offset and were presented binaurally.

A two-interval forced-choice procedure with adaptive signal-amplitude adjustment was used to determine the threshold for detecting the signal within the notched noise. The two intervals, both containing the noise mask, were presented consecutively, separated by 300 ms of silence. One randomly chosen interval also contained the signal. The amplitude of the signal was adaptively adjusted using two interleaved one-up three-down staircases. Each staircase contained 48 trials, such that a session consisted of 96 trials total for each notch width.

On each trial, participants reported which interval contained the signal by pressing the corresponding button on a keyboard. Auditory feedback (a brief beep) was provided if they were correct. Participants first completed 80 trials of practice and then two sessions, each consisting of 480 trials.

Threshold and attentional lapse rate were measured at each notch width. Because performance depends on how sharply cochlear filters separate frequencies, the resulting "behavioral tuning

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curve" is interpreted as a proxy for early auditory filter bandwidth (Glasberg & Moore, 1990; Patterson, 1976).

Experimental Design and Statistical Analysis

Each participant's threshold to detect the signal tone, as well as the lapse rate at each notch width, was estimated by fitting a Weibull function using the psignifit toolbox (Schütt et al., 2016), using all trials from each staircase within a session. This resulted in 4 threshold measurements, which were then averaged. A linear mixed-effects model analysis was performed to predict thresholds with notch width, group, and their interactions as fixed effects. The early blind and sighted pairing was included as random intercepts, allowing us to account for individual matching between early blind and sighted groups.

To examine whether years of musical training were related to performance in the notched-noise task, we fit mixed-effects models predicting (a) average threshold and (b) selectivity (defined as the difference in threshold between the smallest and largest notch widths) from musical training, group, and their interaction, with a random intercept for matched group pairing. To directly compare our musical-training results against specific effect sizes reported in prior work, we additionally computed the simple Pearson correlation between musical training and average threshold or selectivity across our full sample, mirroring the analysis used previously (Bidelman et al., 2016).

The significance of the fixed effects in the regression models was estimated via F tests using the Satterthwaite approximation, and effect sizes are reported as partial η^2 with 95% confidence interval (CI). To quantify evidence for the findings, we additionally fit the equivalent Bayesian mixed model (JZS prior, r = .707) and report Bayes factors (BF_{01}), indicating the relative evidence for the null over the alternative model. We also conducted a simulation-based sensitivity power analysis (Green et al., 1977; Kumle et al., 2021), accounting for the matched-pairs design, to estimate the smallest group difference in threshold our sample was powered (80%) to detect.

The effect of early blindness on attentional lapse rate was assessed using a Wilcoxon rank-sum test, with effect size reported as the rank-biserial correlation and its 95% CI.

Pitch discrimination task

To assess higher-order cortical processing of pitch, we used a pitch discrimination task. Unlike tone detection in notched-noise, pitch discrimination requires the comparison of frequency representations across successive sounds and is thus thought to depend more strongly on auditory cortical processing. Pitch-related representations are suggested to be encoded in the auditory cortex (Abrams et al., 2025; Bendor & Wang, 2005, 2010), and critically, patients with auditory cortex lesions exhibit markedly impaired pitch discrimination despite preserved pure-tone detection (Johnsrude et al., 2000; Tramo et al., 2002). We therefore used pitch-discrimination performance as a behavioral index of auditory cortical frequency processing.

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Stimulus and Task

Participants listened to tone pairs binaurally at comfortable loudness levels and indicated via a button press whether the tone pair was rising (pitch in the second tone higher than the first) or falling (pitch in the second tone lower than the first) in pitch.

Following Gougoux et al. (Gougoux et al., 2004), who found some of the earliest behavioral evidence for enhanced pitch discrimination in early blind individuals, task difficulty was adjusted by varying both the frequency difference between the two tones (at a fixed duration) as well as the tone duration (at a fixed frequency difference) at each of the four frequency levels (reference frequency: range, 500 – 1200 Hz). Frequency difference levels were 1/8, 1/16, 1/32, 1/64, and 1/128 of an octave, and duration levels were 333, 167, 83, 42, and 21 ms.

There were 72 trials total within a block (4 frequency levels x 2 pitch directions x 9 difficulty levels), and participants completed three blocks. Accuracy was measured for each of the durations and frequency differences.

Experimental Design and Statistical Analysis

Frequency difference and duration conditions were analyzed separately. In both analyses, because proportion correct is a bounded measure (ranging from 0 to 1), a mixed-effects logistic regression predicted proportion correct from either the frequency difference or duration, group, and their interaction as fixed effects, with random intercepts for pair and subject. Type III Wald chi-square tests were then performed to test the significance of fixed effects. Effect sizes are reported as odds ratios (ORs) and corresponding 95% CIs were calculated for the ORs.

Signal detection theory model

Model

To predict each participant's performance in the pitch discrimination task, we used a signal detection theory-based model that estimated the width of each participant's frequency tuning and the level of internal noise. On each trial, the participant's internal responses to presented tones were derived from Gaussian tuning curves centered on the reference and the test frequency, with the standard deviation (σ_f) as a free parameter determining the tuning width. Internal noise, randomly drawn from a zero-mean Gaussian distribution, was then added to the responses. The standard deviation of this noise distribution (σ_n) was a free parameter that determined the level of internal noise. The final level of internal noise was determined by averaging noisy sample estimates over the period of stimulus duration. Thus, the longer the stimulus duration, the larger the number of samples that were averaged, resulting in a lower final level of internal noise.

The responses for the two tones were compared against each other to predict the participant's response. Correct responses occurred when the internal response for the reference frequency was larger than the response to the test frequency (we assume in this model that the order of intervals was unimportant).

