What is specific to music processing? Insights from congenital amusia

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Musical abilities are generally regarded as an evolutionary by-product of more important functions, such as those involved in language. However, there is increasing evidence that humans are born with musical predispositions that develop spontaneously into sophisticated knowledge bases and procedures that are unique to music. Recent findings also suggest that the brain is equipped with music-specific neural networks and that these can be selectively compromised by a congenital anomaly. This results in a disorder, congenital amusia, that appears to be limited to the processing of music. Recent evidence points to fine-grained perception of pitch as the root of musical handicap. Hence, musical abilities appear to depend crucially on the fine-tuning of pitch, in much the same way that language abilities rely on fine time resolution.

Music, as language, is a universal human trait. Throughout human history and across all cultures, individuals have produced and enjoyed music [1]. Despite its ubiquity, music is rarely studied as a basic and distinct cognitive faculty. Musical abilities are generally regarded to be assembled from processors that were not originally designed for this purpose [2]. This is in part owing to the fact that music has no obvious utility [3,4]. The other major reason is that only a select few individuals seem to achieve a level of music proficiency.

However, recent evidence suggests that music might well be distinct from other cognitive functions, in being subserved by specialized neural networks, under the guidance of innate mechanisms. Accordingly, any given individual would be born with the potential to become musically proficient. The goal of the present review is to identify this potential and to assess its specificity for music. To this aim, the relevant evidence emanating from developmental, cognitive and neuropsychological studies will be summarized, with special attention to the rare individuals who appear to be born unmusical.

Musical predispositions

Neurologically intact individuals appear to be born musical. Before one year of age, the pre-linguistic infant displays remarkable musical abilities that are similar, in many respects, to those of adults. Just as mature listeners, infants display sensitivity to musical scales and to temporal regularity. Six to 9-month-old infants process consonant intervals better than dissonant intervals [5] and exhibit learning preferences for musical scales with unequal steps [6]. The latter sensitivity bias does not seem to arise from exposure to ambient music because infants detect mistunings to invented musical scales, when these are built with unequal steps. This property of scales is universal [7] and promotes the organization of pitches around a central tone [8]. Hence, infants are perceptually equipped for assimilating the music pitch structure of any culture. On the time dimension, infants prefer music that is subject to an isochronous temporal pulse. Just as adults, four-month-old infants are biased toward perceiving regularity, in exhibiting sensitivity to slight disruptions of it [9]. The fact that these perceptual skills appear precociously, with no obvious function in language, point to the existence of music-specific predispositions [10].

Core musical knowledge bases and processes

With prolonged exposure, the ordinary listener becomes a kind of musical expert, although s/he is unaware of this. For example, non-musicians are as sensitive as musicians to subtle aspects of music harmony, by processing chords that are harmonically related to a chord context better than less related chords [11]. Musical training or explicit learning of music theory appears unnecessary to acquire sophisticated knowledge of the syntax-like relationships among tones, chords and keys [12,13]. This is a recent discovery. Early research in music cognition has mostly focused on musically trained individuals (e.g. see [14]).

Current research is no longer elitist and has been conducted, with musicians and non-musicians alike, on aspects of musical structure, other than those related to pitch structure [15]. There is no need to cover all of these aspects here, as music-specificity might be rooted in only a few processing components underlying the development of musical competence. As infant studies suggest, these likely anchorage points are the encoding of pitch along musical scales and the ascribing of a regular pulse to incoming events. Both aspects are essential to the hierarchical organization of music, which in turn facilitates perception, memory and performance by creating expectancies [13,16]. Both aspects are also likely to be specialized for music processing, although the issue remains to be settled for temporal processes. By contrast, the processes mediating pitch (tonal) hierarchies can be viewed as unique to music, hence as the 'germ around which a musical faculty could have evolved' ([17], p. 257).

