

Characterization of deficits in pitch perception underlying ‘tone deafness’

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Summary

Congenital amusia is a disorder characterized by life-long, selective deficits in the perception of music. This study examined pitch-perception abilities in a group of 10 adults with this disorder. Tests were administered that assessed fine-grained pitch perception by determining thresholds both for the detection of continuous and segmented pitch changes, and for the recognition of pitch direction. Tests were also administered that assessed the perception of more complex pitch patterns, using pitch-sequence comparison tasks. In addition, the perceptual organization of pitch was also examined,

using stream segregation tasks that assess the assignment of sounds differing in pitch to one or two distinct perceptual sources. In comparison with 10 control subjects, it was found that the participants with congenital amusia exhibited deficits both at the level of detecting fine-grained differences in pitch, and at the level of perceiving patterns in pitch. In contrast, no abnormalities were identified in the perceptual organization of pitch. The pitch deficits identified are able to account for the music perception difficulties in this disorder, and implicate deficient cortical processing.

Keywords: auditory system; congenital amusia; music; pitch; tone deafness

Abbreviations: ANOVA = analysis of variance

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Introduction

It is commonly observed that certain individuals have a particular difficulty with music, and they are colloquially labelled ‘tone deaf’. Case reports in the literature describe such individuals (Grant-Allen, 1878; Geschwind, 1984), but a detailed characterization has only been carried out very recently (Ayotte *et al.*, 2002). That work confirmed that certain individuals exhibit marked deficits on tests of music perception, in spite of normal audiograms, neurological history, education, and performance on tests of intelligence and memory. Ayotte *et al.* (2002) termed the disorder ‘congenital amusia’, and have demonstrated that it cannot be attributed to environmental factors, such as exposure to music or music training. It is estimated that ~4% of the population is affected by this disorder (Kalmus and Fry, 1980).

The specificity of the music perception difficulties in congenital amusia begs the question as to the underlying cause. It has been suggested that selective abnormalities of

pitch perception might underlie congenital deficits of music perception (Peretz *et al.*, 2002). In line with this theory, case reports of individuals with life-long music perception problems have reported marked difficulties in detecting differences in pitch (Grant-Allen, 1878; Geschwind, 1984; Peretz *et al.*, 2002), such as the inability to distinguish between adjacent piano notes. In addition, a recent group study of individuals with congenital amusia has demonstrated a deficit in the detection of pitch changes within a sequence of monotonic piano notes (Hyde and Peretz, 2004). In this study, it was found that there were no analogous deficits in temporal pattern perception, suggesting that the difficulties are limited to pitch perception.

The present study sought to determine the precise nature of pitch perception deficits in congenital amusia. Pitch perception is dependent on the neural representation of the spectral (frequency) and temporal structure of

acoustic stimuli, a process that occurs first in the cochlea (Dallos, 1992). Representations of these stimulus properties relevant to pitch are found in the structures of the ascending auditory pathway and in the primary auditory cortex in the superior temporal plane (Talavage *et al.*, 2000; Patterson *et al.*, 2002). Emerging evidence suggests that there may be a 'pitch centre' in secondary auditory cortex where brain activity correlates with the actual percept of pitch, rather than the physical properties of the acoustic stimulus (Griffiths, 2004). A deficit in the representation of stimulus properties in the ascending pathway and primary auditory cortex, or in the representation of the pitch percept in the secondary auditory cortex, could therefore cause the perceptual abnormalities in congenital amusia. Alternatively, it is possible that the pitch deficits occur at a higher level of complexity, where patterns of pitch changes are perceived. This more complex level depends on distributed processes in the superior temporal lobe distinct from the process for representing the pitch of individual sounds (Patterson *et al.*, 2002). Lesions of the cortex in these areas can produce dissociated deficits in the analysis of pitch pattern. For instance, Johnsrude *et al.* (2000) demonstrated that the perception of pitch direction is impaired as a result of right cortical lobectomy, whilst the detection of simple changes in pitch is unimpaired. It is therefore possible that a selective deficit in the analysis of pitch patterns may occur in congenital amusia as a result of disordered processing in these cortical areas.

The present study assessed different aspects of pitch perception in congenital amusia. The tests were designed to differ in complexity, with the aim of reflecting the different levels of neural processing. At the first level, subjects were required to detect continuous and segmented changes in pitch. Deficits in these tasks might reflect impaired representations of the physical properties of acoustic stimuli, or deficits in the representation of the pitch percept. The next level assessed the ability to determine the direction of pitch changes, a task that can be considered as the simplest form of pitch pattern perception. This task would be expected to involve the superior temporal lobe areas that analyse pitch patterns. Perception of more complex pitch patterns was also assessed through tasks that require the detection of differences between pitch sequences. These differences altered the actual pitches present in the sequences or the contour pattern of rises and falls in pitch. There is evidence that these two different levels of information involve processing in different cortical regions (Peretz, 1990; Liegeois-Chauvel *et al.*, 1998); therefore, dissociated deficits on these tasks might reflect differentially affected cortical areas. Finally, tasks were administered that assess the organization of sounds into perceptual streams on the basis of pitch. The neural basis for this latter process is unclear, but there are indications that the parietal cortices might be involved (Carlyon *et al.*, 2001).

Subjects and methods

Subject characterization

Ten experimental subjects were tested who described life-long music perception difficulties. They were recruited by means of advertisements in local newspapers and on the radio. All participants reported that when they sang, their voice sounded in tune to themselves, but not to others. None reported a history of neurological or psychiatric disease, with the exception of one subject, who reported a history of neonatal seizures. None described difficulties with speech intelligibility, prosody perception or environmental sound perception.

