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Impaired perception of harmonic complexity in congenital amusia: A case study

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This study investigates whether congenital amusia (an inability to perceive music from birth) also impairs the perception of musical qualities that do not rely on fine-grained pitch discrimination. We established that G.G. (64-year-old male, age-typical hearing) met the criteria of congenital amusia and demonstrated music-specific deficits (e.g., language processing, intonation, prosody, fine-grained pitch processing, pitch discrimination, identification of discrepant tones and direction of pitch for tones in a series, pitch discrimination within scale segments, predictability of tone sequences, recognition versus knowing memory for melodies, and short-term memory for melodies). Next, we conducted tests of tonal fusion, harmonic complexity, and affect perception: recognizing timbre, assessing consonance and dissonance, and recognizing musical affect from harmony. G.G. displayed relatively unimpaired perception and production of environmental sounds, prosody, and emotion conveyed by speech compared with impaired fine-grained pitch perception, tonal sequence discrimination, and melody recognition. Importantly, G.G. could not perform tests of tonal fusion that do not rely on pitch discrimination: He could not distinguish concurrent notes, timbre, consonance/dissonance, simultaneous notes, and musical affect. Results indicate at least three distinct problems—one with pitch discrimination, one with harmonic simultaneity, and one with musical affect—and each has distinct consequences for music perception.

Keywords: Music; Congenital amusia; Tonal fusion; Harmonic complexity; Music perception.

Music presents listeners with a complex acoustical stimulus that requires the encoding of pitch, harmony, rhythm, timbre, dynamic intensity changes, and other components. Most people's auditory and neural systems integrate these components effortlessly to create multifaceted, aesthetic

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representations of music. However, an individual with congenital amusia, a music-processing deficit present from birth, is unable to perceive, produce or appreciate music.

Brain damage can produce selective deficits for music (cf. Basso, 1999; Peretz & Zatorre, 2005). However, functional deficits in musical processing without cortical damage have been documented only recently (Ayotte, Peretz, & Hyde, 2002; Foxton, Dean, Gee, Peretz, & Griffiths, 2004; Peretz et al., 2002; Peretz & Hyde, 2003; but see Hyde, Zatorre, Griffiths, Lerch, & Peretz, 2006, for white matter abnormalities). Extensive testing of these individuals has revealed a profound deficit in discriminating fine-grained melodic pitch intervals—that is, tones and semitones—which has become the defining deficit for this condition. Despite marked impairments in pitch perception, a proportion of these individuals tend to be relatively unimpaired in the perception of rhythm and other temporal components of music (Ayotte et al., 2002; Hyde & Peretz, 2003, 2004). Most also have a normal audiogram and neurological history and are unimpaired in intelligence, memory, attention, and other cognitive functions. Curiously, a number of individuals with congenital amusia often have had considerable exposure to music and have even taken music lessons.

Although music comprises a number of different components, Peretz and colleagues (e.g., Peretz et al., 2002) attribute congenital amusia to a deficit in processing fine-grained melodic pitch intervals. They suggest that people with congenital amusia are unable to map pitches onto scales, leading to widespread music-processing deficits. Developmentally, the inability to detect the small changes in pitch that occur frequently in melodies could prevent the normal internalization of musical scales (Tillmann, Bharucha, & Bigand, 2000). This theory claims that accurate fine-grained pitch discrimination is a prerequisite ability for further musical processing. However, given the profundity of the music perception deficit in congenital amusia, as well as the complexity of the musical signal that gives rise to musical perception, it is possible that other components of music may be factors in congenital amusia.

In particular, a musical sonority's harmonic complexity, which is the basis for how it is perceived vis-à-vis quality of timbre, degree of consonance, and harmonic function, may be one such factor. With respect to timbre, the spectral content of a musical tone is a crucial dimension of harmonic complexity that allows a violin to sound like a violin throughout its range. Spectral content also allows us to distinguish an oboe from a flute. When we compare two or more tones, consonance and dissonance are among the most salient features of sounds in appreciating music (Bregman, 1990; Terhardt, 1984; Tramo, Cariani, Delgutte, & Braida, 2001, 2003). With respect to consonance and harmony, the overtone series, especially the first 16 overtones, constitutes a crucial dimension of harmonic complexity. Every time we hear a musical tone, such as a vibrating piano string, what we hear as a synthesis is a composite of many frequencies together. A string vibrates in even-number multiple parts of its fundamental frequency. Each of these vibrating parts produces an overtone or harmonic. An overtone of a sound wave is a component frequency of the signal that is an integer multiple of the fundamental frequency. Those overtones that occur earliest in the series vibrate in the simplest proportions to the fundamental frequency (2:1, 3:1, 4:1, 5:1, 6:1); they are the strongest and more consonant overtones. Those overtones that vibrate in more complex proportions to the fundamental are weaker and more dissonant (DeWitt & Crowder, 1987). We encounter the harmonic complexity of sound in almost all of our auditory experiences. In music, we rarely hear entirely pure tones or pure tones played individually.

When tones are played together, tonal fusion may occur. Tonal fusion is defined as the tendency of tones to "fuse", or perceptually combine so that the perception of sound becomes a single tone or something different from the mere concurrence of its two tonal components (Boring, 1942). Specifically, the higher tone tends to fuse into the overtone series of the lower (Huron, 2001). In general, the octave and perfect fifth, the most consonant overtones in the series, are especially prone to tonal fusion (i.e., heard as one tone; DeWitt & Crowder, 1987). What is important about the ability to perceive perfect intervals distinctly is that they are the source for our notions of consonance and dissonance. The perfect fifth as a harmonic interval (i.e., two tones sounding together) makes explicit the consonance that is otherwise implicit between the second and third overtones—for example, C3 G3 (if C4 = middle C) of the overtone series. There is an association of the consonance of musical intervals with detailed properties of the harmonic series that reveals gradations of consonance and dissonance. Thus, the additional musical components of harmonic intervals that emerge in the overtone series are essential for enriching the musical palette. This enrichment, which derives from the harmonic complexity of the tone itself, influences the perception of affect and emotion from musical sequences. A problem with tonal fusion could be a severe impediment to an accurate perception of harmonic complexity. Even if the fine-grained pitch perception deficit precludes the internalization of scales as a structural basis for melody, people with congenital amusia could still have independent deficits on account of tonal fusion, further contributing to the profoundness of their music deficit.