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In music, pitch variations generate a determinate scale, whereas speech intonation contours do not usually elicit such effects [8]. Moreover, as mentioned previously, the use of scales is universal and makes use of unequal-spaced pitches that are organized around 5 to 7 focal pitches [7,18]. Scale tones are not equivalent and are organized around a central tone, called the tonic. Usually, a piece starts and ends on the tonic. Among the other scale tones, there is a hierarchy of importance or stability. The non-scale tones are the least related and often sound anomalous. This implicit tonal knowledge allows any given individual to detect when a musician strikes a wrong note, for example. This widespread ability may, however, be lost or compromised as a consequence of brain damage.

Music-specific neural networks

Brain damage can disrupt the normal intervention of tonal knowledge in melodic processing, while sparing perception of pitch distances and directions [19]. In such a case, the patient can no longer differentiate tonal from atonal music, nor determine whether an out-of-scale pitch fits a melodic context. The reverse situation can also occur. Brain lesions can impair pitch discrimination abilities and maintain the ability to generate expectancies based on tonal context [20]. Thus, the processes that mediate tonal perception of pitch appear to be subserved by a separable neural substrate that can be selectively impaired or spared by brain damage. Recent data obtained with functional neuroimaging point to the rostromedial prefrontal cortex as the likely host for this tonal network [21].

The existence of music-specific neural networks is not limited to the tonal encoding of pitch. Other distinct neural networks have been identified for music memories [22] and for singing [23,24]. Among these, the networks that contribute to music recognition are of most relevance here because their specificity is well documented. Indeed, brain-damaged patients may suffer from recognition failures that affect the musical domain exclusively [25–29]. Such patients can no longer recognize melodies (presented without words) that were highly familiar to them before brain damage. By contrast, they are normal at recognizing spoken lyrics (and spoken words, in general), familiar voices and other environmental sounds (such as animal cries, traffic noises, and human vocal sounds). This condition is termed *acquired music agnosia*. Conversely, isolated sparing of music may also be observed after brain damage. Non-musicians may lose their ability to recognize spoken words and yet remain able to recognize music [30,31]. The existence of such cases of selective impairment and sparing of musical abilities is incompatible with any claim that there is a single processing system responsible for the recognition of speech and music. Rather, the evidence points to the existence of at least two distinct processing modules: one for music and one for speech [32].

Congenital amusia as a music-specific disorder

The fact that music processing appears to be associated with distinct neural networks entails that music-specific impairments should not only occur in the event of brain damage (*acquired amusia*), but may also occur as a result of a congenital anomaly (*congenital amusia*). In the language domain, such cases, often termed *Specific Language Impairments* (SLI), have been identified for quite some time, and a large research effort has been undertaken to understand the origin and varieties of these disorders. Some researchers claim that language impairments arise from failures specific to language processing [33]. Others hold that language deficiencies result from a more elemental problem that results in individuals being unable to perceive fine acoustic temporal changes [34].

The possibility that certain individuals may be born with a specific deficit for music processing has been entertained for more than a century [35,36]. This condition has been variously called tone-deafness, dysmusia and dysmelodia. However, the term 'congenital amusia' seems preferable to acknowledge the possibility that there exist as many forms of congenital amusias as they are forms of acquired amusias [37]. Congenital amusia refers to the observation of musical failures that cannot be explained by obvious sensory or brain anomalies, low intelligence nor lack of environmental stimulation to music. Notorious examples are Che Guevara (the highly educated revolutionary) and Milton Friedman (Nobel Prize in Economics), who reported life-long musical handicaps despite having taken music lessons in childhood [38,39]. However, much early evidence rests on anecdotal case descriptions.

In an attempt to quantify this disorder and to measure its prevalence, Kalmus and Fry [40] administered a test that required the detection of anomalous pitches inserted in popular melodies to more than 600 participants in the UK. Approximately 4% of these subjects performed as poorly as 20 self-declared amusic individuals. Since then, a similar estimate (5%), based on the low tail of the normal score distribution has been obtained in the USA with a similar test (Drayna, pers. commun.). While these estimates are based upon performance on a single measure of musical ability, which may have poor validity, they are interesting for two reasons. First, they are consistent with the prevalence of other domain-specific disabilities, such as SLI (7% [41]). Second, the estimates have been obtained with a test that has been recently shown to tap a genetically transmitted ability. The anomalous pitch detection test has been completed by 136 identical (monozygotic) twins and 148 fraternal (dizygotic) twins. Genetic model-fitting indicates that the influence of shared genes is more important than shared environments, with a heritability of 70–80% [42]. This suggests that the 4 to 5% of the general population that is amusic may suffer from a genetically determined defect in perceiving pitch structure in music.