The procedure was repeated 10,000 times to derive the predicted proportion correct for each frequency difference and stimulus duration combination. When fitting the data for individual participants, the two free parameters describing the standard deviations for the tuning curve and

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the Gaussian noise distributions, respectively, were estimated as values that maximized the likelihood of the participant's responses.

Experimental Design and Statistical Analysis

To understand whether the two model parameters were different between the two groups, we used a one-sample t-test on the differences in the parameter estimates between the sighted and early blind pairs. Because parameter estimates for internal noise (σ_n) and frequency-tuning width (σ_f) are bounded at zero, we examined their distributions prior to statistical comparison. Both parameters showed positive skew in their raw, untransformed form (skewness = 1.12 for σ_f, 2.64 for σ_n). Log10-transforming these estimates reduced this skew (skewness = 0.49 for σ_f, 0.93 for σ_n). We therefore used log10-transformed values for both parameters throughout for further statistical testing. Because the two t-tests on the two parameters (σ_f, σ_n) test the same conceptual hypothesis (a group difference) from the same signal detection model, we applied a Holm-Bonferroni correction across this pair of tests. Effect sizes for the one-sample t-tests are reported as Cohen's d with corresponding 95% CIs.

To assess whether group differences in pitch discrimination were better explained by frequency tuning or internal noise, we fit different versions of the model to data from both groups. The full model included separate free parameters for frequency tuning (σ_f) and internal noise (σ_n) for early blind and sighted groups (4 free parameters total). We then constructed two reduced (nested) models (3 free parameters total): one in which frequency tuning was fixed to a single parameter that was shared across groups while internal noise was free to vary between groups, and another in which internal noise was fixed while tuning was free to vary between groups.

We compared each reduced model against the full model using likelihood ratio tests (LRTs). Specifically, we calculated the change in deviance (Δ–2LL) between models, which is χ^2-distributed with degrees of freedom equal to the difference in the number of free parameters. We also computed Akaike information criterion (AIC) values to compare relative model fit. In this framework, a significant LRT ($p < .05$) indicates that the additional free parameter in the full model provides a significantly better account of the data than the reduced model, whereas AIC differences > 10 are generally taken as strong evidence favoring the lower-AIC model.

To examine the effects of blindness and musical training on the parameter estimates, we fit mixed-effects regression models predicting each parameter from group, years of musical training, and their interaction, with random intercepts for matched pairs. For each parameter, we first tested the group × musical training interaction via a likelihood ratio test comparing the interaction model to a reduced model without it, computing semi-partial R^2 and Cohen's f^2 for the interaction. Where no interaction was found (internal noise), we report the simpler additive model without the interaction and test whether group remained a significant predictor after accounting for musical training.

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Results

No significant difference between early blind and sighted individuals for the notched-noise task.

The early blind and sighted individuals showed similar performance for detecting a signal tone embedded in notched noise (Figure 2A). As expected, both early blind and sighted groups

showed increasing sensitivity (i.e., lower thresholds) as the notch width became wider (linear mixed-effects model: $F(4, 100) = 320.87$, $p < .001$, partial $\eta^2 = .93$, 95% CI [.91, 1.00]). However, the two groups had comparable sensitivity ($F(1, 17) = .36$, $p = .56$, partial $\eta^2 = .02$, 95% CI [.00, 1.00]), and there was no interaction between group and notch width ($F(4, 100) = 1.23$, $p = .30$, partial $\eta^2 = .05$, 95% CI [.00, 1.00]). Because residual variance differed across notch widths (Breusch–Pagan test: $\chi^2(1) = 6.61$, $p = .010$), we repeated the analysis using cluster-robust CR2 standard errors, clustered by matched pairs. The conclusions were unchanged: neither the main effect of group ($F(1,8) = 0.09$, $p= .77$), nor group × notch width interaction ($F(4,5) = 0.46$, $p = .77$) was significant.

A simulation-based sensitivity power analysis, which accounted for the matched pairing between early blind and sighted participants, indicated that our design had 80% power to detect a group difference of approximately 5.6 dB or larger. However, the observed group difference in threshold was close to zero, approximately 0.23 dB (95% CI [-3.31, 3.78])—much smaller relative to our design's minimum detectable effect. This suggests that the null result is unlikely to reflect inadequate power. Consistently, the equivalent Bayesian mixed model analysis suggested moderate evidence for the absence of a group × notch width interaction ($BF_{01} = 3.33$) and for the absence of a main effect of group ($BF_{01} = 3.17$). The two groups also had similar attentional lapse rates (EB: mean = 0.0036, SD = 0.0031; SC: mean = 0.0057, SD = 0.0039; Wilcoxon rank-sum test: $W = 54$, $p = .18$, rank-biserial $r = -.33$, 95% CI [-.67, .12]). Together, these results suggest that there is little effect of early blindness on frequency selectivity within the early stages of auditory processing.

Given the previous reports of sharper cochlear selectivity in musicians (Bidelman et al., 2014, 2016), we additionally examined whether musical training predicted performance in the notched-noise task. We fit a linear mixed-effects model with musical training (years), group, and their interaction as fixed effects, and a random intercept for matched group pairing, predicting either the average threshold or selectivity (defined as the difference in thresholds between the smallest and largest notch widths). Unlike prior reports, years of musical training did not predict overall average threshold ($F(1, 9.0) = 0.11$, $p = .74$, partial $\eta^2 = .01$, 95% CI [.00, 1.00]) nor did it predict the selectivity ($F(1, 9.2) = 0.37$, $p = .56$, partial $\eta^2 = .04$, 95% CI [.00, 1.00]), and this did not differ by group (threshold interaction: $F(1, 16.2) = 0.57$, $p = .46$, partial $\eta^2 = .03$, 95% CI [.00, 1.00]; selectivity interaction: $F(1, 16.3) = 0.01$, $p = .94$, partial $\eta^2 < .001$, 95% CI [.00, 1.00]). Thus, neither early blindness nor musical training enhanced behavioral tuning at the early stages of auditory frequency selectivity.

