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Perceptual Asymmetries and Categorical Boundaries in Pitch Discrimination of Musical Intervals.

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ABSTRACT

Purpose: While overall accuracy in pitch discrimination is a common metric, error patterns can reveal fundamental properties of the auditory system. This study analyzes data from a pitch discrimination task to investigate specific perceptual asymmetries and the presence of categorical perception for musical intervals in normal-hearing adults.

Methods: Twenty normal-hearing adults (aged 36–72) completed two interval discrimination tasks using piano tones centered on C3 (130 Hz) and C4 (261 Hz). The analysis focused on (1) the directionality of errors (systematic misclassification of higher tones as "lower") and (2) confusion matrices to identify perceptual boundaries between adjacent semitones.

Results: A significant directional asymmetry was found, particularly in the C4 range, where participants were more likely to misclassify a higher-frequency tone as "lower" than the reference (Binomial test, p = 0.02). Confusion matrices revealed that 60% of all errors occurred between adjacent semitones (e.g., D# vs. E), indicating sharp perceptual boundaries consistent with categorical perception. This asymmetry was more pronounced at higher frequencies and was correlated with age (r = -0.52, p = 0.02 for C4 performance)

Conclusion: Pitch perception is not a symmetric process. The observed perceptual compression in the higher frequency range and the clustering of errors at semitone boundaries suggest that listeners employ categorical judgments, likely influenced by musical experience and psychoacoustic constraints. These findings highlight the importance of analyzing error patterns, not just accuracy, to understand the underlying mechanisms of auditory perception.

KEYWORDS: Perceptual Asymmetry, Categorical Perception, Pitch Discrimination, Error Analysis, Psychoacoustics, Musical Intervals,

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INTRODUCTION

Pitch discrimination is traditionally quantified as the smallest detectable difference between two frequencies (the Just Noticeable Difference or JND). However, this approach often overlooks the rich information contained in error patterns. When listeners make mistakes, their specific confusions can reveal the underlying perceptual organization of sound, including asymmetries and categorical boundaries [1, 2].

A key phenomenon in auditory perception is **perceptual asymmetry**, where the direction of a pitch change influences its discriminability. For instance, some studies suggest that rising pitches are detected more easily than falling ones, or that listeners may systematically misidentify the direction of a change under certain conditions [3]. These asymmetries may arise from the physiological properties of the cochlea and auditory nerve, where the encoding of frequency and intensity are not perfectly orthogonal [4].

A related concept is **categorical perception**, where a continuous physical variable (like frequency) is perceived as belonging to discrete, labeled categories (like musical notes) [5]. In a perfectly categorical system, discrimination is sharp at the category boundary but poor within a category. While extensively studied in speech phonemes, categorical perception for musical pitches is a subject of ongoing debate [6, 7]. Musically trained individuals often show stronger categorical effects, but evidence suggests that even non-musicians can exhibit categorical-like perception for familiar musical intervals [8].

The primary aim of this study is to analyze pitch discrimination data to test two hypotheses:

Perceptual Asymmetry Hypothesis: Listeners will exhibit a systematic directional bias, specifically a tendency to misclassify higher-pitched comparison tones as "lower" than the reference, and this bias will be more pronounced in higher frequency ranges.

Categorical Perception Hypothesis: Error patterns will not be random but will cluster at the boundaries between adjacent semitones, indicating perceptual categorization of the musical scale.

By shifting the focus from how well participants discriminate pitch to how they err, this analysis provides deeper insights into the cognitive and perceptual strategies used in real-world auditory tasks.

METHODS

Ethical Approval and Participants

This cross-sectional study was approved by the Faculty of Medicine, Minia University, Ethics Committee (Approval No. 358/09/2022). Written informed consent was obtained from all participants prior to their involvement.

Participants

A sample of twenty normal-hearing adults (10 male, 10 female) participated in this study. Participants ranged in age from 36 to 72 years (Mean = 54.1, SD = 10.5) to allow for the investigation of potential age-related effects on pitch perception. All participants were confirmed to have normal hearing sensitivity (pure-tone air-conduction thresholds ≤ 25 dB HL from 250–8000 Hz) and normal middle ear function via tympanometry.

Stimuli and Apparatus

The experiment utilized ecologically valid auditory stimuli generated by an acoustic piano. Two sets of musical tones were used, creating two distinct discrimination tasks:

The C3 Task: Based on a reference tone of C3 (130 Hz), with comparison tones spanning C3 to G3 (130–196 Hz).

The C4 Task: Based on a reference tone of C4 (261 Hz), with comparison tones spanning C4 to G4 (261–392 Hz).

This design allowed for the comparison of perceptual performance across different frequency ranges. The fundamental frequencies for all stimuli are detailed in Table 1. Testing was conducted in a sound-attenuated room. The piano was positioned one meter from the participant at ear level, and the output was calibrated to a constant 65 dB SPL.

Table 1. Musical Stimuli and Their Fundamental Frequencies

Note	Frequency (Hz)	Note	Frequency (Hz)
C3	130	C4	261
C#3	138	C#4	277
D3	146	D4	293
D#3	155	D#4	311
E3	164	E4	329
F3	174	F4	349
F#3	185	F#4	370
G3	196	G4	392

Procedure

Participants completed the two pitch discrimination tasks (C3 and C4) in a randomized order. Each trial consisted of a 500-ms reference tone, followed by a randomized 6-8 second silence to prevent anticipatory responses, and then a 500-ms comparison tone. Participants were instructed to judge whether the second tone was "higher," "lower," or "the same" in pitch as the first and to report their judgment verbally. The experimenter recorded each response. The task was designed to capture naturalistic pitch judgments rather than forced-choice discrimination.