This hypothesis has been largely confirmed in a recent effort to document the presence and nature of the disorder in adults reporting a lifelong disability for music [37,43,44]. All amusics lacked basic musical abilities on objective and detailed testing (see Box 1). For example, they are unable to recognize or hum a familiar tune, despite normal audiometry and above average intellectual, memory and language skills. They also showed little sensitivity to the presence of obvious dissonant chords in classical music [43], a sensitivity that is normally present in infants [45]. Most notably, in line with previous work [40], the pitch-based deficit is most distinctive when amusics are required

Box 1. Identification and selection criteria for congenital amusia

The educational system does not screen for musical disabilities or, worse, does not even consider that this sort of deficit might exist, targeting lack of musical education or lack of effort as the source of the problem [53]. To identify individuals with congenital amusia, one can either conduct large survey studies (as in [40]), or adopt the methods of cognitive neuropsychology, by conducting multiple case studies that allow in depth analysis of the deficits. As the latter approach is more desirable at this early research stage, a systematic search for self-reported amusics was conducted by way of advertisements in the media. Reports varied greatly, from an inability to read musical scores (i.e. a form of musical developmental dyslexia [54]), to an aversion for music. In line with previous studies [35,36], only individuals who attested to be unable to recognize tunes (without the help of lyrics), nor to detect when they sang out of tune (but were told by others), were selected. Furthermore, to rule out lack of educational opportunities, only volunteers who had achieved a solid level of education and reported unsuccessful attempts at mastering music, despite having had musical lessons during childhood, were thoroughly evaluated [37,43,44].

The selected individuals were initially evaluated with the Montreal Battery of Evaluation of Amusia (MBEA), which has been effective in diagnosing musical disorders in large groups of brain-damaged patients of various etiologies [55,56]. The battery includes six tests which assess the different components that are known to be involved in melody processing of Western tonal music, namely pitch contour, musical scales, pitch intervals, rhythm, metre and memory. Self-declared amusic individuals whose global score (averaged across the six tests) lies two standard deviations below the mean of normal controls are considered as confirmed cases. This amounts to ~90% (24 out of 27) of the self-declared amusic volunteers tested to date.

Their subjective complaints were also confirmed by way of further testing, probing their memory and recognition abilities for music and nonmusical auditory events [37,43,44]. Indeed, congenital amusic subjects failed to recognize well-known tunes as compared with normal controls. Yet they easily recognized the songs, from which the tunes were taken, when hearing the spoken lyrics. Moreover, under identical testing conditions, the amusics showed no difficulty in recognizing and memorizing common environmental sounds and in recognizing the voices of famous people. Thus, amusics do not seem to suffer from a general auditory attentional or learning disorder; their disorder is limited to music.

to detect 'a wrong note' (a note not in the scale) in a conventional melody [37,43,44]. The test was found to be diagnostic as there was no overlap between the distributions of the amusics' and controls' scores. The results could not be attributed to a memory failure, because the melodies were unfamiliar. Rather, what amusics seem to be lacking is the knowledge and procedures required for mapping pitches onto musical scales. Thus, amusics seem to lack a pitch-processing component that is unique to music, for which infants seem to be predisposed, and which appears to be genetically transmittable [42].