All of the participants had normal hearing in at least one ear, defined as a mean hearing level of 20 dB or less, measured by pure tone audiometry at 250, 500 and 1000 Hz. These frequencies overlapped with those employed in the experimental tasks.

Ten control subjects were tested who reported that they were able to sing in tune, and who matched the experimental subjects for the number of years spent in education. None had previously participated in any psychoacoustic research. All reported normal hearing and no history of neurological or psychiatric disease. Table 1 summarizes the characteristics of the two groups.

Informed consent was obtained from all of the participants, and ethical approval was attained from the local research ethics committee for the University of Newcastle-upon-Tyne.

A standardized battery of music perception tests (Peretz *et al.*, 2004) formally confirmed the presence of music perception difficulties in the experimental participants. This battery assesses subjects' ability to detect differences in melodic features between pairs of novel melodies: the key of the melody, the size of the pitch jumps (intervals) between adjacent notes, the pattern of rises and falls in pitch (contour), and the rhythm. The battery also includes a test of the ability to identify the metre or 'beat' of a melody, and a test of memory for tunes. The scores on these tests were added together to form a composite score, and these were compared against normal control data (Peretz *et al.*, 2004). It was found that all of the experimental subjects' scores fell in the impaired range, defined as 2 SD below the mean score of the control population ($n = 160$). In addition, scores for the subtests were compared against age-appropriate control data for each subject, with control groups aged 30–44 years ($n = 18$), 45–69 years ($n = 49$) and 70+ years ($n = 14$) (Peretz *et al.*, 2004). It was found that all of the experimental subjects were impaired on at least three of the six subtests at the $P < 0.05$ level (see Table 2). Critically, all were impaired on the pitch subtests (key, interval and contour), with the exception of one participant, who scored in the normal range on the scale subtest. In line with previous reports, some of the experimental participants performed normally on the temporal subtests (rhythm and metre).

The control participants in the present study were administered the scale subtest of the music perception battery. The mean score on this test was 26.5 (SD 2.1) for these subjects compared with a mean score of 20.4 (SD 2.6) for the experimental participants. An independent samples *t*-test confirmed that there were significant differences between the groups on this test [$t(18) = -5.8$, $P < 0.01$].

Tests were administered to assess reading ability in the experimental subjects. This was considered to be important, as pitch perception has been related to reading skills in studies of developmental dyslexia (Tallal, 1980; Witton *et al.*, 1998; France

et al., 2002). Participants were administered the National Adult Reading Test (Nelson and Willison, 1991), which requires participants to read aloud a list of irregular words, such as 'cellist'. They were also administered a non-word reading test (Olson *et al.*, 1994), which requires participants to read aloud a list of two-syllable nonsense words, such as 'tegwop', and an orthographic recognition test based on that of Olson *et al.* (1994), which requires subjects to identify the correctly spelled word in homophone pairs, such as 'rain-rane'. In addition, the digit span test from the Wechsler Adult Intelligence Scale III (Wechsler, 1997) was administered, as this measure has been related to reading skills (Torgeson, 1978). A measure of verbal intelligence was obtained as a control measure (the Mill Hill Vocabulary Senior Scale Form; Raven *et al.*, 1988). For this latter test, participants were required to identify words' synonyms in a multiple-choice format. Independent samples *t*-tests showed that there were no significant group differences for any of the reading tests, the digit span test or the verbal intelligence measure (Table 3). Note that the non-word reading test errors measure is not included, as most of the participants did not make any

errors. For the orthographic recognition test, the scores were log-transformed to yield a normal distribution (Shapiro-Wilk test, $P < 0.05$ level).

Auditory tests

The auditory tests were administered in a stereotyped order for all of the participants over three or four test sessions, each of ~1.5 h duration. For all of the tests, the stimuli were created digitally and presented diotically through Sennheiser HD 265 headphones (Sennheiser, Wedeburg, Germany) at a sound pressure level of at least 70 dB. Tests were conducted in either a sound-proofed room (the experimental subjects) or a quiet room (the control subjects). The pitch streaming tests were all conducted in a quiet room.

Pitch difference detection thresholds (see Fig. 1)

Segmented pitch change detection. Subjects were presented with two pairs of sounds. One pair consisted of two identical tones, and the other pair consisted of two tones of different frequencies. The task was to decide whether the first or the second pair of sounds was different.

Gliding pitch change detection. Subjects were presented with two sounds. One was a steady pure tone, and the other was a tone that contained a frequency glide, either upwards or downwards. The task was to decide whether the first or the second sound contained the glide.

Pitch direction determination. Subjects were presented with two sounds. One was a tone that contained an upward frequency glide, and the other was a tone that contained a downward frequency glide. The task was to decide whether the first or the second sound 'went up'.

Table 1 Subject group characteristics

	Amusia group (<i>n</i> = 10)	Control group (<i>n</i> = 10)
Mean age (SD)	55.8 (12.3)	51.0 (6.5)
Sex	7 F; 3 M	6 F; 4 M
Years education (SD)	16.4 (3.1)	17.1 (2.8)
Years music training (SD)	1.35 (1.1)	0.7 (1.3)

F = female; M = male.

