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Tracking of pitch probabilities in congenital amusia

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ABSTRACT

Auditory perception involves not only hearing a series of sounds but also making predictions about future ones. For typical listeners, these predictions are formed on the basis of long-term schematic knowledge, gained over a lifetime of exposure to the auditory environment. Individuals with a developmental disorder known as congenital amusia show marked difficulties with music perception and production. The current study investigated whether these difficulties can be explained, either by a failure to internalise the statistical regularities present in music, or by a failure to consciously access this information. Two versions of a melodic priming paradigm were used to probe participants' abilities to form melodic pitch expectations, in an implicit and an explicit manner. In the implicit version (Experiment 1), participants made speeded, forced-choice discriminations concerning the timbre of a cued target note. In the explicit version (Experiment 2), participants used a 1–7 rating scale to indicate the degree to which the pitch of the cued target note was expected or unexpected. Target notes were chosen to have high or low probability in the context of the melody, based on the predictions of a computational model of melodic expectation. Analysis of the data from the implicit task revealed a melodic priming effect in both amusic and control participants whereby both groups showed faster responses to high probability than low probability notes rendered in the same timbre as the context. However, analysis of the data from the explicit task revealed that amusic participants were significantly worse than controls at using explicit ratings to differentiate between high and low probability events in a melodic context. Taken together, findings from the current study make an important contribution in demonstrating that amusic individuals track melodic pitch probabilities at an implicit level despite an impairment, relative to controls, when required to make explicit judgments in this regard. However the unexpected finding that amusics nevertheless are able to use explicit ratings to distinguish between high and low probability notes (albeit not as well as controls) makes a similarly important contribution in revealing a sensitivity to musical structure that has not previously been demonstrated in these individuals.

1. Introduction

Expectations can be conceived of as a form of mental or corporeal belief that some event or class of events is likely to happen in the future (Olsen, Roese, & Zanna, 1996). As early as 1870, the German physician Hermann von Helmholtz argued that predictions based on prior experience influence how we perceive our environment. Since then, the view of the brain as an anticipatory machine (Bubic, von Cramon, & Schubotz, 2010; Friston, 2005), has been supported by work across multiple domains including decision making (Platt & Glimcher, 1999), motor sequencing (Wolpert & Flanagan, 2001), visual perception (Egner, Monti, & Summerfield, 2010) and language comprehension (DeLong, Urbach, & Kutas, 2005). It is widely held that the tendency of our perceptual and cognitive systems to anticipate future events is evolutionarily advantageous and neuro-imaging studies have revealed that reward circuits in the brain are modulated by predictive successes and failures (Salimpoor, Benovoy, Larcher, Dagher, & Zatorre, 2011; Schultz, Dayan, & Montague, 1997).

The ability to form expectations is thought to result from implicit learning mechanisms that allow us to extract the rules and regularities present in structured systems we are exposed to (Reber, 1992; Seger, 1994). Music and language constitute two examples of structured systems in our environment that are guided by deep organisational principles (Bod, 2002; Lerdahl & Jackendoff, 1983). Despite being made up of numerous discrete events that can vary on several dimensions (e.g. pitch, loudness, timbre, duration), the majority of works from a musical culture tend to follow a definable set of conventions, and the enculturation of humans to music in their environment is a striking illustration of their cognitive capacity for learning and the formation of expectancies (Bigand & Poulin-Charronnat, 2006; Tillmann, 2005).

Expectancy has been described as the anticipation of an event based on its probability of occurring (Chaplin, 1985) and statistical learning is the proposed mechanism by which humans

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internalise the regularities in music (Tillmann, Bharucha, & Bigand, 2000). Listeners have the capacity to extract patterns from novel tonal materials after sufficient exposure (Saffran, Johnson, Aslin, & Newport, 1999) and there is empirical evidence that even newly acquired tone structures subsequently influence pitch expectations (Krumhansl et al., 2000; Oram & Cuddy, 1995; Tillmann & Poulin-Charronnat, 2010). Tillmann and Poulin-Charronnat (2010) demonstrated that participants exposed to structured tone sequences later showed a processing advantage for grammatical tones relative to ungrammatical ones in a subsequent task in which they were required to make speeded judgements regarding the intonation (in tune-ness) of target tones in new sequences. The influence, on listeners' expectations, of long term exposure to music's statistical regularities is also in clear evidence when real musical stimuli are used (Bigand & Poulin-Charronnat, 2006; Brown, Butler, & Jones, 1994; Cuddy & Badertscher, 1987; Krumhansl & Keil, 1982; Toiviainen & Krumhansl, 2003; Schmuckler, 1989; Smith, Nelson, Groskoph, & Appleton, 1994). For instance, listeners rate small intervals as more expected than large ones, reflecting the relative frequency with which they occur in melodies (Huron, 2006). Further, when required to give subjective ratings of how well each of a set of notes fits a musical pattern, listeners produce rating profiles that reflect the tonal hierarchy present in western music whereby some notes are more stable than others within a key (Cuddy & Badertscher, 1987).