In this paper, we present a case study of congenital amusia that investigates whether tonal fusion and the processing of harmonic complexities, in addition to fine-grained pitch discrimination, may contribute to the subject's, G.G.'s, music-processing deficit. The first set of tests establishes congenital amusia and that the deficit is specific to music. The second set of tests assesses fine-grained pitch perception. The third set of tests evaluates perceptions of tonal fusion and harmonic complexity. The final set of tests examines musical affect through examples that are either purely melodic or harmonized: All examples are drawn from well-defined genres (wedding march, funeral procession, etc.). We argue that a combined processing deficit in fine-grained pitch processing and tonal fusion will predict the profundity of the musical perception and memory deficits observed in G.G.'s performance.

Method

Participants

G.G. G.G. is a 64-year-old man, born in Hungary, with a life-long inability to recognize, perceive, or produce music. G.G. is a retired electrical engineer, with an M.S. in Electrical Engineering, who worked for a major corporation for 36 years. He is multilingual: His native language is Hungarian but he is fluent in English and has studied German, Russian, and Hebrew. In addition to being intelligent with no language difficulties, G.G. has no social deficits; he is happily married, has several children, and is an active member of his community.

G.G.'s hearing is within normal bounds for his age. Audiometry tests indicate normal hearing through 2000 Hz, but show moderately severe bilateral sensorineural loss at higher frequencies (3000–4000 Hz), with poorer thresholds in the left ear (Table 1). He has excellent bilateral word recognition (96%). Tympanograms are normal for both ears. Acoustic reflexes are present, except the right contralateral reflex. Follow-up examinations determined that G.G. did not require hearing enhancers. G.G. has no history of stroke, neurological events, or psychiatric, alcohol, or drug problems. Thus, any deficit in music perception cannot be attributed to a

Table 1. *Hearing levels from audiogram of pure frequencies for G.G.*

	Hearing level (dB HL)	
Frequency (Hz)	*Right ear (O)*	*Left ear (X)*
250	10	15
500	17	20
750	17	20
1000	20	20
1500	10	15
2000	20	25
3000	50	30
4000	60	45
5000	65	60
6000	65	60

Note: Tests carried out via earphones. Hearing levels standardized according to American National Standards Institute (ANSI 1989).

general learning or language disability, hearing difficulties, substance abuse, or overt neural injury. Further, none of G.G.'s siblings, children, or grandchildren shares G.G.'s music perception difficulties.

Further, G.G.'s musical impairments cannot be attributed to limited musical exposure. Since early childhood, G.G. had a number of opportunities for musical education. He received musical training through the Kodály method offered in Hungarian schools (Choksy, 1988), which included pitch, rhythm, voice, and instrument training. From Grades 1–12, he failed his music courses despite high grades in all other topics. Outside school, he reports that his piano teacher quit after one lesson, saying that G.G. could not learn music.

How does G.G. describe his own perception of music? He describes music as "organized noise" with no more tonality than the sound of a car door slamming. To him, music has a beginning and an end, interspersed with noise segments. He reports that he forms no memories of musical experiences. He does not listen to music because he finds it aversive and prefers to work in silence. Nonetheless, G.G. has taken adult education courses in music history, because "the people are interesting even if the music is not".

Unlike most reports of congenital amusia (Ayotte et al., 2002; Foxton et al., 2004; Peretz et al., 2002; Peretz & Hyde, 2003), G.G. does not associate lyrics with songs, nor do lyrics provide melodic or rhythmic cues. (Note: We test this dissociation between words and music in the third part of the experimental tests.) He describes his own singing as "terrible". When he attends worship services, his Hebrew prayers, which are typically chanted, are uttered in a rhythmical wooden monotone distinct from his normal, highly inflected voice.

Structural functional magnetic resonance imaging (MRI). G.G.'s structural MRI revealed no clinically relevant abnormalities. A small lacunar infarct in the cerebellum was observed. There was little degeneration and atrophy of grey or white matter, despite G.G.'s age. Although these findings do not exclude the possibility of abnormalities at the microstructural level, they indicate no obvious pathology or cortical atrophy. Thus, G.G.'s music perception deficits stem from the functionality of music-relevant neural networks. These networks include cortical areas and potentially some subcortical networks. For example, several studies have indicated a possible support role for the cerebellum in auditory processing, including pitch and fine temporal relations (e.g., Parsons, Petacchi, Schmahmann, & Bower 2009; Petacchi, Laird, Fox, & Bower, 2005).

Control participants. Six age-matched participants (3 male, mean age = 66.7 years) volunteered to participate. All control participants reported normal hearing for their age and no difficulties perceiving and enjoying music. All had received some form of music education through their schooling but were not musicians. The tests reported below represent skills that most people can perform at near-perfect performance, and this control group performed at this level too.

Results

Establishing congenital amusia and musical specificity

G.G. performed in a manner consistent with other reported cases of congenital amusia. On the Montreal Battery of Evaluation of Amusia (Ayotte et al., 2002; Peretz, Champod, & Hyde, 2003), G.G.'s performance was at chance, and his test scores were two standard deviations below mean performance on all the subtests of scale, contour, interval, rhythm, and memory except for the metre test (Table 2; Peretz et al., 2003). Based on this battery, his lack of brain damage, and excellent health history, G.G. fits the criteria for congenital amusia.

To document the musical specificity of G.G.'s deficits, G.G. had typical speech and language functions as demonstrated by his multilingual competence. In addition, he had good recognition of environmental sounds as well as affect and emotion from speech (Table 3). G.G. could recognize 81.8% (18/22) of 22 digitally recorded sounds of everyday objects (e.g., whistle, buzzer, ocean,

Table 2. *Performance on Montreal Battery of Evaluation of Amusia*

	Score	
Subtest	*Mean control*	*G.G.*
Scale	27 (2.3)	15
Contour	27 (2.2)	17
Interval	26 (2.4)	16
Rhythm	27 (2.1)	22
Metre[a]	25 (3.5)	19
Memory	27 (2.3)	15

Note: Standard deviations in parentheses. Subtests had 30 items each.
[a]Nonharmonized version.