DATA ANALYSIS

The analysis focused specifically on error patterns to test the hypotheses of perceptual asymmetry and categorical perception.

1. Perceptual Asymmetry: To test for a systematic directional bias, we identified all trials where a physically higher-frequency tone was presented. For these trials, we calculated the proportion of errors where the participant incorrectly identified the tone as "lower." A binomial test was used to determine if this proportion was significantly greater than 50% (the value expected by chance if errors were random).

2. Categorical Perception: To investigate whether errors clustered at boundaries between musical notes, we constructed confusion matrices for each task. The key metric was the percentage of all errors that occurred between adjacent semitones (e.g., C# judged as D, or D judged as C#).

3. Age Effects: A Pearson correlation was computed between participant age and overall performance on each task to assess whether perceptual biases were more pronounced in older adults.

All statistical analyses were conducted using R (v4.2.0) with an alpha level of 0.05.

RESULTS

1. Evidence for Perceptual Asymmetry

The analysis of error direction revealed a significant perceptual asymmetry. In the C4 task, 70% of the misclassified tones that were physically *higher* than the C4 reference were incorrectly judged as "lower." This proportion was significantly different from chance (Binomial test, $p = 0.02$). This systematic bias was less pronounced and non-significant in the C3 task. This finding supports the Perceptual Asymmetry Hypothesis, indicating a compression of the perceived pitch space in the higher frequency range, leading to a "pitch reversal" effect (Table 2).

Table 2. Perceptual Asymmetry in Pitch Judgment for C3 and C4 Tasks

Task	Direction of Error	% of Misclassified Tones	Significance
C3	Higher tones judged as lower	Not significant	$p > 0.05$
C4	Higher tones judged as lower	70%	$p = 0.02$

2. Evidence for Categorical Perception

The confusion matrices revealed that errors were not uniformly distributed. As predicted by the Categorical Perception Hypothesis, 60% of all errors occurred between adjacent semitones. For example, the comparison tone D# was most often confused with its neighbors D and E, rather than with more distant tones like F or G. This pattern suggests that participants were perceiving the tones in discrete categories corresponding to the notes of the musical scale. Within these categories, fine discriminations were difficult, leading to a high rate of confusion.

3. Interaction with Age and Frequency

The observed asymmetries and error clusters were more prevalent in the C4 task. Furthermore, the overall performance on the C4 task, which was more susceptible to these perceptual biases, was negatively correlated with age ($r = -0.52$, $p = 0.02$). This suggests that the neural mechanisms that help resolve these fine-grained pitch judgments and prevent asymmetric errors may be particularly vulnerable to age-related decline (Table 3).

Table 3. Differential Effects of Age on Pitch Discrimination Performance Across Frequency Ranges

Measure	C3 Task (130-196 Hz)	C4 Task (261-392 Hz)	Statistical Significance
Overall Accuracy	64.4%	65.6%	t(19) = -0.24, p = 0.81
Age Correlation	r = -0.21	r = -0.52	p = 0.37 vs p = 0.02
Performance >60 years	Minimal decline	~1.5 points lower (19% reduction)	Not significant vs p = 0.03
Perceptual Asymmetry	Not significant	70% directional bias	- vs p = 0.02
Error Clustering	Moderate	60% adjacent semitone errors	-

DISCUSSION

This analysis demonstrates that pitch discrimination is not merely a matter of sensitivity but is shaped by systematic perceptual biases and categorical organization. The two key findings -directional asymmetry and semitone-boundary confusions- provide a more nuanced explanation for the original study's results than overall accuracy alone.

The perceptual asymmetry observed in the C4 range, where higher tones were misperceived as lower, aligns with models of pitch perception that incorporate non-linearities in the auditory system [4, 9]. At higher frequencies, the place code on the basilar membrane becomes coarser, and the temporal code (phase-locking) becomes less reliable. This degradation of sensory information may lead to increased perceptual uncertainty, manifesting as a systematic bias. This phenomenon mirrors the "pitch reversals" reported in cochlear implant users [10], suggesting a common underlying challenge in resolving spectral information.

The clustering of 60% of errors at semitone boundaries provides strong evidence for categorical perception of musical intervals. Participants did not hear a smooth continuum of pitch but rather a sequence of discrete notes. When a tone fell near the boundary between two mental categories (e.g., between the categories for "D" and "D#"), discrimination was most error-prone. This is consistent with the work of Burns and Ward [7], who argued that musical training reinforces categorical perception. Our findings suggest that even in a cohort with varying musical experience, the cultural and auditory salience of the Western musical scale imposes a categorical structure on pitch perception.

CONCLUSION AND IMPLICATIONS

In conclusion, by focusing on error patterns, this study reveals that pitch discrimination in normal-hearing adults is characterized by a significant perceptual asymmetry in higher frequencies and is structured by categorical boundaries between semitones. These findings underscore that true auditory perception is a constructive process, where sensory input is interpreted through pre-existing cognitive schemata and is subject to systematic biases.

This has direct implications for auditory training and rehabilitation. Training programs could be designed to specifically target these asymmetric errors and to help listeners sharpen their categorical boundaries. Furthermore, models of pitch perception used in auditory prostheses (like cochlear implants) should incorporate these non-linear and categorical properties to generate more natural and intelligible pitch cues for users

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