Table 2 Experimental participants' raw score on the Montreal battery subtests (all items are out of 30)

Subject	Age	Scale	Contour	Interval	Rhythm	Metre	Memory
1	51	16*	15*	15*	21*	9*	20*
2	58	18*	17*	14*	19*	23	23
3	48	22†	18*	19*	26	18†	24
4	30	19*	21*	20*	20*	20†	27
5	55	24	19*	21†	17*	19	22†
6	73	18*	18*	21*	17*	13*	23
7	50	23†	22†	19*	17*	15*	23
8	71	20*	20*	19*	25*	28*	22†
9	60	22†	20*	18*	21*	23	25
10	62	22†	16*	17*	25	27	24

*Fell outside 99% limits of normal performance; †fell outside 95% limits of normal performance.

Table 3 Group scores on the reading, digit span and vocabulary measures

	Mean (SD) – experimental	Mean (SD) – controls	<i>t</i>	Significant ($P < 0.05$ level)
National Adult Reading Test errors	8.5 (5.4)	6.7 (2.5)	0.95	No
Non-word Reading Test time	42.5 (11.3)	39.4 (8.2)	0.70	No
Orthographic Recognition Test errors	3.2 (3.1)	1.9 (2.3)	1.0	No
Digit Span Test total score	10.5 (1.7)	12.2 (2.0)	-2.0	No
Mill Hill Vocabulary Test errors	5.8 (4.6)	6.1 (3.3)	-0.17	No

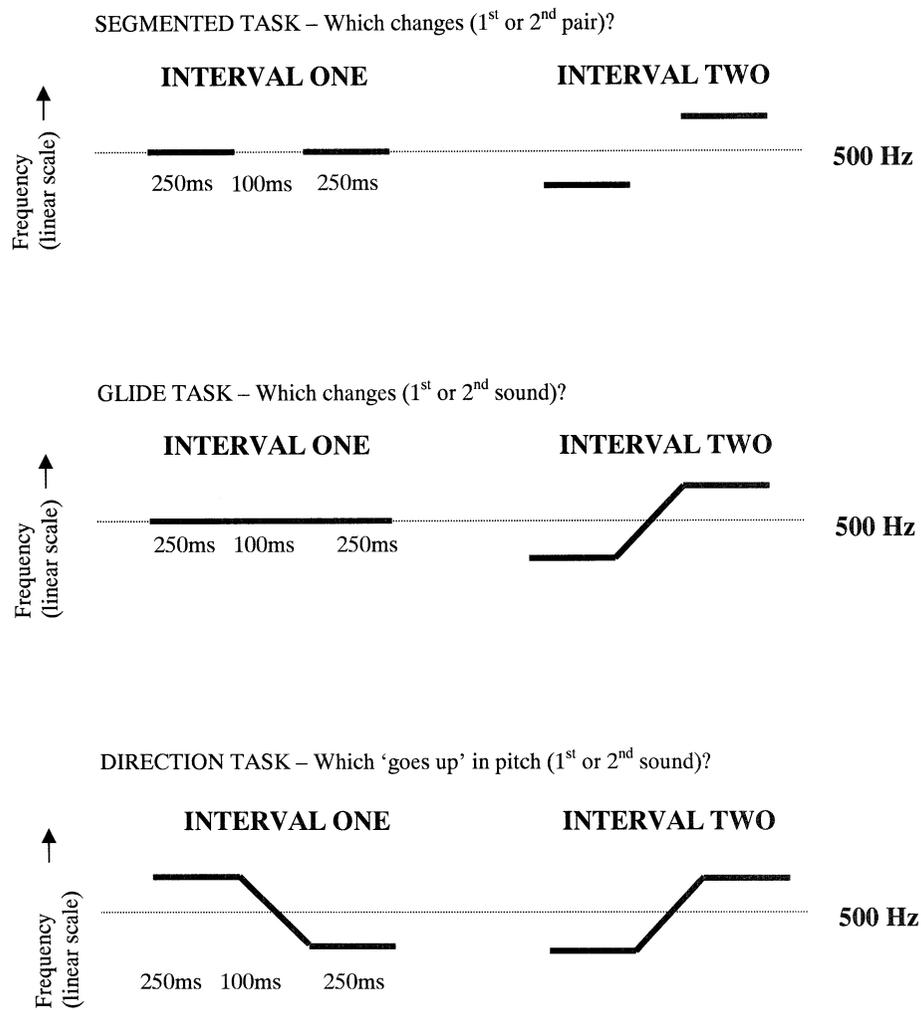


Fig. 1 Pitch threshold tasks. The solid lines represent the auditory stimuli. The dotted line shows the 500 Hz base frequency. Note that for segmented and glide tasks, the change was a rise in pitch for half of the trials, and a fall in pitch for the other half.

For each task, the size of the frequency excursions varied to include levels where the subjects performed at chance (50% correct) and levels where subjects were able to perform the task with a score close to 100% correct. This allowed the determination of a full psychometric function for each participant in order to measure the pitch excursion required for a score of 75% correct. The runs tested six, equally spaced pitch values in a random order.

For the segmented sounds, the ‘same frequency’ pairs were 500 Hz pure tones of 250 ms duration. For the ‘different frequency’ pairs, the frequencies were taken from above and below 500 Hz by equal amounts on a linear scale. The sounds within each pair were separated by a silent gap of 100 ms. For the gliding sounds, the details are identical, but the gaps were filled with 100 ms linear frequency ramps that began at the frequency of the first sound and ended at the frequency of the second sound. For all conditions, the comparison sounds were separated by 1100 ms gaps. Each sound was gated with 20 ms onset and offset amplitude ramps.