Table 3. *Recognition by G.G. of environmental sounds, affect, and rhythm*

Test	*Score*
Identification of sounds	
Common sounds & white noise	18/22
Sounds from International Affective Digitized Sounds battery (IAF)	24/28
Identification and production of affect & intonation	
Affect (±) of sounds	20/25
Intonation from speech	12/12
Affect from neutral sentences	20/20
Shared emotion of two actors	20/20
Emotion labels for acted scenes	40/40
Production of vocal intonation	12/12
Production of vocal affect	40/40

white noise), erring only on the identification of musical instruments. For the International Affective Digitized Sounds battery (Lang, Bradley, & Cuthbert, 2008), G.G. correctly identified 85.7% (24/28) of the items. G.G. also demonstrated long-term memory for object sounds in an auditory imagery tasks in which he compared the sounds of two items from memory based on their pitch, intensity, or quality of sound (e.g., Which makes a higher noise, a dentist drill or a door bell?); G.G. was 86.67% correct (26/30), and his performance was not significantly different from that of controls (27/30). Finally, G.G. could identify the affective valence conveyed by environmental sounds in the International Affective Digitized Sounds collection (Lang, Bradley & Cuthbert, 2008); compared to 82% (20.5/25) performance for controls, G.G. was 80% (20/25) correct.

G.G. also demonstrated intact recognition and production of prosody and affect in speech. He was 100% (12/12) accurate in judging whether sentences recorded by actors were questions, statements, or exclamations and whether they had positive, negative, or neutral affect (20/20). He was also 100% accurate (20/20) for identifying the emotion of two actors' reading of a script and determining whether the two actors' affect was congruent.

Intonation and affective speech production. To determine whether G.G. could produce appropriate intonation for prosody, G.G. read 4 different sentences as (a) statements, (b) questions, or (c) exclamations for a total of 12 different sentences. Independent scoring of these recordings indicated that G.G. had no difficulty producing recognizable and appropriate intonations. In addition, G.G. was asked to read 4 sentences expressing each of 10 different emotionally charged intonations (mischievous; fearful–nervous & uncertain; happy–content; sad–hurt; angry–annoyed; happy–excited; indifferent–neutral; angry–furious; fearful–dread; and sad–depressed). Again, independent scoring of his recordings indicated that although G.G. is not an actor, his voice conveyed the appropriate and recognizable affect in each sentence.

In sum, G.G.'s performance is consistent with other cases of congenital amusia (Peretz et al., 2002). His test performance on the musical disabilities battery was severely impaired. In contrast, G.G. displayed relatively unimpaired perception and production of environmental sounds, prosody, and emotion conveyed by speech. Further, his ability to understand sentence content and emotions over the course of a verbal interaction suggests that his general auditory working memory is within normal bounds. Together, these tests support the dissociations between functional neural networks for music and speech (Peretz & Zatorre, 2005).

Tests of pitch discrimination and melody recognition

The following tests investigate pitch-processing impairments (Table 4) and the melodic perception consequences of these impairments (Table 5): pure tone ranking, pitch discrimination, discrepant tones, direction of pitch discrepancy for tones in a series, pitch discrimination with scale segments, predictability of tone sequences, memory for familiar melodies, prompted memory for familiar melodies, and the production of familiar melodies. The purpose of this set of tests, organized in order of increasing difficulty, was to document a fine-grained pitch perception deficit using similar tests to those reported in Peretz et al. (2002), as well as some novel tests.

Pure tone rating and ranking. To determine whether G.G. had some representation of pitch and scalar order for large intervals, four single pure tones at octave intervals (1600, 800, 400, 200 Hz) were presented, and participants rated each tone as a high-, medium-, or low-pitched tone and then ranked the tones in pitch from low to high. Like controls, G.G. was 100% accurate at rating (4/4) and ranking (4/4) the pure tones.

Pitch discrimination. This test determined whether G.G. had any capacity to discriminate two pitches with fine- and large-interval differences in various registers. Participants were presented with 10 pairs of successive tones played on a piano. The notation used here denotes middle C as C4. Melodic intervals, which ranged from semitone to large-interval differences, included: semitone (Eb5 E5); whole tone (Eb6 F6), (G4 A4); 6-semitones (D2 G#2), (C#5 G4); perfect fifth (C4 G4) and octave (A4 A5); major sixth (F3 Ab2); and intervals exceeding an octave (C4 A5) (B3 G2). The task was to determine whether the second tone was higher or lower than the first. The tones of each pair were sounded in succession with a second's pause between the tones. In half the pairs, the higher tone was presented first. Also, the keyboard player's hands were hidden from participants' view. Controls were 100% accurate (10/10) but G.G. could not discriminate semitone or whole-tone intervals (0/3), only intervals greater than a whole step (7/7). Unlike another congenital amusic

Table 4. *Pitch discrimination by G.G.*

Test	*Score*
Single pure tone rating and ranking	
Rate 4 tones (1600, 800, 400, 200 Hz) as high, medium, or low	4/4
Rank same 4 tones from lowest to highest	4/4
Pitch discrimination: higher/lower judgements	
Intervals larger than a whole step	7/7
Whole-step and half-step intervals (fine-grained)	0/3
Discrepant tone in a 5-tone series	
Intervals larger than a whole step	32/32
Whole-step and half-step intervals (fine-grained)	7/16
Direction of pitch: discrepancy for tones in a series	
Is the last tone higher or lower than the previous tones?	18/25
Fine-grained pitch discrimination within scale segments	
Are two 5-tone scale segments the same?	17/34
Predictability of tone sequences	
In a 6-tone sequence, is final tone a wrong note?	5/10

Table 5. *Melody recognition by G.G.*

	Responses			
Test	*1 (No recognition)*	*2 (Vaguely familiar)*	*3 (Strong association)*	*Score*
Recognition vs. “knowing” familiar melodies				
Large leaps (10 trials)	4	3	3	
Strong rhythms (10 trials)	4	6	0	
Stepwise melodic motion (10 trials)	3	5	2	
Familiarity, recognition, and production				
Able to sing simple familiar songs with verbal prompts				0/10
Able to match melodies with titles and lyrics				0/10
Song production with melody prompts				0/10

“Monica” (Peretz et al., 2002), G.G.’s performance was similar for both ascending (4/4) and descending (3/3) pitch changes for intervals greater than a step.