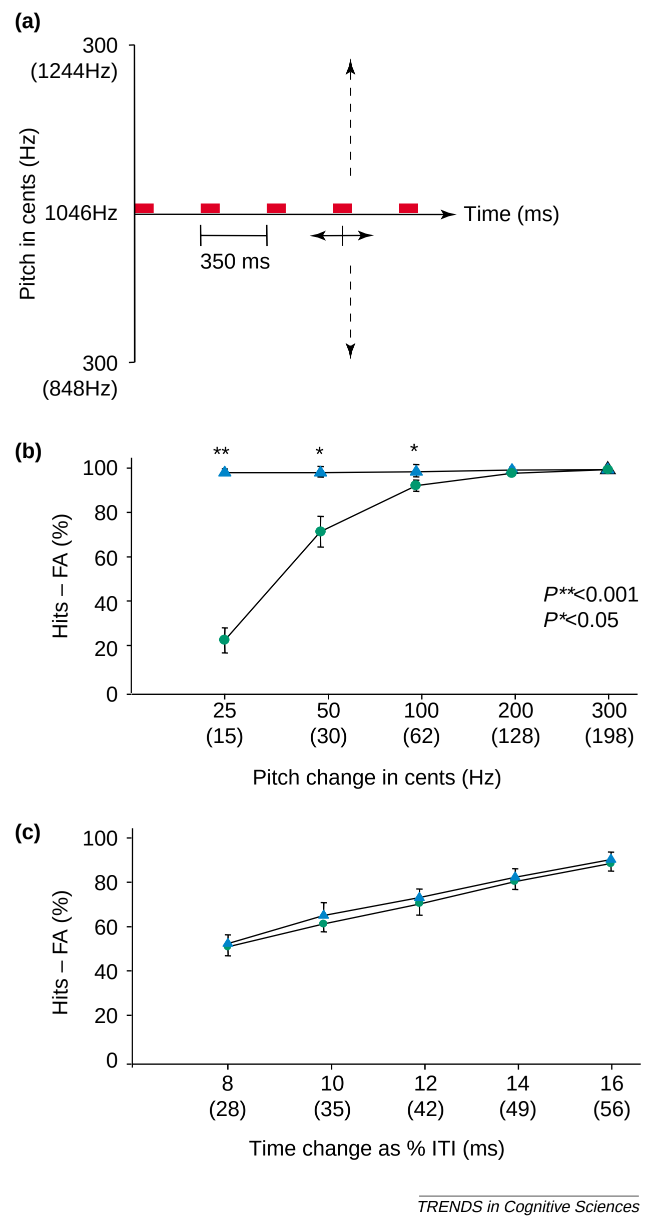

Fig. 1. Psychoacoustic tests of pitch and time discrimination in sequences. Ten amusic and 10 control adults were presented with 360 sequences, each comprising five tones. (a) When a sequence differed from monotony (same pitch) or isochrony (same time), its fourth tone was altered. In the pitch-altered sequences, the fourth tone was displaced upwards or downwards by one of five pitch distances (dotted vertical arrows), ranging from 25 to 300 cents (where 100 cents corresponds to 1 semitone). In the time-altered sequences, the fourth tone was displaced from its isochronous position (horizontal arrows), occurring earlier or later by one of five temporal increments that ranged from 8 to 16% of the 350 ms inter-tone onset. (b,c) The scores of amusics (green circles) and controls (blue triangles) are represented in mean percentage of hits ('yes' responses to an altered sequence) minus false alarms ('yes' responses to the non-altered sequence) in the pitch condition (b) and in the time condition (c). Error bars represent mean standard error. Adapted with permission from Ref. [44].

Congenital amusia, as an acoustical disorder of fine-pitch discrimination

Nonetheless, the musical deficit might arise from a more elemental problem. This possibility was suggested by the discovery of a severe deficit in acoustic pitch perception in the first documented cases of congenital amusia [35,37], which in turn may account for the emergence of a lifelong musical impairment. Poor pitch perception may prevent the normal internalization of musical scales that have steps between consecutive notes of 1 or 2 semitones (corresponding to 1 or 2 adjacent keys on a keyboard). Western melodies are constructed with such small pitch distances; 70% are 0 (repeated pitches), 1, or 2 semitones in size [46]. Similar pitch size distributions are observed across musical styles and cultures [47]. Thus, a perceptual system that is unable to detect small pitch changes is bound to miss an essential part of musical structure.