Pitch sequence tasks (see Fig. 2)

For these tests participants were presented with pairs of four-note pitch sequences, and were required to decide whether the sequences

within each pair were the same or different. The sequences consisted of a series of 250 ms pure tones, gated with 20 ms onset and offset ramps. For each test there were four runs where subjects were presented with 40 sequence pairs. Each run employed sequences with pitches taken from an octave divided into different numbers of logarithmically equally spaced steps. For the first run the octave was split into 3.5 steps, for the second run this was 7 steps, for the third run this was 11.5 steps, and for the final run this was 3.5 steps again. The repeat was carried out to determine whether there were performance improvements on the tests. The lowest note of each sequence pair was taken from a randomly selected value between 300 and 500 Hz.

Contour violation not transposed. For this test, the ‘same’ sequence pairs were identical. The ‘different’ sequence pairs differed at either the second or third note by a magnitude of two notes. These differences always violated the contour pattern of rises and falls in pitch.

Actual pitch differences with identical contour patterns. For this test the ‘same’ sequence pairs were identical. The ‘different’ sequence pairs differed at the second or third note by a magnitude of two notes, but these did not violate the contour pattern of rises and falls in pitch.

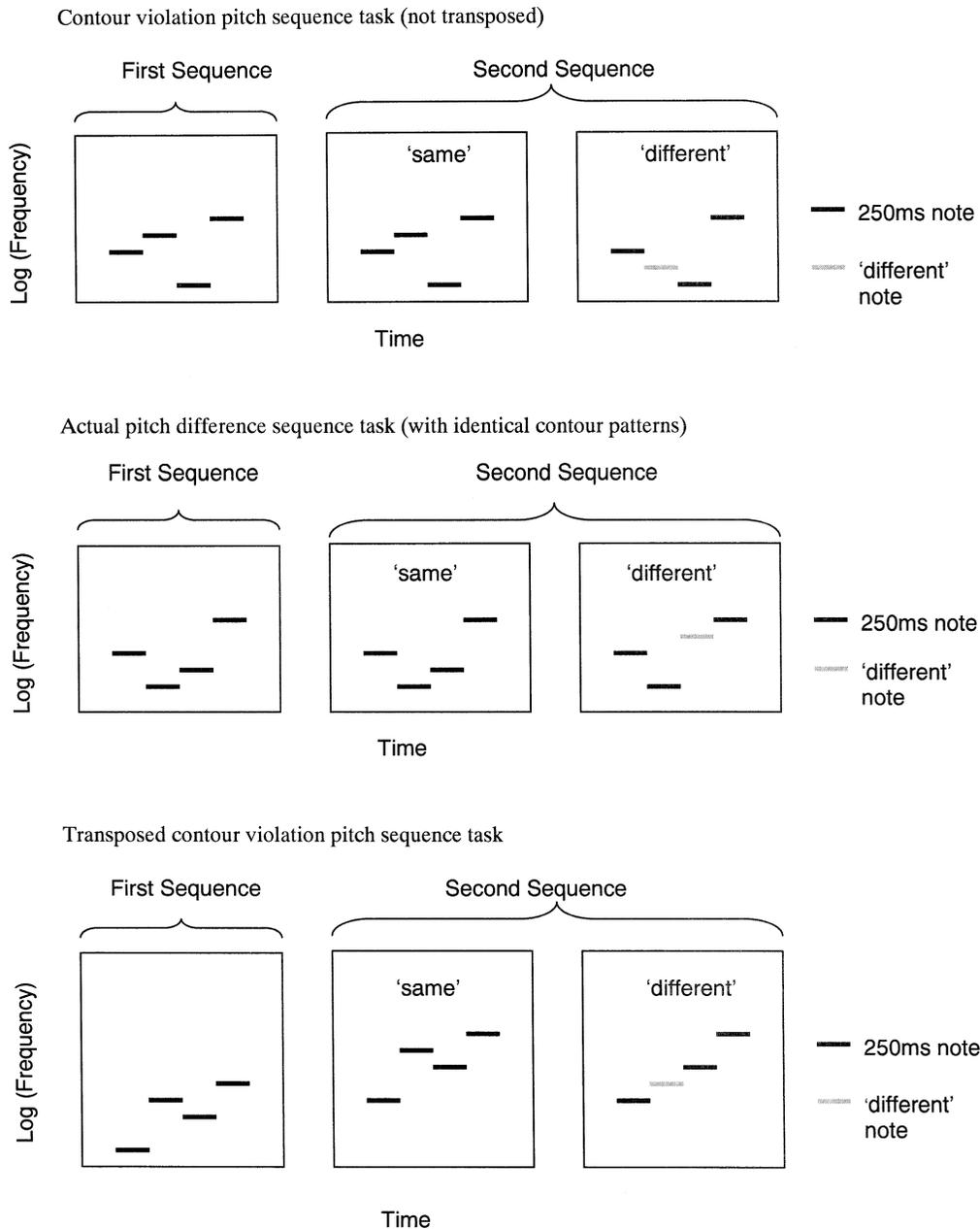


Fig. 2 Examples of items for each pitch sequence perception task.

Transposed contour violation (see Fig. 2). This test was identical to the non-transposed contour violation task, with the exception that the second sequence in each pair was transposed (shifted) up or down by half an octave. For this test, participants were instructed to ignore the overall shift in pitch and to decide whether the pattern of rises and falls was the same or different between the sequences.

It should be noted that for all of the sequence tasks, the sequence pairs spanned either four or five notes.