Discrepant tones embedded in a single-tone series. Participants were presented with 48 five-tone series, played on a piano at a single-note pace (~0.5 s duration). The task was to determine whether all notes were the same pitch or one was different. The tone series could either be the same tone (C5) repeated five times or the same tone repeated four times with one discrepant note within the series. The discrepant tone varied between 0 and ±7 semitones above and below C5. The placement of the discrepant note was rotated across positions within the series. Each interval was tested twice; fine-grained pitch intervals ±2 semitones above and below C5 were tested four times. Trials were presented in random order. Controls were 100% accurate (48/48). In contrast, G.G. was only 81.25% (39/48) accurate overall. For trials in which the pitch did not change or when the discrepant pitch varied by more than two semitones, he was 100% accurate (32/32), but for trials in which pitch discrepancies were one and two semitones above the reference tone or one semitone below the reference tone, his performance dropped to chance (7/16).

Direction of pitch discrepancy for tones in a series. To assess detection of what *type* of pitch discrepancy occurred for tones in a series, participants listened to five notes played one at a time on a piano. Their task was to indicate after hearing four repeated tones in which *direction* (i.e., higher or lower) the fifth pitch in the series changed. The last pitch could vary from a semitone to an octave with respect to the repeated tone in the series. Control performance was 100% (25/25) but G.G.’s performance was 72% (18/25) correct. Of particular interest was that G.G.’s errors were distributed across ascending and descending directions. G.G. guessed incorrectly one third of the time for minor seconds, major seconds, and minor thirds, respectively. Three errors occurred in the bass register, which caused him hesitation even with perfect intervals.

Pitch discrimination with stepwise scale segments. To assess the use of scale representations for pitch discrimination, participants were asked to compare 34 three-, four-, and five-note scale segment pairs (i.e., trichords, tetrachords, pentachords, and scales) and to determine whether the pairs were the same or different. Notes were played one at a time with (~0.5 s duration per note). Discrepant trichord pairs included: (C5 Db5 Eb5) (C5 D5 Eb5) and (C5 Bb4 A4) (C5 B4 A4). Tetrachord pairs included: (C5 Db5 Eb5 F5) (C5 D5 Eb5 F5) and (F5 Eb5 Db5 C5) (F5 Eb5 D5 C5). Pentachord pairs included: (C5 Db5 Eb F5 G5) (C5 D5 Eb5 F5 G5), and (C5 Bb4 Ab4 G4 F4) (C5 Bb4 Ab4 G4 F4). Control performance was

100% (34/34), but G.G. was at chance (17/34). He reported that every pair sounded exactly the same; he discerned no differences between the segments.

Predictability of tone sequences. This test assessed G.G.'s ability to map a series of pitches to a structured musical representation such as a major scale or arpeggio. Participants listened to 10 series of 6- to 9-tone sequences, repeated twice on the piano. The following 10 tone sequences were used in this test. Correct pattern-completing tones are shown in parentheses:

1. <C4 D4 E4 C4 D4 E4 C4 D4 Eb4 (E4)>
2. <F4 A4 C5 F4 A4 C5 F4A 4 C#5 (C5)>
3. <D4 G4 E4 A4 F4 D5 (Bb4)>
4. <C4 G4 F#4 F#4 C#5 C5 C5 G5 F5 (F#5) >
5. <E5 D5 C5 E5 D5 C5 E5 D5 C#5 (C5)>
6. <F5 C5 A4 F4 A4 C5 F5 C5 A4 F4 …>
7. <G4 F#4 F4 E4 Eb4>
8. <C4 B3 C4 E4 D#4 E4 G4 F#4 G4 Db5 (C4)>
9. <C4 D4 E4 F4 G4 A4 B4 C5>
10. <A4 G#4 F4 E4 D4 C4 B3 A3>

In addition to pure scales and arpeggios (2, 6, 9, 10), tone sequences also included intervallic patterns that were purely stepwise (1, 5, 7) or alternated steps and leaps (3, 4, 8). In Tests 1–5, after establishing a 2- or 3-tone pattern through repetition, a third cycle of the pattern was sounded, finishing with a tone that either did or did not belong to the pattern or key. To break the pattern, a tone a semitone away from the expected tone was used to conclude the sequence; in Test 3, a tone that was a major third was used. In half of the sequences, the final tone did not belong to the sequence. Controls' performance was at 100% accuracy, but G.G. was at chance for stepwise, arpeggiated, and leaping patterns (5/10). Notably, complete scales (9, 10) generated no sense of sequential tonal expectancy.

Recognition versus "knowing" of familiar melodies. One consequence of G.G.'s not being able to use previously heard tone sequences to help his melodic recognition is that it may affect his memory for melodies, even those heard many times over the course of one's life. The ability to recognize a test item can be dissociated from the feeling of familiarity or "knowing" (Donaldson, MacKenzie, & Underhill, 1996). We examined whether G.G. had long-term representations of music that could be recognized explicitly or weaker representations that could lead to a sense of familiarity. G.G. was presented with 30 familiar melodies that were selected specifically to correspond with his personal experiences. Each of these melodies had one of the following features: (a) wide leaps (large characteristic pitch changes); (b) strong rhythm (distinctive beat patterns); and (c) stepwise melodic motion (small changes in pitch). We were interested in whether distinctive melodies with salient large pitch changes ("Somewhere Over the Rainbow") or whether melodies with salient rhythm ("Mexican Hat Dance") or with predominantly stepwise motion ("Twinkle, Twinkle Little Star") could aid recognition and sense of familiarity. For this task, G.G. was asked to name each melody and assign a number that corresponded with his feelings of familiarity—1: no recognition; 2: vaguely familiar, no strong association; 3: strong association or actual title of the melody. The melodies, fully harmonized, were played on a grand piano by a professional musician. G.G. recognized 13.33% (4/30) of the songs at some level. The best he could do was to classify two melodies as nationalistic songs ("National Anthem of Israel", "Star Spangled Banner") and two other melodies as children's songs ("Maoz Tzur", "Frère Jacques"). However, his familiarity was the same for all three types of melodies (see Table 5). G.G.'s abilities to discriminate larger pitch changes and rhythms do not aid either his explicit recognition or his feeling of "knowing".

Short-term recognition of melodies. To determine whether the recent listening of melodies could influence memory for melody, we tested G.G. again at the end of the session on his recognition of a subset of melodies played previously for the familiar melodies described above. He had been provided with correct feedback for each of the songs played in the earlier test. G.G. was presented with nine melodies (five old, four new). His recognition was at chance (4/9).