However, in contrast to typical listeners, individuals with the perceptual disorder termed congenital amusia (henceforth simply amusia), show behaviours that suggest they have failed to acquire the long-term knowledge necessary for normal music processing (Ayotte, Peretz, & Hyde, 2002; Peretz & Hyde, 2003). These individuals show difficulty with the simplest of musical tasks in the absence of any other demonstrable cognitive deficits. This lack of proficiency cannot be explained by abnormal hearing or lack of exposure to music in early life (Ayotte et al., 2002; Peretz et al., 2002). While the disorder cannot be linked to acquired neurological injury, structural imaging studies have associated the disorder with subtle neurological abnormalities in a number of brain regions (Hyde, Zatorre, Griffiths, Lerch, & Peretz, 2006; Hyde et al., 2007; Mandell, Schulze, & Schlaug, 2007). Individuals with amusia are unable to recognise melodies which should be familiar to them and have difficulty discriminating one melody from another. Perhaps most striking of all is their insensitivity to out-of-key notes that have deliberately been inserted in a melody–stylistically ungrammatical events that typical listeners would find highly salient (Ayotte et al., 2002; Peretz et al., 2002).

Results from a diagnostic tool, the Montreal Battery of the Evaluation of Amusia (MBEA: Peretz, Champod, & Hyde, 2003), have shown that amusic individuals are most critically impaired on the pitch-based subtests of the MBEA (scale, contour, interval), while their performance on the rhythm subtest can be in the normal range (Peretz et al., 2003). Behavioural and psychophysical studies following up this observation have associated the disorder with elevated thresholds in the detection of pitch change, the discrimination of pitch direction, and memory for pitched events (Foxton, Dean, Gee, Peretz, & Griffiths, 2004; Gosselin, Jolicoeur, & Peretz, 2009; Peretz et al., 2002; Tillmann, Schultze, & Foxton, 2009; Williamson & Stewart, 2010; Williamson, McDonald, Deutsch, Griffiths, & Stewart, 2010). However, one question which remains unanswered is whether these amusic individuals have failed to assimilate the organisational principles of music, that even musically untrained listeners acquire effortlessly, or whether they have internalised music's regularities, but lack conscious awareness to it.

The current study sought to address this issue by probing melodic expectations using both an implicit and an explicit task. The implicit task employed an adaptation of the classic implicit priming paradigm which has been widely used as a measure of implicit knowledge across perceptual and cognitive domains (e.g. Mimura, Goodglass, & Milberg, 1996; Young, Hellawell, & DeHaan, 1988). In a musical context, the implicit priming paradigm involves manipulating the relationship between a 'prime context' and a 'target' so that the two vary in their musical congruity. The ability to form musical expectations is then studied by observing whether performance on an irrelevant task is influenced by the degree to which the prime context and target are musically related. In the previous literature, this irrelevant task has included making intonation judgments (e.g. Bharucha & Stoeckig, 1987; Bigand, Poulin, Tillmann, Madurell, & D'Adamo, 2003; Marmel, Tillmann, & Dowling, 2008), identifying phonemes in sung music (e.g. Bigand, Tillmann, Poulin, D'Adamo, & Madurell, 2001; Tillmann, Peretz, Bigand, & Gosselin, 2007), and indicating the timbre in which a target note or chord has been played (e.g. Marmel & Tillmann, 2008; Tillmann, Bigand, Escoffier, & Lalitte, 2006; Tillmann et al., 2007).

A large body of studies has demonstrated that a reliable facilitation effect may be observed for more versus less expected targets (especially those targets rendered in the same timbre as the preceding context in a timbre discrimination task, or consonant target chords following an in-tune context in an intonation judgment task) (Bharucha & Stoeckig, 1986, 1987; Bigand & Pineau, 1997; Marmel & Tillmann, 2008; Marmel, Tillmann, & Delbe, 2010; Tillmann, Bigand, & Pineau, 1998; Tillmann et al., 2006, 2007). This facilitation effect is typically measured in terms of reaction time although it may also be observed in performance accuracy (e.g. Bharucha & Stoeckig, 1986). Based on this robust phenomenon, the musical priming paradigm is commonly used to probe musical expectation formation and has convincingly demonstrated that listeners lacking in formal musical training nevertheless possess knowledge of musical structure (Bharucha & Stoeckig, 1986; Bigand & Pineau, 1997; Bigand et al., 2001; Margulis & Levine, 2006; Marmel & Tillmann, 2008; Marmel et al., 2008, 2010; Tillmann et al., 2006). In addition, the priming paradigm was also able to reveal spared musical knowledge in an acquired amusic individual I.R. (Tillmann et al., 2007). Tillmann et al. (2007) demonstrated that patient I.R. was unable to make subjective judgments regarding the extent to which target chords completed a chord progression, but nevertheless showed a processing advantage for targets that were more harmonically related to the context.