The presence of such a basic pitch discrimination deficit has been confirmed in each amusic subject tested so far ([44], Foxton, unpublished) for both isolated tones and tone sequences. Amusics were impaired in detecting a small pitch deviation in monotonic and isochronous sequences, whereas they performed as controls in detecting a slight time deviation in the same context (see Fig. 1). Thus, amusics' poor pitch perception cannot be ascribed to nonspecific problems with the task, nor to poor hearing in general. Rather, the data point to the presence of a congenital anomaly that selectively impairs sequential pitch processing.

In addition to being specific to pitch, the deficit is also fine-grained and includes the critical semitone distance. Because the problem is revealed in the context of a single repeating tone, the same defect is likely to be greatly amplified when additional uncertainty is added, such as in a musical context. Given that amusics are probably born with this deficit – normal infants' pitch acuity lies in the order of half a semitone [48] – they have probably never assimilated the structure of musical scales nor acquired the sophisticated tonal knowledge that every normally developing individual implicitly builds on scales.

One major implication of these findings is that fine-grained pitch perception appears essential for the normal development of musical abilities. A corollary proposal is that precocious, enhanced pitch acuity may predispose individuals to superior musical skills or talent. These conditions have been recently met in autism ([49] see Box 2).

The pitch defect spares speech intonation

The importance of pitch for the musical domain is obvious. However, pitch also contributes to speech communication. Over half the languages of the world use pitch to alter the meaning of words. Such languages (e.g. Mandarin, Thai and Vietnamese) are known as tonal languages. In non-tonal languages, the most easily measurable use of linguistic pitch lies in the final pitch rise that is indicative of a question. Yet, these variations in pitch intonation are well perceived by congenital amusic individuals [43]. This is because pitch variations in speech [50] are very coarse compared with those used in music (Fig. 2). Hence, a deficient pitch perception system might compromise music perception exclusively, not because it is specialized for that domain, but because music requirements are more fine-grained. Accordingly, the disorder experienced by congenital amusic individuals may not be music-specific, but merely *music-relevant*.

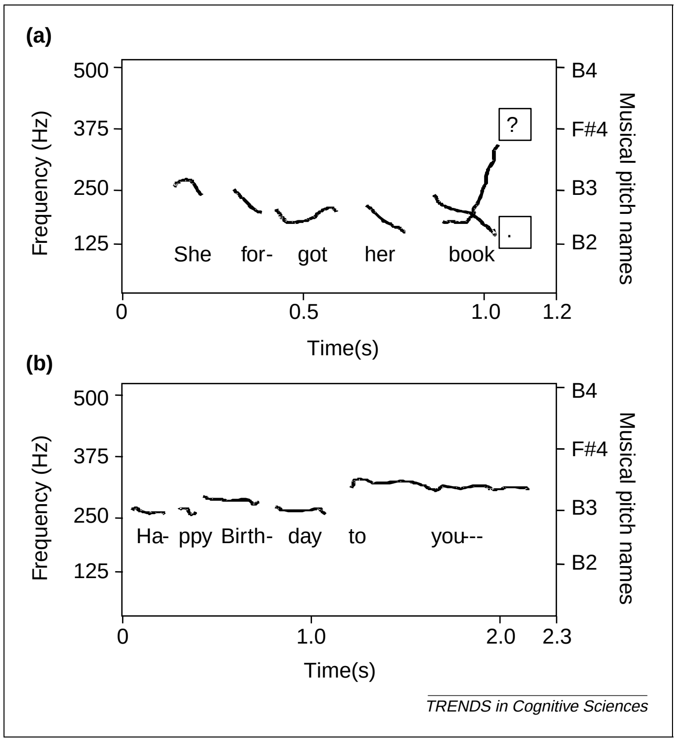

Fig. 2. Pitch variations in speaking and singing. (a) The fundamental frequency (F_0) of the sentence 'She forgot her book' with the intonation pattern of a question (?) and a statement (.). (b) The same analysis of the song 'Happy Birthday'. Both renditions were spoken and sung naturally by a female English speaker and analysed with Praat software (www.praat.org). The final pitch rise and fall in (a) are typical of the English and French language, with a range spanning more than 12 semitones [50]. The significantly smaller pitch variations in singing (b) is typical of music, ranging mostly from 0 to 2 semitones [46,47].