Familiarity, recognition, and production. Some people with congenital amusia use verbal representations of songs to aid their melody recognition. We assessed whether familiarity and verbal prompts would improve G.G.'s recognition and vocal production. First, G.G. was given the title and opening words to 10 familiar songs and was asked to sing the songs. G.G. did not know the lyrics to the familiar songs other than those written on the test page (0/10). His singing was monotonic and sounded like speech. He attempted some melodic contour at a very basic level in that he knew he should vary pitch within the song, but the attempt was rough at best. Second, G.G. was provided with 10 titles of songs and their lyrics. Songs were played on the piano, and G.G. was asked to match the melody with the title and lyrics. Unlike most typically developing people and even many people with congenital amusia, G.G. made no connection between the words and the music and could not match them. Third, melody prompts were provided to G.G. for 10 different familiar songs. After listening to the opening lines to familiar songs, G.G. was asked to sing the rest of the song. The melody prompt did not help him, and he performed no differently from when he did not hear the melody (0/10).

Summary. The above tests document that G.G. shares the previously reported impairment in fine-grained pitch perception (e.g., Peretz et al., 2002). Moreover he could not discriminate between sequences that vary patterns of semitones and tones at all. Further, this pitch processing deficit influenced his ability to recognize melody. He could not use prior experience, recent memory, or his linguistic abilities to aid him in the recognition of personally familiar melodies. Unlike other cases of congenital amusia, G.G. was even unable to use lyrics to help him identify melodies.

Tests of tonal fusion, harmonic complexity, and affect

The following tests investigate G.G.'s tendency for tonal fusion with consonant musical intervals and the harmonic impairments that might arise from this tendency: recognizing timbre, assessing consonance and dissonance, and recognizing musical affect from harmony (Tables 6 and 7). In order to ascertain how G.G. hears harmonic intervals, we begin with tests of tonal fusion.

Tonal fusion: Perceptions of one note from two. The first test of tonal fusion is adapted from

Table 6. *G.G.'s performance on tests of tonal fusion, timbre, and harmonic quality*

Test	*Score*
Tonal fusion	
Judging 1 vs. 2 tones at different harmonic intervals	20/24
Octaves, perfect fifths	0/4
Which sound heard: lower or upper tone for 12 pairs? Lower tone:	12/12
Discriminating 18 harmonic interval pairs	11/18
Timbre discrimination of single tones	
16 pairs of identical single tones: same or different timbre	5/16
Timbre discrimination of triad chords	
10 pairs of 3-tone identical chord pairs: same or different timbre	5/10
Harmonics: Consonant/dissonant dyads	
11 classic consonant and dissonant dyads on piano	6/11
Harmonics: Consonant/dissonant trichords	
10 assorted consonant and dissonant trichords on piano	5/10

Table 7. *G.G.'s performance on tests of emotion and affect*

	Score		
Test	*1 (Neutral)*	*2 (Positive)*	*3 (Negative)*
Identifying musical affect			
10 assorted musical sequences	9	0	1
Discriminating affect from melodic sequences			
10 assorted 1-minute segments	10	0	0
Musical affect and familiarity			
10 (5 positive, 5 negative) passages from classical repertoire	10	0	0

Experiment 1 of DeWitt and Crowder (1987) and has not previously been considered in testing congenital amusia. DeWitt and Crowder's goal in Experiment 1 was to identify the harmonic intervals susceptible to tonal fusion. All harmonic intervals between 1 and 12 semitones, as well as single tones and unisons, were presented to 7 subjects in numerous trials. Two kinds of responses signalled tonal fusion: a subject's slow response time, or a subject's indicating hearing one tone when two tones were sounding. For Experiment 1, DeWitt and Crowder reported that in their sample of typically developing individuals with varying degrees of musical training, the highest error rates occurred for the most consonant harmonic intervals: octaves at 25% and the perfect fifths at 6%. Participants reported that this experiment was very easy.

G.G. did not find this task easy. Modelled on the above experiment, G.G.'s tests covered all harmonic intervals between 1 and 12 semitones. Sounds were produced on a grand piano in the range between C4 and C5. Each interval was presented six times in random alternation with a single tone; G.G.'s task was to indicate whether he heard one tone or two tones sounding. In trials testing single tones versus octaves, and single tones versus perfect fifths, G.G. heard single tones 100% of the time, much more frequently than typically developing individuals. Like typical performance, G.G. was error free for the other intervals. This test suggests that G.G. has abnormal perception on account of tonal fusion. It also raises a question: When tonal fusion occurs, is it the case that the lower note is heard as a fundamental while the upper note is fused into its overtone series? The following test seeks to identify which tone is heard when tonal fusion occurs.

Tonal fusion: Which tone of the interval is heard? The purpose of this test was to assess which of the two tones of a harmonic interval is heard—the lower or the upper tone. DeWitt and Crowder (1987) argue that if tonal fusion influences the perception of the interval, then the lower tone would act as the fundamental, and the upper tone would act as an overtone. Thus the upper tone would bear on the perception of timbre rather than harmony (DeWitt & Crowder, 1987). In this test, G.G. was presented with a harmonic interval (i.e., two notes played together) followed by a single tone between C4 and C5 played on the piano. The task was to determine whether the fused tone and the single tone sounded the same pitch. Trials included all 12 harmonic intervals presented twice. For all 24 trials, G.G. responded that he heard the lower tone of the harmonic interval. For example, when the perfect fifth C4–G4 was presented, followed by the note C4, G.G. responded that these two sounds were alike. However, when the same perfect fifth was followed by the upper note G4, he responded that the two sounds were not alike. When the G4 was sounded first, then followed by the perfect fifth C4–G4, he reported that he heard the pitch go lower. When the C4 was sounded first, then followed by the perfect fifth C4–G4, he said that the pitch remained the same.

This result conforms to the hypothesis that when tonal fusion occurs, the lower tone assumes the role of fundamental, and the higher tone is subordinated to it. But it raises questions about the global effect of such consistent tonal fusion: What does it means to lack perception of the perfect fifth, or octave, as a consonant harmonic interval? Moreover, when tonal fusion does not occur, can G.G. distinguish same intervals from different intervals? Does the added complexity of harmonic intervals impair his ability with melodic intervals? Finally, does G.G. actually process the higher tone as timbre or do higher tones evaporate into the overtone series?