Prior work previously reported a correlation of $r = .53$ ($p = .005$, $n = 27$) between years of musical training and behavioral cochlear selectivity sharpness, computed across a combined sample of musicians and nonmusicians (Bidelman et al., 2016). When we computed the analogous pooled correlation across our full sample ($n = 27$), we found no relationship between musical training and either average threshold ($r = -.01$, 95% CI [-.39, .37], $p = .95$) or selectivity ($r = .13$, 95% CI [-.27, .48], $p = .53$). A sensitivity power analysis indicated that our pooled analysis had 84% power to detect a correlation of the magnitude previously reported by Bidelman et al., suggesting that our design was well-positioned to detect an effect of similar size.

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Early blind individuals can discriminate pitch better than sighted individuals.

In contrast, early blind individuals were better than sighted controls at the pitch discrimination task. Figure 2B shows the observed data, and Figure 2C shows the logistic regression model fits.

As expected, for the frequency difference conditions (Figures 2B & 2C, left), performance for both groups improved as the frequency difference between the two tones became larger (mixed-effects logistic regression, Type III Wald test: $\chi^2(1) = 247.03$, $p < .001$; OR = 2.66, 95% CI [2.36, 3.01]). There was a significant main effect of group ($\chi^2(1) = 4.94$, $p = .026$, OR = 1.52, 95% CI [1.05, 2.20]), with early blind individuals showing higher odds of a correct response than sighted controls at the average tested frequency difference. There was also a significant interaction between frequency difference and group ($\chi^2(1) = 9.64$, $p = .002$; OR = 1.21, 95% CI [1.07, 1.37]). Specifically, early blind individuals showed a greater improvement in performance as the frequency difference increased. This indicates that the group advantage was more pronounced at larger frequency differences.

In the duration conditions (Figures 2B & 2C, right), as expected, performance for both groups increased as the duration of the sounds became longer ($\chi^2(1) = 98.51$, $p < .001$; OR = 2.03, 95% CI [1.77, 2.34]). There was a significant main effect of group, in which early blind individuals showed higher odds of a correct response than sighted controls at the average tested duration ($\chi^2(1) = 6.06$, $p = .014$; OR = 1.92, 95% CI [1.14, 3.22]). Similar to the frequency difference conditions, we also observed a significant interaction between group and duration ($\chi^2(1) = 5.09$, $p = .024$; OR = 1.17, 95% CI [1.02, 1.35]), with the better performance of early blind individuals more pronounced for longer stimulus durations. These findings indicate that early blind individuals showed a performance advantage over sighted controls in both the frequency and duration conditions, an advantage that was more pronounced under easier task conditions (larger frequency differences, longer durations) in both cases.

Enhanced pitch discrimination in early blind individuals can be explained by reduced internal noise.

To determine through what mechanism—frequency tuning vs internal noise—pitch discrimination performance can be enhanced via early blindness at higher levels of auditory processing, we used a simple model based on signal detection theory to fit behavioral performance in the pitch discrimination task. The model assumes that the internal neural representation of each of the two tones is determined by two parameters: (i) frequency tuning (σ_f), which determines how broadly or narrowly the participant's tuning mechanism responds to nearby tones, and (ii) internal noise (σ_n), which captures trial-to-trial variability or "jitter" in the response to a given tone.

We fit this signal detection model to each participant's pitch discrimination data (both frequency difference and duration conditions combined), estimating frequency tuning width (σ_f) and internal noise (σ_n) as two free parameters. Representative model fits for a sighted and an early blind participant are shown in Figure 3A.

The model successfully predicted pitch discrimination performance as a function of frequency difference and duration across individuals. The mean correlation coefficient between observed

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and predicted performances was 0.96 for the early blind (SD = 0.04), and 0.87 for the sighted (SD = 0.21) groups, with no evidence of any systematic deviation between model predictions and data, Figure 3B.

Best-fitting parameter estimates showed no significant difference in frequency tuning between early blind and sighted groups (one-sample t-test: t(17) = 0.98, p = 0.34, Holm-adjusted p = 0.34, d = 0.23, 95% CI [-0.24, 0.70], Figure 3C, left panel). In contrast, the parameter representing internal noise was significantly lower in early blind individuals as compared to sighted controls (one-sample t-test: t(17) = -3.20, p = 0.005, Holm-adjusted p = 0.010, d = -0.75, 95% CI [-1.27, -0.22], Figure 3C, right panel).

Given the observed pattern that early blind individuals show lower internal noise but comparable frequency tuning to sighted controls, we next asked how much each parameter, considered on its own, contributes to explaining the group difference in pitch discrimination performance. To do this, we compared the full model, in which both σ_f and σ_n were each estimated freely for each group, against two reduced, nested versions of it: one in which σ_f was fixed to a single value shared by both groups (only σ_n could differ between groups), and another in which σ_n was instead fixed to a single shared value (only σ_f could differ). If a parameter meaningfully contributes to the group difference in performance, fixing it to a single shared value should substantially worsen the model's fit to the data.