Conclusion

Congenital amusia is a genuine disability that affects music specifically. Affected individuals, who are otherwise unimpaired, have extreme difficulties appreciating, perceiving and memorizing music, despite their efforts to do so. A likely perceptual cause of this difficulty is a deficit in fine-grained pitch discrimination that would have prevented the normal development of the neural networks that ascribe musical function to pitch. Thus, the origin of the disorder appears to be acoustic and music-relevant, rather than music-specific.

A major implication of this finding is that the brain would not be pre-wired or specialized for music. The brain would be specialized at a more acoustic level, for processing fine spectral acoustic cues. This is consistent with the model proposed by Zatorre and collaborators [51],

Box 2. Musical proficiency and enhanced pitch abilities in autism

Musical abilities, and pitch processing in particular, are remarkable traits of individuals afflicted with autism, a neuro-developmental disorder characterized by impaired social and communicative development [57]. Certain autistic individuals, known as 'savant' musicians, exhibit high proficiency in musical abilities, including creativity and understanding of tonal harmony that are indistinguishable from those of typical musicians [58]. Moreover, although such 'musical savants' often suffer from cognitive and language retardation, they succeed to develop 'absolute pitch' [59]. Possessors of absolute pitch are able to name a specific tone without hearing a reference tone, which is often regarded as the ultimate musical endowment [60].

Music and pitch processing are also enhanced in non-savant autists, who have no musical training. Children with autism and mental retardation perform better than typically developing children in their ability to associate tones with pictures [61]. Non-savant autists also exhibit superior discrimination of non-transposed melodies that differ by a single pitch interval, as compared with age-matched controls [62]. This remarkable performance with musical sounds and patterns is not only associated to an extraordinary memory for pitch, but also to an enhanced ability to detect fine frequency changes in isolated tones [49].

Box 3. Questions for future research

- The neural correlates of congenital amusia are unknown. Having established that the origin can be an aberrant pitch perceptual system, narrows down the possible neural loci where an anomaly can be uncovered. Finding a neural anomaly would provide evidence that congenital amusia might arise from a faulty wiring mechanism. Presently, congenital amusia can be regarded as the low tail of a normal distribution.
- About half of the congenital amusic individuals suffer from associated impairments in discriminating musical rhythms, despite the fact that they are able to detect slight time deviations from isochrony. The question for future research is to determine whether the rhythmic difficulties are a cascade effect of the pitch defect or rather associated problems that may pertain to another form of congenital amusia.
- If congenital amusia is genetically inherited, a characteristic pedigree should be discerned in the families of the congenital amusic participants.

postulating that the differences in music and speech processing be related to complementary specialization for fine spectral resolution in the right auditory cortex and for rapid temporal processing in the left auditory cortical areas, respectively. Hence, one can consider congenital amusia as the mirror image of SLI, whereby pitch is to music what time is to speech [34].

Such an account of congenital amusia modifies the way the disorder, and the process of music acquisition in general, should be studied [52] (see also Box 3. Questions for future research). If the development of music competence emerges, at least in part, from the integrity of a mechanism that mediates fine-grained specification of pitch, then early training at the acoustic level should impact music processes, such as those involved in the tonal encoding of pitch. Furthermore, a disorder of fine-pitch resolution might produce several subtle impairments in domains other than music, even though it is to music that it will be most detrimental. For example, slight co-occurring difficulties might be found in the processing of tonal languages by native (amusic) speakers.

Gaining insight into every aspect of this seemingly music-specific disorder should not only enrich current brain theories of normal and abnormal music development, but may someday offer some light for afflicted individuals. Amusic individuals are reluctant to acknowledge their deficit because they feel it as a social handicap and, worse, as a lack of a sensitivity that is basic to humankind.

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