Pitch streaming tasks (see Fig. 3)

These tasks employed an alternating series of high and low pure tones (125 ms duration; 20 ms onset and offset ramps), with a silent 125 ms gap in the place of every fourth note. The low tone always

had a frequency of 500 Hz; the high tone's frequency was varied. Previous research has shown that a small pitch separation between the high and low tones gives rise to a unified percept of one perceptual stream, such that it is possible to follow the triplet rhythm '1-2-3-gap-1-2-3-gap', etc. (Van Noorden, 1975; Bregman, 1990). With a larger pitch separation the high and low tones no longer form a unified percept, but rather form two separate streams. In this situation, it is no longer possible to follow the triplet rhythm.

Temporal coherence boundary task. The temporal coherence boundary is the pitch separation between the high and low tones where it is not possible to follow the triplet rhythm. To identify this boundary, participants were presented with the alternating tones. The high tone started off close to 500 Hz, and then, for each consecutive triplet, got higher in logarithmic steps. The size of these

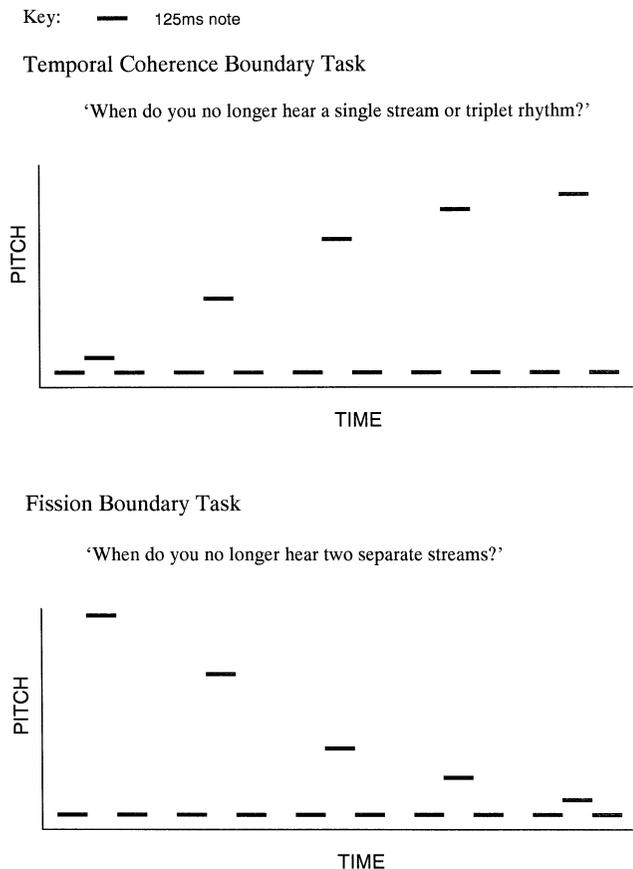


Fig. 3 Pitch stream segregation tasks.

pitch increases was large at first, and then became progressively smaller, in order to more accurately determine the boundary. Participants were asked to press a key when they were no longer able to hear the triplet rhythm.

Fission boundary task. The fission boundary is the pitch separation when subjects cannot hear the high and low tones as two separate perceptual streams. For this task, subjects were presented with the alternating tones, with the high tone starting off at 2000 Hz and descending logarithmically for each consecutive triplet. These decreases in pitch were large at first, and then became progressively smaller. Participants were asked to attend to the high tones and to try to hear these separately from the low tones. They were asked to press a key when this was no longer possible.

The above procedures were repeated 10 times for each task, administered in two blocks of five trials.

Results

Pitch difference tasks

Subjects' scores were plotted as proportion correct against the size of the frequency excursion. A sigmoid (Weibull) function was fitted to the data, which ran from 50% correct (chance) up to 100% correct. This fit was achieved through maximum likelihood estimation (Wichmann and Hill, 2001), and enabled the threshold frequency excursion to be determined, which was defined as the point at which a score of

75% correct was achieved. An example of a Weibull fit is shown in Fig. 4 for the scores from one of the experimental subjects. It should be noted that all of the participants scored between 90% and 100% correct at the maximum pitch excursion tested.

The thresholds are shown in Fig. 5. It can be seen that there is overlap between the two groups of subjects for all of the tasks. However, the thresholds were generally worse (higher) for the experimental participants on all of the tasks. The thresholds were log-transformed to yield distributions that did not depart from normality (Shapiro-Wilk, $P < 0.05$ level), and these were analysed in a repeated measures analysis of variance (ANOVA), where the threshold task was the within-subjects independent variable, and subject group was the between-subjects independent variable. This analysis revealed a main effect of subject group [$F(1,18) = 34.1$, $P < 0.01$], a main effect of the threshold task [$F(2,17) = 17.0$, $P < 0.01$] and a significant interaction [$F(2,17) = 5.8$, $P < 0.05$]. *Post hoc* Bonferroni-corrected *t*-tests revealed significant group differences for all of the threshold tasks ($P < 0.01$). Interestingly, thresholds only ever exceeded one semitone for the segmented pitch-change task and the direction tasks. This suggests that only these aspects of pitch perception are relevant to the music perception deficits, as pitch changes in western music are all at least one semitone in magnitude.