We compared each reduced model against the full model using likelihood ratio tests. Fixing frequency tuning (σ_f) resulted in only a modest loss of fit relative to the full model (Δ–2LL (full - reduced) = 10.62, $\chi^2(1) = 10.62$, p = .0011; ΔAIC (full - reduced) = -8.62). By contrast, fixing internal noise led to a much larger deterioration in fit (Δ–2LL = 68.33, $\chi^2(1) = 68.33$, $p < .001$; ΔAIC = -66.33). These model comparisons indicate that reduced internal noise provides the primary explanation for the superior pitch discrimination observed in early blind participants.

Reduced internal noise is associated with both blindness and longer years of musical training.

The reduced internal noise observed in early blind individuals might be explained either by loss of vision or as a result of extensive auditory experience, of which musical training is one measurable form. While we matched our early blind and sighted groups on years of musical training, our design allowed us to directly examine the effect of musical training on our signal detection model parameters, and to test whether the effect varies by group. We fit linear mixed-effects regression models predicting each parameter (frequency tuning and internal noise) from group and years of musical training, with random intercepts for matched pairs. For each parameter, we first tested whether the effect of musical training on that parameter differed by group (group × training interaction) through a likelihood ratio test; where no interaction was found, we then tested whether group remained a significant predictor after accounting for musical training.

For the frequency tuning parameter (Figure 4A), a model including the interaction between group and musical training tended to explain the data better than a model without the interaction, though this improvement did not reach significance ($\chi^2(1) = 3.20$, p = .074; semi-partial $R^2 = 0.111$, Cohen's $f^2 = 0.130$). A simulation-based sensitivity power analysis indicated that the present design had approximately 80% power to detect an interaction coefficient of $\beta \approx -0.0072$ or larger. The observed interaction ($\beta = -0.0050$, 95% CI [-0.01, 0.0003], SE = .0026,

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t(27) = -1.84, p = .076) was closer to this sensitivity threshold, indicating that our study had limited power to detect an interaction of the observed magnitude.

Exploratorily, within early blind participants, longer musical training tended to be associated with *broader* tuning width estimates (exploratory slope estimate from the interaction model: β = 0.0041, 95% CI [-0.0002, 0.0085], SE = .0022, t(27) = 1.85, p = .075). Note that this is a direction opposite to what would typically be expected, given that greater musical experience is generally hypothesized to produce sharper, not broader, tuning. The corresponding estimated slope in sighted controls was near zero (β ≈ -0.0009). Given the nonsignificant interaction and the limited sensitivity to an effect of the observed magnitude, however, these group-specific patterns should be regarded as exploratory and inconclusive. We thus note it primarily as a pattern that stands in contrast to the effect of musical training on internal noise explained below.

For internal noise, a comparison between a linear mixed-effects model including the group × musical training interaction and one without it found no evidence that the interaction improved model fit ($\chi^2(1) = 0.10$, p = .75, semi-partial $R^2 = 0.0005$, Cohen's $f^2 = 0.001$). Consistent with this observation, the interaction coefficient itself was not significant (β = -0.0014, 95% CI [-0.0101, 0.0073], SE = .004, t(18) = -0.32, p = .75). A simulation-based sensitivity power analysis indicated that the present design had approximately 80% power to detect an interaction coefficient of β ≈ -0.0122 or larger, which is ~8.7 times larger than our observed effect, making it less likely that the lack of interaction effect is due to an underpowered sample.

Thus, we report the simpler, no-interaction model, which assumes that the effects of musical training, if any, are similar in the two groups. The results showed that longer musical training was associated with reduced internal noise (β = -0.011, 95% CI [-0.019, -0.003], SE = .004, t(10.27) = -2.77, p = .019). Critically, early blindness remained a significant predictor of internal noise even after controlling for musical training (β = 0.29, 95% CI [0.10, 0.48], SE = .096, t(17.88) = 3.05, p = .007). Thus, both early blindness and musical experience were independently associated with lower estimated internal noise, and the reduced noise observed in early blind listeners cannot be explained solely by musical training.

Discussion

Our findings demonstrate that early blindness is associated with enhanced pitch discrimination. This enhancement likely arises from higher stages of auditory processing, as no group differences were observed in a task designed to assess peripheral frequency selectivity. Computational modeling indicated that the enhancement in early blind individuals was explained primarily by reduced internal noise rather than by narrower frequency tuning. Across participants, lower internal noise was also associated with longer musical training, suggesting that both blindness and musical experience may similarly improve the reliability of auditory processing. These results challenge the common view that auditory plasticity, whether driven by blindness or by musical expertise, is associated with changes in cortical frequency tuning.

No effects of early blindness or musical training in frequency selectivity measured by the notched-noise task

We found no differences in frequency selectivity between early blind and sighted participants in the notched-noise task. Similarly, we found no significant association between years of musical

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training and performance in the notched-noise task. Previous findings concerning musical training and peripheral frequency selectivity have been mixed. Some studies reported sharper behavioral and physiological estimates of cochlear tuning in trained musicians (Bidelman et al., 2014, 2016), whereas others, including studies using notched-noise paradigms, have found comparable auditory-filter bandwidth in musicians and non-musicians (Fine & Moore, 1993; Moore et al., 2019; Oxenham et al., 2003; Tarnowska et al., 2020).

Our findings are more consistent with the latter pattern and do not support a relationship between years of musical training and peripheral filter sharpness. Methodological differences may contribute to these discrepancies. As discussed by Moore et al. (Moore et al., 2019), psychophysical tuning curves can be influenced by off-frequency listening, whereas notched-noise methods limit this influence when estimating auditory filter shape. Behavioral tuning may thus partly reflect filter-selection strategies in addition to cochlear tuning.