Tonal fusion: Discriminating harmonic intervals. To test discrimination of harmonic intervals, participants were presented with pairs of harmonic intervals and were asked whether the pair were the same or a different interval. Two series of harmonic intervals were presented in random order: pairs of major thirds and perfect fourths, and pairs including imperfect consonances and dissonances. Half of the trials were the same. For harmonic major thirds and perfect fourths, G.G. was at chance (3/6), consistently confusing the pair C4–F4 and C4–E4 as the same. Given that the melodic interval between the upper notes of this pair is a semitone, G.G.'s problem with fine-grained pitch discrimination may also play a role in his inability to distinguish between the major third and perfect fourth. The second series compared imperfect consonant and dissonant intervals: [C4–Eb4 C4–Ab4], [C4–Ab4 C4–Eb4], [C4–Bb4 C4–Ab4], [C4–F#4 C4–Db4], [C4–B4 C4–F#4], and [C4–Eb4 C4–F#4]. Among different pairings, G.G. was also at chance (3/6), confusing the [C4–Ab4 C4–Eb4], [C4–B4 C4–F#4], and [C4–Eb4 C4–F#4] pairs. On the one hand, the experiments of DeWitt and Crowder (1987) suggest that the effects of tonal fusion should be less prominent as dissonance increases. On the other hand, the experiments of Peretz et al. (2002) suggest that pitch discrimination should improve with larger melodic intervals that occur between the upper notes of the interval pairs, such as the perfect fourth between the B4 and F#4 of the fifth pair. Both theories predict that G.G. should be able to do this task accurately, but he could not. The harmonic complexity of the sounds seems to disrupt G.G.'s performance. Is their failure in timbre comparable to the failure in harmonic recognition?

Timbre discrimination: Single tone. Participants were presented with 16 pairs of single tones in the same register, played on a digital keyboard (6) or recorded from instruments (10). Each tone in the pair was sampled from a different family of instruments (trombone vs. cello). The task was to determine whether two tones had the same timbre or came from the same instrument. In contrast to 100% performance by controls, G.G. could only distinguish 31.25% (5/16) timbre discriminations. His performance indicated that he could recognize sounds as coming from musical instruments but could not always identify the instrument.

Timbre discrimination: Chords. Participants were presented with 10 pairs of timbres expressed through a major triad (chord built on scale degrees 1, 3, and 5) played on a Yamaha DX-7 digital keyboard. The task was to determine whether the sounds were the same, or from the same instrument. The chord remained invariant (viz. a C-major 6/3 chord, E3 G3 C4), but was sampled from different families of instruments (strings vs. brass). In contrast to the 100% performance of the controls, G.G. performed at chance (5/10), reporting that at times he heard only a single sound instead of a chord.

Harmonic 2-tone intervals (consonant/dissonant). Participants were presented with 11 different intervals consisting of two tones played together on the piano. The task was to report whether the interval sounded pleasant (consonant) or unpleasant (dissonant). The intervals were selected to be classic examples of consonance—P8 (F3 F4), P5 (C4 G4), M3 (Db4 F4)—and dissonance—M2 (F4 G4), m2 (E3 F3), d5 (D3 Ab3). In contrast to controls, who responded consistently with classic harmonic perceptions (11/11), G.G. could not discriminate between consonant (e.g., major third) and dissonant (e.g., augmented fourth) intervals (6/11), reporting that they sounded neither pleasant nor unpleasant. Even for the intervals greater than a whole step apart, he could not distinguish between consonance and dissonance. Of particular interest, he often reported hearing only one sound. Unlike the tonal fusion test, in which fusion appeared limited to harmonic octaves and perfect fifths, evidence of fusion was more pervasive when G.G. was listening for intervallic quality: consonance and dissonance. The perfect fifth interval nevertheless stood out as a special case that he consistently heard as a single tone when two tones [C–G] sounded simultaneously.

Harmonic trichords (consonant/dissonant). Participants were presented with 10 trichords or three tones played together on the piano. The task was to report whether each trichord sounded pleasant/consonant or unpleasant/dissonant. The trichords, identified by set-class (Forte, 1973), are classic examples of chords conveying consonance or dissonance: 3–5[016] (F#3 C4 G4), 3–11[037] (F3 A3 D4), M7[0–11] (F3 F4 E5), 3–10[036] (B3 D4 F4), 3–3[014] (G3 B3 Ab5), 3–7[025] (B2 Db5 E5), 3–8[026] (Db3 F4 G4), 3–1[012] (Eb E3 F3), and 3–3[014] (Ab3 A3 F4). In contrast to control performance (10/10), G.G. was at chance (5/10). He judged all trials to be "pleasant" and reported that he could not distinguish between consonance and dissonance of the different trichords. Again, he often reported hearing only one sound. The results of G.G.'s performance on the timbre and harmonic tasks suggest that tonal fusion was a source of difficulty in his making these qualitative distinctions.

Musical affect: Identification of affect from musical sequences. The tests above focused on the ability to perceive and compare individual tone relations. The next set of tests use full-fledged musical excerpts to assess the holistic processing of tones in terms of recognizing musical affect. We investigated the hypothesis that even in melodies that have large intervallic changes in pitch, G.G.'s atypical perception of tonal fusion and harmony would also influence his perception of musical affect. In the first test, G.G. listened to nine pieces of orchestrated classical music with multiple timbres, voices, tempos, rhythms, and melodies. Each piece was approximately 2 min in duration. Importantly, each piece was pretested to induce neutral, positive, or negative affect (Pignatiello, Camp, & Raser, 1986) and was selected because the perceived affect was related to large pitch differences in the melodies. In contrast to controls who were 100% accurate, G.G. was only 0.11% (1/9) accurate and correctly assigned correct affect to only one neutral piece. Despite cues from musical tempo, harmony, and large interval changes in pitch, G.G. could not discern affect from fully orchestrated pieces.

Musical affect: Discriminating affect from melodic sequences. Participants were played 10 one-minute segments of vocal music selected from *Solfège des Solfèges Volume 2b—Anthology of Melodies* (Danhauser, Lemoine & Lavignac, 1923). After hearing the melody, they judged whether it sounded happy, sad, or neutral. In contrast to controls who performed with 100% (10/10) accuracy, G.G. performed at 30% (3/10) accuracy, judging all segments as neutral. Again, despite cues from tempo and rhythm as well as his ability to discern emotion and affect in speech, G.G. had no affective response to music.