Pitch sequence tasks

The total scores for all of the tests were normally distributed (Shapiro-Wilk, $P > 0.05$). Scores are shown in Table 4 and Fig. 6. Repeated measures ANOVAs were run with the subject group as the between-subjects variable, and the sequence task as the within-subjects variable. The octave split was entered as a further within-subjects variable. It should be noted that the final runs of each test were excluded from the analysis (the repeat runs with octave split 3.5). The analysis revealed a main effect of the sequence task [$F(2, 17) = 34.1$, $P < 0.01$] and a main effect of subject group [$F(1,18) = 75.3$, $P < 0.01$]. There was no main effect of octave split [$F(2, 36) = 1.2$, $P > 0.05$], and none of the interaction terms was significant ($P < 0.05$ level). These analyses demonstrate that for all of the sequence tests, scores did not differ with changes in the octave split, and the experimental group scored at a significantly lower level than the controls. In addition, the results demonstrate that the sequence tasks differ in difficulty.

An additional repeated measures ANOVA was carried out for scores on the first and last runs of the sequence tests, which employed octave splits of 3.5. This analysis was to investigate whether there were performance improvements on the tests. The subject group was the between-subjects variable, and the sequence task and test run were the within-subjects variables. This analysis revealed main effects of sequence task [$F(2,36) = 77.7$, $P < 0.01$], test run [$F(1,18) = 15.2$, $P < 0.01$] and subject group [$F(1,18) = 59.7$, $P < 0.01$]. None of the interaction terms was significant at the $P < 0.05$ level. These results confirm the group and task differences

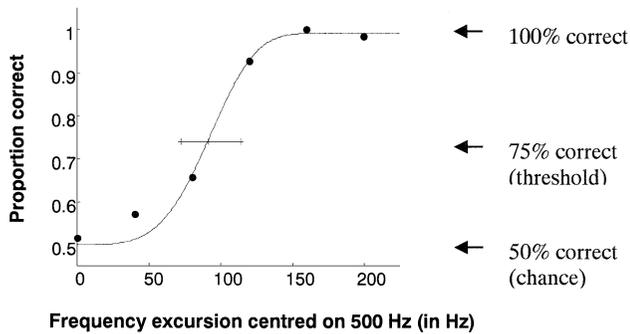


Fig. 4 An example of a Weibull fit for the scores from one of the experimental subjects (direction task). The black circles show the subject's scores at each level; the continuous line shows the fitted function; the horizontal bar shows the 95% confidence intervals for the threshold.

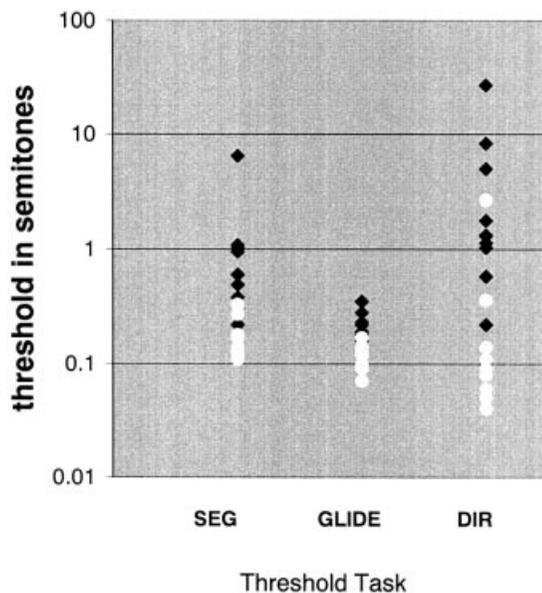


Fig. 5 The black diamonds show the thresholds for the experimental participants. The white circles show the control subjects' thresholds.

found in the previous analysis. In addition, the results show that there are improvements on the repeat runs for all of the sequence tasks.

Auditory stream segregation tests

Table 5 displays the mean boundaries for the two groups. One experimental participant did not complete these tests due to time constraints. A repeated measures ANOVA was run with group as the between-subjects variable and boundary as the within-subjects variable. The analysis revealed a main effect of boundary [$F(1,17) = 42.3, P < 0.01$], but no main effect of group [$F(1,17) = 0.05, P > 0.05$] and no significant interaction [$F(1,17) = 0.00, P > 0.05$]. This demonstrates that the

perceptual segregation of sequences into high and low pitches does not differ between the two groups of subjects.

The boundary task results were analysed further, to determine whether there were differences across the runs (shown in Fig. 7). Repeated measures ANOVAs were run with the subject group as the between-subjects variable, and the test block (first or second) and the within-block run (from one to five) as within-subjects variables. For both boundary tasks there were main effects of test block and within-block runs ($P < 0.05$). None of the interaction terms was significant, and there were no main effects of group. These results show that the boundary estimates change across the runs and that these do not differ for the two subject groups. However, it should be noted that there do appear to be group differences in how the fission boundary measures vary over runs (see Fig. 7). It may be that there was not sufficient power to demonstrate these differences in this study.

Discussion

Abnormalities in pitch perception have been proposed to underlie music perception deficits in congenital amusia (Peretz *et al.*, 2002; Peretz and Hyde, 2003). The present study supports this by demonstrating deficits in a range of pitch tasks in a group of subjects with this disorder. Deficits were identified in 'low-level' pitch perception tasks that require the detection of segmented and gliding frequency changes. Deficits were also identified on the pitch pattern perception tasks, from the simplest case of determining the direction of pitch changes to the more complex case of detecting differences between pitch sequences. In contrast, the perceptual organization of sounds into distinct streams on the basis of pitch was not found to differ between comparison and control participants.