Importantly, the absence of group differences in the notched-noise task helps rule out several alternative explanations for enhanced pitch discrimination in early blind individuals. First, our failure to find a difference in the notched-noise task challenges the simplistic notion of across-the-board "enhanced hearing" following blindness. On a related note, it excludes the possibility (always a concern in a small sample study) that we selectively recruited early blind individuals with particularly good hearing. Additionally, it excludes the possibility that group differences were due to high-level cognitive differences – for example, that early blind individuals might have been more capable of prolonged attention to an auditory task.

Enhanced pitch discrimination in early blind individuals depends on stimulus conditions

The advantage of early blind individuals in pitch discrimination was not uniform across conditions. It emerged more strongly at larger frequency differences and longer stimulus durations, suggesting that sufficient sensory information was needed for the benefit to emerge. This condition dependence may help reconcile inconsistencies in the literature.

Our task was based on an earlier study that reported enhanced pitch discrimination in early blind individuals (Gougoux et al., 2004), although this study did not control for musical training. A later study, also based on the same methods, examining pitch discrimination in a small number of individuals with anophthalmia, failed to replicate this finding and similarly did not account for musical training (Watkins et al., 2013). In contrast, studies that matched musical training across groups found a pattern consistent with ours: enhanced performance in early blind people for larger frequency differences (0.5 – 2%; (Wan et al., 2010)) and longer stimuli (300 ms; (Voss & Zatorre, 2012)), but not for shorter durations (150 ms; (Collignon et al., 2013)). These findings suggest that enhanced pitch discrimination in early blindness is conditional on the strength or duration of the available sensory evidence.

Enhanced pitch discrimination in both early blind individuals and musicians seems to be mediated by reduced internal noise.

Unexpectedly, enhanced pitch discrimination in early blind individuals was best explained by reduced internal noise, and not by sharpened frequency tuning. Although a previous fMRI study reported narrower tuning in the primary and secondary auditory cortices of early blind individuals (Huber et al., 2019), these reductions were very small – on the order of 3%. Thus, while there may be small reductions in frequency tuning bandwidth as a result of early

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blindness, any such reductions in tuning seem not to be the primary cause of improved pitch discrimination.

Another possibility is that experience-related changes in cortical frequency representations do not necessarily take the form of narrower tuning. Our data suggested that longer musical training may be associated with *broader* tuning in early blind individuals. Although sharper tuning is conventionally expected to improve discrimination by producing steeper response slopes, exceptional pitch abilities have also been associated with broader cortical tuning and expanded cortical representation (McKetton et al., 2019). More broadly, expansion of cortical territory representing behaviorally relevant frequencies has been associated with improved frequency discrimination following training (Recanzone et al., 1993).

In contrast, reduced internal noise was independently associated with both blindness and musical training. Our analysis assumed a linear effect of training duration, and the present sample cannot distinguish this from a broader trained–untrained difference or any other nonlinear effects. Nevertheless, the association between blindness, musical training, and lower internal noise suggests that internal noise may be a meaningful dimension of auditory processing that varies with both blindness and individual experience.

What might internal noise represent?

Internal noise is commonly conceptualized as trial-to-trial variability in neural responses to repeated presentations of an identical stimulus (Arazi et al., 2017; Carandini, 2004; Churchland et al., 2010; Dinstein et al., 2015; Goris et al., 2014; Shadlen & Newsome, 1994; Tomko & Crapper, 1974). Reducing the influence of this variability would increase the reliability of internal representation of each tone and, consequently, the precision with which successive tone representations can be compared across trials. However, the internal noise parameter in our model does not directly measure spontaneous neural variability. Rather, it indexes effective trial-to-trial variability across the combined encoding and decision processes in pitch discrimination.

One possible mechanism underlying reduced internal noise is experience-dependent reweighting of sensory information. Through musical training or increased reliance on audition, listeners may learn to upweight neural populations carrying reliable, task-relevant frequency information and downweight less informative signals. Such reweighting, when not optimal, could amplify the effects of sensory noise and increase response variability (Beck et al., 2012). This interpretation is consistent with perceptual learning accounts in which discrimination improves through more efficient sensory readout rather than substantial changes in receptive field tuning (Bejjanki et al., 2011; Dosher & Lu, 1998; Law & Gold, 2008). Perceptual improvement could thus result from more accurate weighting or inference rather than a literal reduction in neural noise.

The reweighting account may be particularly relevant to early blindness. Early blind individuals have been shown to outperform sighted controls in auditory motion perception in background noise by relying on spatiotemporal filters more precisely matched to the stimulus (Park & Fine, 2023). This raises the possibility that early blindness results in perceptual “templates” that are better matched to task-relevant auditory information. More effective weighting of informative sensory signals could reduce the behavioral impact of noise across a wide range of tasks.

Other mechanisms could also contribute to lower effective internal noise, including more reliable sensory responses and reduced neural variability (Strait & Kraus, 2011; von Trapp et al., 2016),

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greater temporal precision in auditory encoding (Chandrasekaran et al., 2012; Russo et al., 2005), or more efficient integration of information over time (Amitay et al., 2012). These possibilities are not mutually exclusive and cannot be distinguished by our current model.

In conclusion, our findings show that enhanced pitch discrimination in both early blind individuals and musicians is well explained by reduced internal noise that occurs at later stages of auditory processing. In blind individuals, this reduction of internal noise could influence performance across a wide variety of auditory tasks. One limitation of our study is that it is impossible to determine whether the effect of blindness is due to the loss of vision or the increased reliance on auditory cues that occurs as a result of the loss of vision. A way to separate these might be to examine whether perceptual enhancements as a result of early blindness are more pronounced for stimuli that are ecologically critical for early blind individuals.