Musical affect: Familiarity. To determine whether prior exposure and nonmusical experiences to musical pieces could cue emotional responses to music, participants were presented with 10 pieces of well-known Western classical music (e.g., "The Blue Danube Waltz", Chopin's "Funeral March") and were asked to indicate whether the music was positive or negative in affect and whether it was familiar. Half of the pieces were positive in affect. Controls performed with 100% accuracy (10/10) for affective judgements and judged all pieces to be familiar. In contrast, G.G. performed with 10% accuracy (1/10), judging all pieces to be neutral except for Beethoven's "Pathetique" sonata, which he judged to have negative affect. Further, G.G. reported that none of the pieces was familiar. Thus, familiarity did not aid G.G.'s recognition of musical affect. Even though other studies have emphasized the dissociation of musical identification and affect (Halpern, Bartlett, & Dowling, 1998; Peretz & Gagnon, 1999), G.G. was unable to use tempo and mode to make qualitative judgements consistently, nor could he rely on his familiarity with the music from previous exposure.

In summary, the tests in this section document G.G.'s problem with tonal fusion for musical sounds. He had a difficulty perceiving concurrent notes, and especially the perfect fifth. When the tones of the perfect fifth were sounded together (C4–G4), he had an instantaneous and nervous reaction: "Wait! I only hear one note." The tonal fusion tests are key understanding to how G.G. hears timbre, harmony, and affect. This impairment appears to be separate from the fine-grained pitch discrimination impairment because these judgements are grounded in harmony and do not rely purely on melodic fine-grained pitch discrimination. Further, this simultaneous grouping impairment may be restricted to musical sounds, because G.G. reports no difficulty in picking out speakers in a crowd.

GENERAL DISCUSSION

Congenital amusia is a profound life-long deficit in music perception and production that cannot be attributed to neurological events or cognitive deficits. Recent research has attributed the musical-processing impairments primarily to a deficit in fine-grained pitch discrimination (e.g., Peretz et al., 2002). In this study, we investigated the hypothesis that, given the complexity of the musical signal and the profundity of the musical processing deficit, other perceptual deficits might be present in at least some cases of congenital amusia. Based on the complex pattern of what G.G. can and cannot do on a variety of musical tasks, G.G.'s performance cannot be attributed to a single deficit in fine-grained pitch discrimination. Our results provide evidence of at least two distinct problems that contribute to this case of congenital amusia. One is G.G.'s problem with the discrimination of fine-grained pitch intervals common in melodies. The second of G.G.'s problems occurs with consonant harmonic intervals whose upper tone is not perceived as such on account of tonal fusion. Each of these problems has distinct consequences for his difficulty with music perception.

Recent research has focused on impaired fine-grained pitch perception. One reason for this is music's distinctness from speech; the discrimination of whole/half-step (i.e. tone/semitone) pitch differences is not as critical for speech in which far wider pitch variations predominate (Peretz et al., 2002). Another reason is the high rate at which fine-grained pitch intervals occur in music, which far surpasses that of all other intervals (Peretz & Hyde, 2003; Vos & Troost, 1989). The core deficit of congenital amusia—impaired perception of fine-grained pitch intervals—is put forth in terms of criteria that are music specific and statistically significant (Peretz et al., 2002; Peretz & Zatorre, 2005). The argument states that the problem in discriminating the small intervals (tones and semitones) that proliferate in melodies makes it difficult if not impossible to perceive melodies, map scales, predict melodic patterns, and memorize melodies. It also implies that all further music-specific impairments, such as the sense of a melody being in a key, stem from this problem because this deficit precludes the development of scale representations upon which melodies are constructed, and other musical processing occurs (Hyde & Peretz, 2004). However, the kinds of music and musical activities that are normally effective in developing fine-grained pitch interval discrimination are not specified. Given the diversity and complexity of musical activities, the context in which music perception develops involves more than the processing of fine-grained intervals per se.

The tonal fusion argument states that in consonant harmonic simultaneities with as few as two notes, the higher note gets lost or becomes fused into the overtone series of the lower note, so only one note is heard. This has repercussions for G.G.'s perception of harmony, timbre, consonance, and dissonance, as well as the perception of all musical simultaneities. From a musical standpoint, the fact that the perfect fifth (e.g., C3 G3) formed by the second and third overtones in the series (C2, C3, G3 . . .) is especially susceptible to fusion problems jeopardizes all the intrinsically musical relationships, harmonic and melodic, that arise from it: The fifth is the interval that defines a critical tonal space in which melodies are organized (i.e., fine-grained pitch intervals are regulated in the context of the certain acoustical consonance of the perfect fifth), and the fifth is the interval that structures the modes and scales and plays a role in forming the relationship between tonic and dominant (i.e., the second and third overtones harmonically, the first and fifth scale degrees melodically) that establishes a key and the fifth as the basis for harmonic progression (Rameau, 1722/1971). The perception of harmony is an essential aspect of music perception because all Western melodies are based on progressions of consonant intervals and resolutions of dissonant ones (Foss, Altschuler, & James, 2007). Thus, atypical tonal fusion and harmonic processing could also fundamentally affect music and melody perception.

G.G.'s performance supports the argument that congenital amusia may involve impairments in both fine-grained pitch discrimination and tonal fusion. First, we documented that G.G. performs like other reported cases of congenital amusia. G.G.'s lifelong inability to hear music stands in stark contrast to his linguistic and cognitive abilities. He has no history of learning disabilities, cognitive deficits, or drug abuse. His structural MRI revealed no critical anatomical abnormalities, suggesting that any music perception deficits arise from the atypical functionality of music-relevant neural networks. G.G.'s performance on the Montreal Battery of Evaluation of Amusia (MBEA) establishes his severe case of congenital amusia (Peretz et al., 2003). Similar to other cases of congenital amusia (Ayotte et al., 2002; Peretz et al., 2002), G.G. had good recognition of environmental sounds as well as intact language and speech processing for affect, prosody, and emotion. Unfortunately, G.G. cannot use these auditory abilities to benefit his music perception. Thus, G.G.'s selective musical deficit supports the dissociations between music perception and other auditory perception capabilities.