Pitch task deficits

The participants with congenital amusia obtained higher (worse) thresholds for the detection of both segmented and continuous pitch changes. For the continuous pitch change task, thresholds were well below one semitone, the smallest pitch change in western music. In contrast, for the segmented task, the subjects with congenital amusia obtained thresholds that were close to or exceeded this value. This suggests that the deficit in segmented pitch change detection will adversely affect the perception of western music.

Deficits in pitch-direction determination were also identified in the congenital amusia group. Thresholds on this task generally exceeded those for simple pitch-difference detection. This demonstrates that the deficit cannot be attributed to an inability to detect the pitch changes, but rather suggests that it represents a deficit at the level of pitch-pattern perception. As the thresholds on this task generally exceeded one semitone, this aspect of pitch perception is also expected to adversely affect the perception of western music.

Table 4 Mean scores on the pitch sequence tasks (SD in brackets)

	Run 1: octave split 3.5	Run 2: octave split 7	Run 3: octave split 11.5	Run 4: octave split 3.5 repeat
Contour violation not transposed				
Experimental group	29.2 (2.5)	29.2 (3.9)	28.8 (4.6)	32.9 (4.0)
Control group	38.2 (1.6)	38.7 (2.2)	37.4 (2.6)	38.3 (2.3)
Actual pitch violation				
Experimental group	30.5 (3.3)	29.8 (4.3)	28.8 (3.3)	30.7 (3.7)
Control group	36.7 (2.3)	36.7 (2.0)	36.5 (1.9)	37.4 (1.8)
Contour violation transposed				
Experimental group	24.1 (2.1)	21.2 (3.1)	23.5 (2.1)	25.8 (3.5)
Control group	31.1 (3.7)	32.0 (4.1)	31.8 (5.4)	33.8 (2.6)

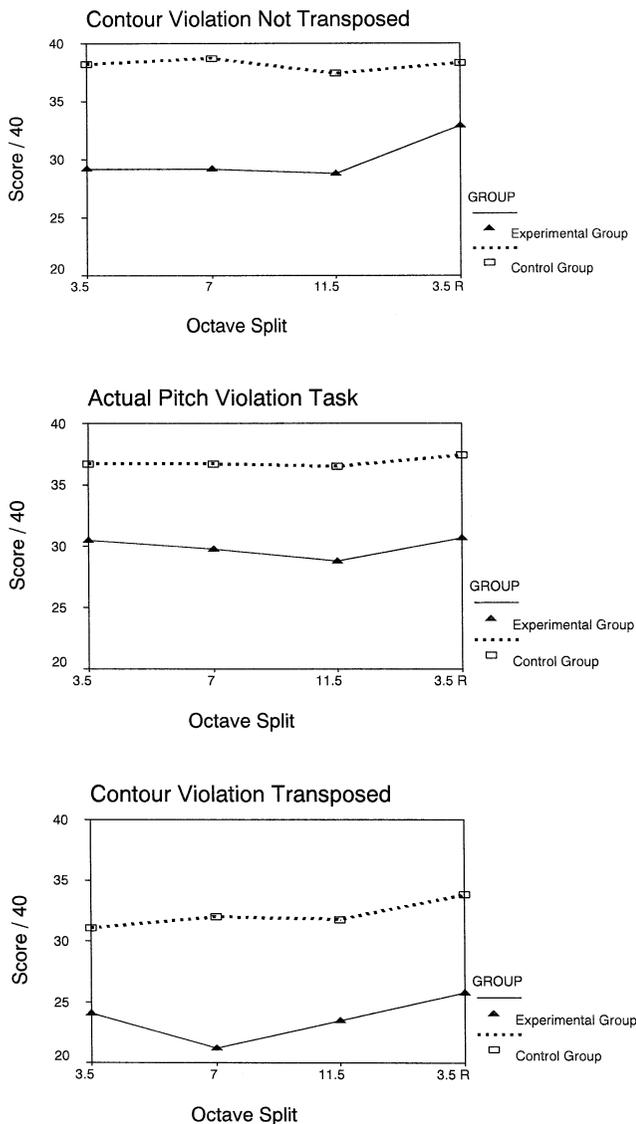


Fig. 6 Scores on the sequence tasks. The numbers along the x-axis show the octave split. 3.5 R represents the repeat run with the octave split of 3.5.

The congenital amusia group was also found to perform at a significantly poorer level on the pitch-sequence perception tasks. Abnormalities were identified in both the actual pitch-perception task and on the pitch-contour perception tasks. These abnormalities cannot be attributed to deficits in pitch change detection, as the pitch changes in the sequences generally exceeded these thresholds. In addition, performance was not found to improve for the sequences with larger pitch changes, which would be expected if the deficit arose from pitch-change detection deficits. We therefore conclude that the results demonstrate pitch perception deficits in congenital amusia, both at the level of detecting fine-grained differences in pitch, and at the level of perceiving patterns in pitch.

It should be noted that memory or attention deficits could affect performance on all of the pitch tasks. However, all of the subjects were able to achieve a high level of performance on the pitch threshold tasks with large enough pitch excursions, which would not have been possible if the deficits had been due to memory or attention abnormalities. In addition, scores on the digit span test, a verbal memory measure, did not differ between the two groups, again arguing against the possibility of memory deficits accounting for the pitch task abnormalities.