Data Availability

The current IRB at the University of Washington restricts publicly sharing data that contain individual visual and medical histories. Data, in anonymized format, are available from the corresponding author upon request.

Code Availability

Code for the experiments and analyses is openly available at https://github.com/VisCog/pitch-notch .

Competing Interests

The authors declare no competing interests.

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Figure 1. Methods. A. Tone detection in notched-noise task. Participants were asked to detect a signal tone (1200 Hz) embedded in two notched noise bands (300 - 4800 Hz). The notch width (frequency difference between the two noise bands) was manipulated to adjust difficulty. Participants indicated which interval contained the signal tone. B. Pitch discrimination task. Participants discriminated between two consecutively presented pure tones and reported whether the two tones were rising (the second sound higher) or falling (the second sound lower) in pitch. The frequency difference between the two tones or the duration of the tones was varied to adjust task difficulty.

Figure 2. Behavioral performance across tasks and model predictions. A. Notched-noise detection thresholds plotted as a function of notch width for sighted (green) and early blind (purple) individuals. Lighter points represent individual participants, darker circles represent group means, and error bars indicate the standard error of the mean (SEM). B. Pitch discrimination accuracy plotted as a function of frequency difference (left) and stimulus duration (right), shown on a logit-scaled y-axis, corresponding to the scale on which the models were fit. Lighter points represent individual participants, darker circles represent group means, and error bars indicate SEM. Proportions equal to 100% correct were adjusted using a small continuity correction, with half a trial added to both the numerator and denominator for each block, to ensure finite values on the logit scale. C. Predicted pitch discrimination performance from the mixed-effects logistic regression models for the frequency difference (left) and duration (right) conditions, shown on a logit-scaled y-axis. Solid lines show group-level predictions. Shaded regions represent 68% confidence intervals around model predictions, approximately equivalent to ±1 standard error.

Figure 3. Model fits and parameter estimates for pitch discrimination performance. A. Observed and model-predicted performance for representative sighted (top) and early blind (bottom) participants. B. Fitted model predictions in comparison to the observed performance. A dot represents each condition for an individual participant. Black and gray lines are the identity line and regression fits across all data points, respectively. C. Individual estimates of frequency tuning (σ_f; left) and internal noise (σ_n; right). Colored points show individual data, and thick black horizontal bars show group means. Gray lines connect participants within matched sets. The asterisk indicates a significant group difference. Black error bars indicate group means ± SEM. The y-axes are logarithmically scaled, with tick labels shown in the original, untransformed units.

Figure 4. Relationship between musical training and model parameter estimates. A. Frequency tuning width (log10, Δf/f) as a function of years of musical training, separately for sighted controls (green) and early blind individuals (purple). Lines show fitted values from a linear mixed-effects model with a group × music training interaction and a random intercept for group matching. B. Internal noise (log10, a.u.) as a function of years of musical training. Because the group × music training interaction did not improve model fit (see text), lines show fitted values from the reduced model retaining only the main effects of group and music training. Asterisks indicate significant effects. Points show individual participants.

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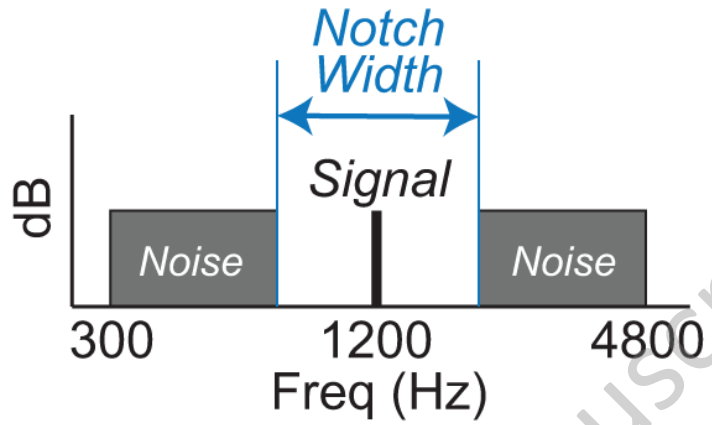
ID	Age	Blindness Onset Category	Light Perception	Years Musical Training	Matched Age (SC1/SC2)	Matched Years Musical Training (SC1/SC2)
EB1	37	Congenital	Low	0	32 / 35	0 / 0
EB2	60	Congenital	No	10	63 / 62	5 / 10
EB3	56	Congenital	No	50	57 / 50	41 / 42
EB4	29	Acquired	No	22	34 / 36	27 / 28
EB5	58	Acquired	No	50	65 / 65	60 / 58
EB6	32	Acquired	No	10	29 / 26	8 / 8
EB7	43	Congenital	No	4	52 / 48	10 / 2
EB8	67	Congenital	No	59	73 / 61	66 / 55
EB9	49	Congenital	Low	41	48 / 43	40 / 38

Table 1. Early blind (EB) participant characteristics and matched sighted control (SC) comparison. For each early blind participant, age, blindness onset category, residual light perception, and years of musical training are shown, along with the age and years of musical training of their two matched sighted control participants (SC1, SC2).