Second, we confirmed that G.G., like other individuals with congenital amusia, demonstrated a problem with fine-grained pitch discrimination. The basic prediction of the fine-grained pitch hypothesis is that G.G. would be highly impaired discriminating whole and half steps, far more than he would be impaired discriminating larger intervals. Results from pure-tone pitch ranking, pitch discrimination, and discrepant-tone tests established his difficulty perceiving pitch differences of semitone and some whole-tone intervals. Additional tests for tonal sequence predictability, affect, singing, and melodic memory demonstrate the further consequences of pitch discrimination impairments. However, unlike other reported cases of congenital amusia, G.G. could not use lyrics to help him remember melodies. This novel finding suggested that G.G. may have more than a pitch-processing deficit.

Third, and novel to this study, we demonstrated that G.G. has problem with tonal fusion and processing harmonically complex musical tones. The tonal fusion test (DeWitt & Crowder, 1987, Experiment 1), in which he could not discriminate two tones sounding at all for the octave and perfect fifth intervals, establishes the problem. G.G. always hears the lower of two tones, which is what tonal fusion predicts. This difficulty was evident in other tests that required discriminating musical simultaneities such as discriminating between two dissonant intervals as same or different, and evaluating intervals as consonant or dissonant. Tests that assessed his ability to perceive consonance and dissonance of harmonic dyads (two notes sounding together) and triads (three notes sounding together) demonstrated that he had no discrimination of sonority. His inability to perceive harmony probably arises from the fact that he hears only one "sound" or "note" for harmonic intervals. Further, tests for discriminating timbre and musical affect demonstrate the consequences of tonal fusion impairments. G.G. could not distinguish the timbre from the sounds of two different instruments. He also could not discriminate affect from classic orchestral pieces even though he could potentially use the cues from tempo, large pitch interval changes, and rhythmic progressions. Together, the tests in this case study suggest two distinct problems that contribute to the profound music-processing deficit for this individual and potentially for other cases of congenital amusia. It is also possible that his combined problems with both musical succession and tonal fusion contribute to and exacerbate problems with memory and affect because they require holistic tonal processing.

This is the first study on congenital amusia to connect problems with tonal fusion to problems with fine-grained pitch discrimination. Further, there is evidence from neuroimaging studies on typically developing individuals to suggest that pitch discrimination and harmonic perception may be distinct neural networks. As measured by functional MRI (fMRI), cortical activation patterns for processing pitch and interval perception include the right secondary auditory cortex and Heschl's gyrus, especially when pitch changes are small (Johnsrude, Penhune, & Zatorre, 2000; Peretz & Zatorre, 2005; Tramo, Shah, & Braida, 2002; Zatorre & Belin, 2001; Zatorre, Belin, & Penhune, 2002). However, different cortical activation patterns are observed for the primary consonant intervals—namely, the octave and perfect fifth (Foss et al., 2007). Instead, the right inferior frontal gyrus is differentially activated for consonant intervals in general; further, in musicians, increasing activation is observed for perfect consonances, imperfect consonances, and dissonances in the right superior temporal gyrus, medial frontal gyrus, inferior parietal lobule, and anterior cingulate. Other studies (Itoh, Miyazako, & Nakada, 2003) have used dichotic listening experiments to show a larger left-ear advantage for dissonant chords than consonant chords. This finding suggests that the brain distinguished dichotic dyads based on consonance because interactions between the dichotically presented tones could not have occurred in the cochlea and are therefore at the level of musical rather than sensory processing.

Thus, it appears that tonal fusion and harmonic complexity may have distinct processing networks in the brain. If a tonic triad precedes and exerts an organizing effect upon its scale (Parncutt, 1989; Schenker, 1906), and the brain has a special relation to primary consonances (intervals with simple ratios: 2:1, 3:2), it is possible that a tonal fusion problem may even precede the fine-grained pitch discrimination problem for individuals with congenital amusia. On this view, the octave and fifth, whose consonance is proved harmonically, govern the intervallic size and melodic patterns of tones and semitones that occur in scales and modes. In commonly used Western musical scales and modes, a perfect fifth and octave must occur between scale degrees 1, 5, and 8. These scale degrees are musical yardsticks (Schenker, 1906). An individual who cannot access the fifth melodically and recognize its consonance, in a sense, would be trying to judge the stepwise distances inherent in the perfect fifth with one eye closed. For example, in "Twinkle, Twinkle Little Star", the quality of perfect consonance defines the first four notes as the first and fifth scale degrees; these structural tones occur as an ascending perfect fifth. In their stepwise motion, all other tones acquire their size and sequence in relation to the structural tones. In the case of G.G., congenital amusia is more than a problem with fine-grained pitch discrimination because his problem with tonal fusion has not been shown to be part of a cascade effect originating from his problem with fine-grained pitch discrimination.

Our results are consistent with two developmentally important processes for music perception. Developmentally, the inability to discriminate fine-grained pitch intervals could impede the internalization of the diatonic scale, which in Western musical practice comprises a particular sequential pattern of tones and semitones. Scales are important because they foster the sense of being in a key, changing key, or returning to an original key (Tillmann et al., 2000). Without a rudimentary internalization of the scale, an individual would not be able to distinguish reliably between the most stable, consonant scale degrees—the first fifth and eighth—and the least stable scale degrees. Therefore, as Peretz and colleagues claim e.g., Peretz et al., 2002), accurate fine-grained pitch discrimination is a prerequisite ability for further musical processing.

However, the capacity to hear consonant intervals harmonically, unimpeded by tonal fusion, may also be a prerequisite ability for musical processing. G.G. hears simultaneous two-note combinations as one tone, primarily for octaves and perfect fifths. Moreover, his inability to judge consonance and dissonance, recognize timbres, and perceive any kind of harmonic complexity whatsoever suggests an inability to process the harmonic dimension of tone. Given that the harmonic dimension of a tone and its fifth structures and determines the magnitude of the fine-grained pitch intervals of a scale, for an individual without the ability to perceive the harmonic dimension of tone, the scale has less, if not little, musical meaning than it would for an individual lacking only the ability to discriminate fine-grained pitch intervals.

In summary, as vital as fine-grained intervals are to scales and melodies, other fundamental components of music that are not all based on small pitch intervals are also critical for music perception. The present work emphasizes the importance of harmony and consonance, which defines sweetness in sonority and builds on the interval of the perfect fifth (Rameau, 1722/1971). In conclusion, G.G.'s case suggests that it is possible that a tonal fusion problem may precede the fine-grained pitch discrimination problem for people with congenital amusia. Some next steps in understanding congenital amusia are to expand investigations to other cases of congenital amusia and the testing of other fundamental properties of the musical signal in addition to pitch.

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