Training

Each pitch sequence task had two runs with the same octave split. This enabled an analysis of whether or not practice-related performance improvements occurred. It was found that performance improvements occurred on all of the tasks for both groups, a finding which suggests that it may be possible to improve certain aspects of pitch perception in congenital amusia. This result contrasts with a recent study by Hyde and Peretz (2004), which demonstrated that practice did not improve the detection of fine-grained pitch differences in individuals with congenital amusia, whereas improvements were observed in control participants. However, it is possible that training can only improve certain aspects of pitch perception in congenital amusia. It may be the case that

Table 5 Mean stream segregation boundaries in semitones (SD in brackets)

	Experimental group	Control group
Temporal coherence boundary	6.7 (1.0)	6.6 (0.7)
Fission boundary	3.6 (1.8)	3.5 (1.8)

practice will improve pitch pattern perception, but not the detection of fine-grained pitch differences. It will be of much interest to investigate this further, and to determine whether such training might help to ameliorate music perception difficulties.

Stream segregation on the basis of pitch

The organization of sounds into perceptual streams on the basis of pitch was not found to differ between the congenital amusia participants and the controls. This demonstrates that this aspect of pitch processing is not abnormal in congenital amusia. This finding supports the selective nature of the music deficit in congenital amusia, as abnormalities in auditory stream segregation might be expected to lead to other auditory perceptual difficulties, such as listening in noisy environments (Bregman, 1990). However, it should be noted that there would appear to be differences in how the fission boundary estimates vary over time in the amusics. It may be the case that limited power prevented this from being identified in the present study. It is of much interest to investigate this further, as this measure is thought to depend upon auditory attentional selection processes (Bregman, 1990), which might be affected in this disorder.

Neural substrate for the deficits

The tests in this study were designed to reflect different levels of neural processing. The results demonstrated deficits in both the simple pitch-difference detection tasks and in the more complex pattern-perception tasks, and are therefore indicative of impairments both at the level of perceiving isolated pitches and at the level of perceiving patterns in pitches. The former depends upon neural processing in the ascending auditory pathway, and in the primary and secondary auditory cortices. The latter involves distributed processing in the superior temporal lobes (Patterson, 2002). The results do not therefore enable a categorical statement about one particular level of neural processing for the pitch deficits in congenital amusia. However, the data do suggest a deficit in the cortical analysis of pitch pattern, which cannot be entirely accounted for by any 'lower-level' deficits.

As noted above, the ability to stream sounds by pitch did not differ between the controls and those with congenital amusia. The neural basis for these stream segregation processes is far from clear. Some have argued that streaming could occur as early as the cochlea (Beauvois and Meddis,

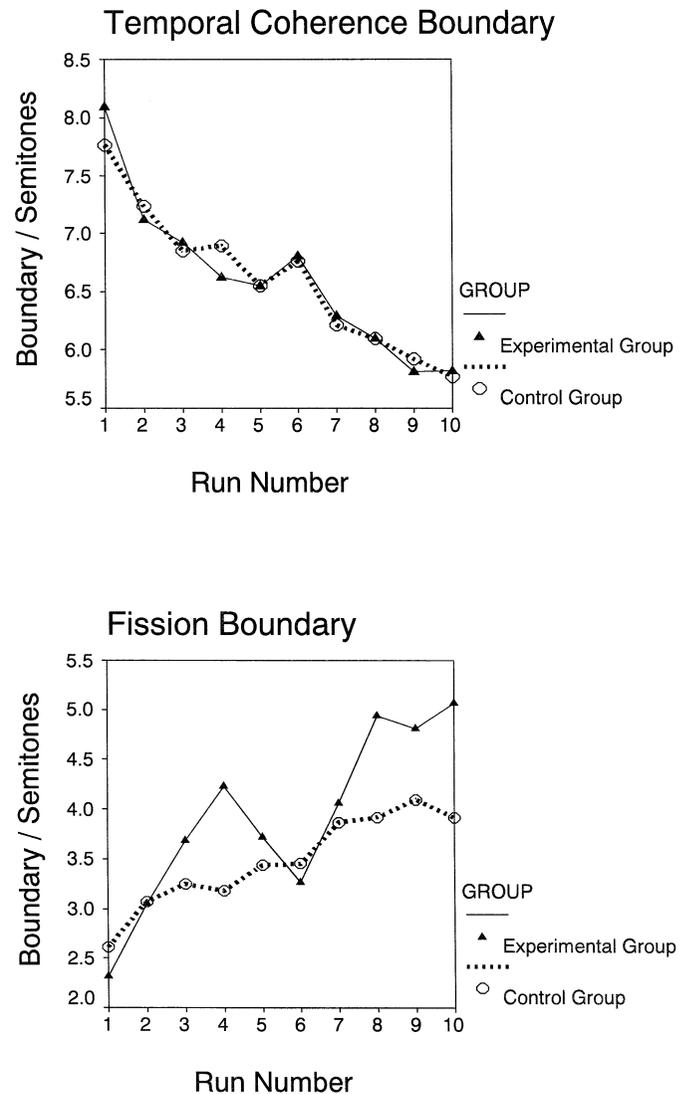


Fig. 7 Streaming boundaries over time. The boundary estimates for each test run are shown. Note that the runs for both test blocks are displayed in one figure.

1991), while others have emphasized the importance of attentional processes likely to reflect cortical function (Carlyon *et al.*, 2001). Until this issue is resolved, we remain unable to make an accurate inference about the neural systems underlying the present results.

Conclusions

The present study has enabled a detailed characterization of the pitch-perception deficits in congenital amusia. The results demonstrate deficits across a range of pitch tasks. Further work is required to determine whether there might be a single underlying factor accounting for these deficits.

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