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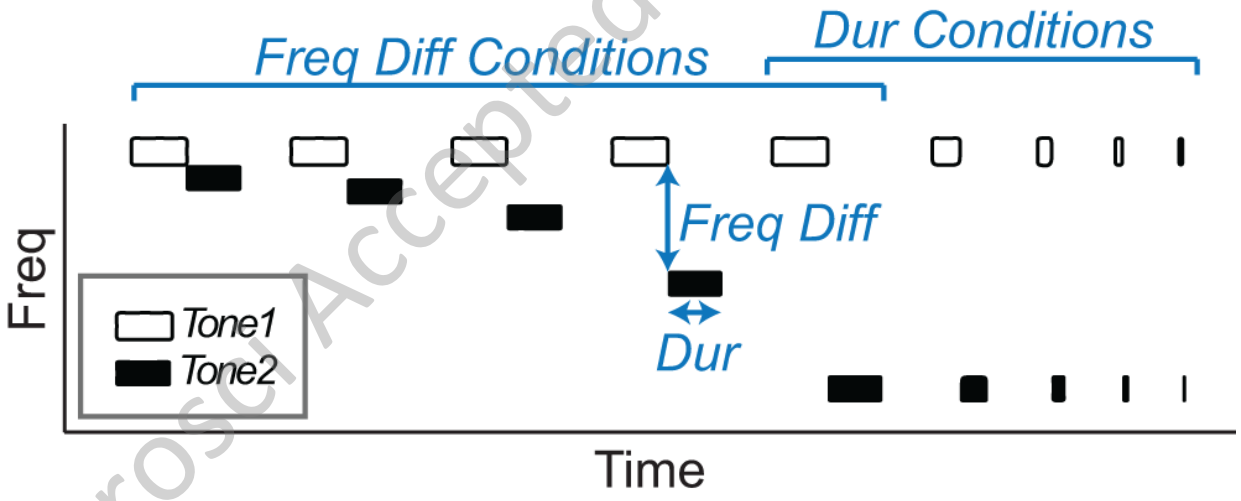
A

Tone Detection in Notched-noise Task

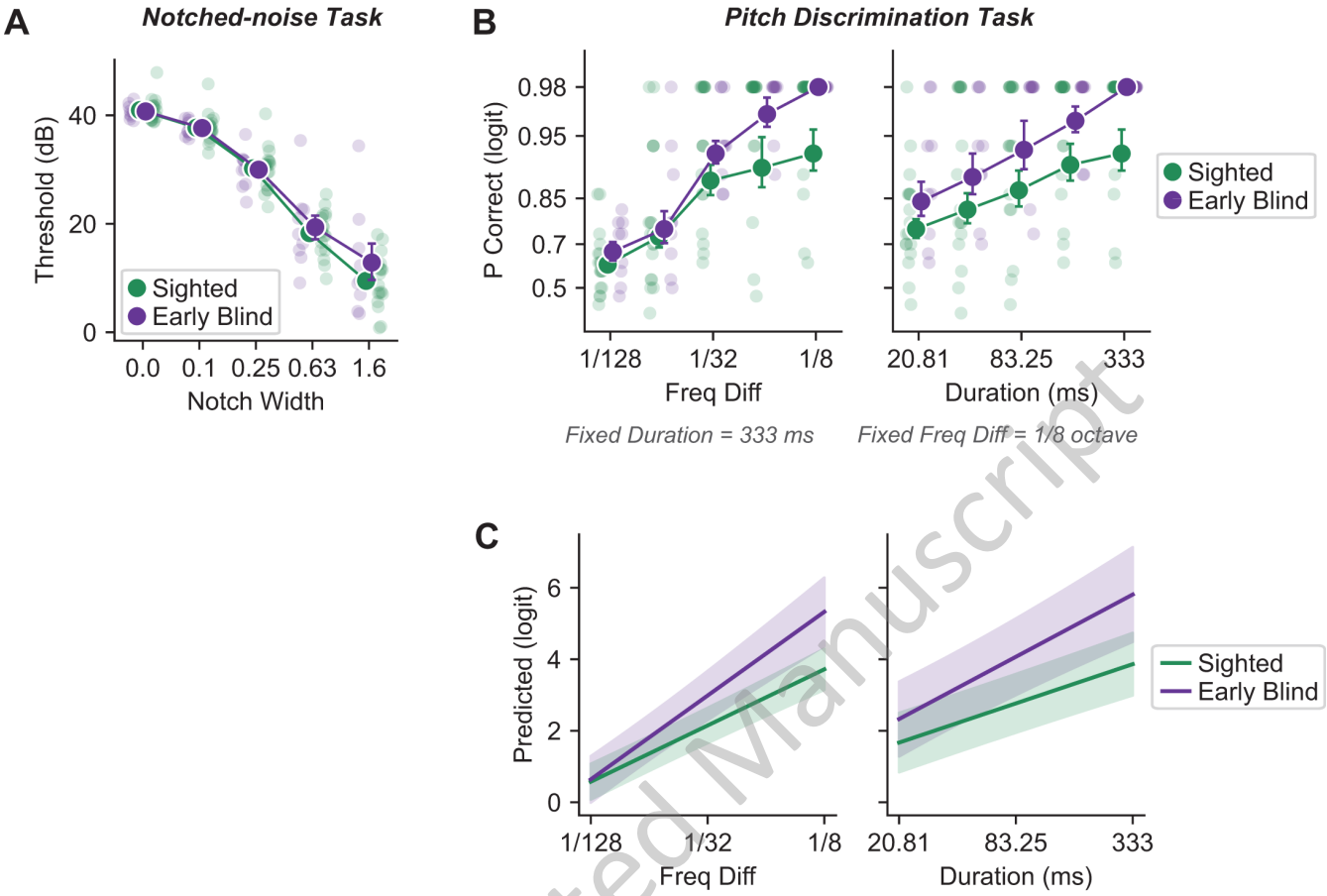


B

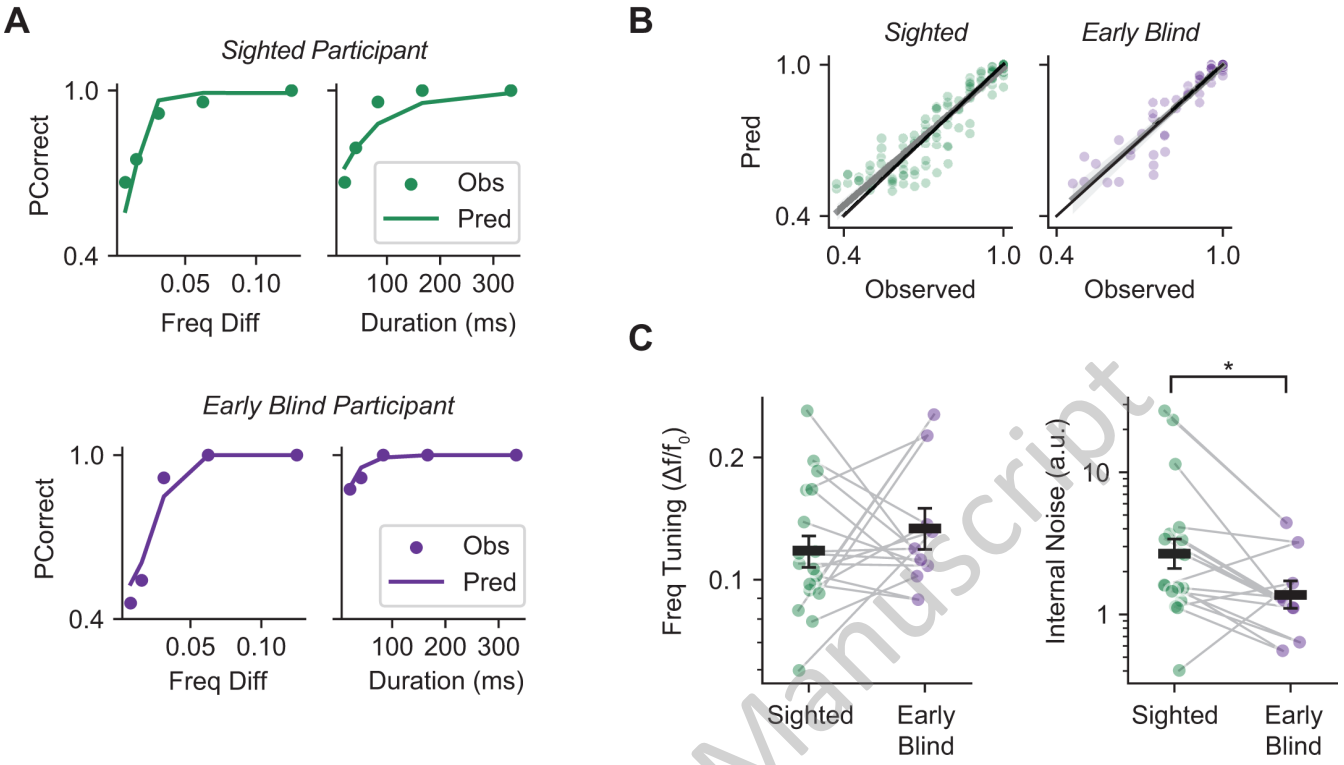
Pitch Discrimination Task



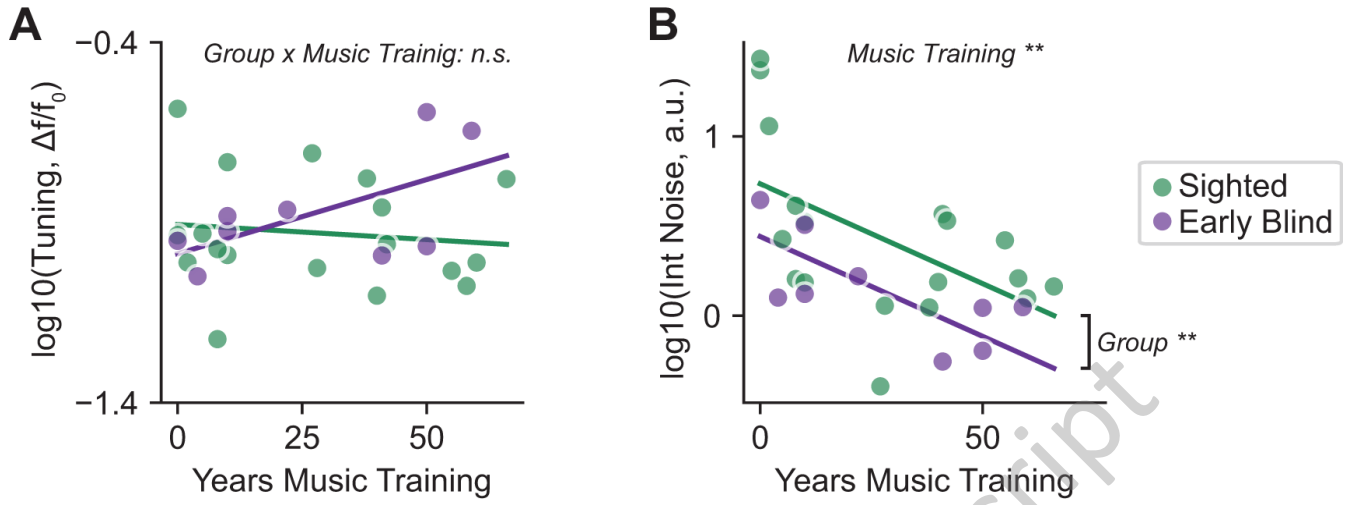
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