The majority of musical priming paradigms have involved harmonic manipulations, where chord progressions can be manipulated to influence the degree to which a subsequent chord is expected (e.g. Bharucha & Stoeckig, 1986, 1987; Bigand & Pineau, 1997; Tillmann et al., 2006, 2007). However, studies have also shown that expectations about the likelihood of occurrence of a single note can be manipulated, in both non-musical and musical contexts (Greenberg & Larkin, 1968; Hafter, Schlauch, & Tang, 1993; Howard, Otoole, Parasuraman, & Bennet, 1984; Lynch & Eilers, 1992; Margulis & Levine, 2006; Marmel & Tillmann, 2008; Marmel et al., 2008, 2010; Watson & Foyle, 1985). In a series of studies by Marmel et al. (2008, 2010), evidence for the influence of musical expectations on the processing of a subsequent pitch has been compellingly demonstrated. Listeners were shown to be facilitated in their processing of more expected versus less expected pitches given a preceding melodic context using both an intonation task (Marmel & Tillmann, 2008; Marmel et al., 2008) and a timbre discrimination task (Marmel & Tillmann, 2008; Marmel et al., 2010). Given the characterisation of amusia as a disorder of melodic perception and production, the current study asked whether individuals with this disorder would be able to use a melodic context to judge the extent to which a subsequent target pitch was expected.

To this end, we used two versions of a melodic priming paradigm to probe participants' abilities to form melodic expectations, in both an implicit and an explicit manner. In the implicit version, half of all target pitches in a set of melodies were altered from their original piano timbre to play in a deviant timbre (the marimba), and participants made speeded, forced-choice discriminations ('piano or marimba?') concerning the timbre of the cued target note. In the explicit version, participants used a 1–7 rating scale to indicate the degree to which the pitch of a cued target note was expected or unexpected. In both cases the expectedness/unexpectedness of cued target notes was defined objectively using a computational model of melodic expectation that yields an estimate of the likelihood of occurrence of a particular note, given the preceding melodic context (Pearce, 2005; Pearce & Wiggins, 2006). In contrast to previous accounts of melodic expectancy (e.g. Narmour, 1990; Schellenberg, 1997), where specified rules account for the order of tones in a melody, this model is based on information theory and statistical learning and suggests that listeners weigh the probability of different possible continuations to a musical excerpt based on the frequency with which different continuations have followed similar contexts in their previous experience.

For the purpose of this study, the model's specific predictions of the probability of a given note was based on both the scale degree of the given note relative to its notated key and the size and direction of the interval preceding it. It is important to emphasise, however, that the probabilities generated by the model for any given pitch interval or scale degree are learned and conditional on the preceding context (Pearce & Wiggins, 2006). In contrast to previous models which make local pitch predictions based on the preceding one or two notes (e.g. Schellenberg, 1997), this model makes its pitch predictions based on preceding melodic contexts of varying lengths and, importantly has been shown to outperform Schellenberg's two-factor model in predicting listeners' subjective expectations (Pearce & Wiggins, 2006; Pearce, Ruiz, Kapasi, Wiggins, & Bhattacharya, 2010). Results from multiple regression analyses revealed that the current model accounted for more variance in the ratings and response times of a group of typical listeners than the influential two-factor model of Schellenberg (1997) (78% of the variance in the ratings and 56% of the variance in the response times compared to approximately 56% and 33% respectively) (Pearce et al., 2010).

Our analysis of results in the implicit task concentrated mainly on cued events that were rendered in the same timbre as the piano context (piano), since previous studies (e.g. Marmel & Tillmann, 2008) reported that cued notes rendered in a deviant timbre failed to produce the predicted facilitation, owing to their timbral incongruence with the preceding melodic context. Further, following previous research, and based on previous reports that amusic individuals have subtle difficulties in the discrimination of timbre compared to controls (Marin, Gringas, & Stewart, 2012) we opted to use facilitation in terms of reaction time as our primary measure of melodic priming. Reaction time analysis is usually limited to those trials on which a correct discrimination response has been made and for this reason we employed a relatively easy timbre discrimination task with the goal of obtaining high levels of accuracy across both groups.

We predicted that, in the implicit task, typical listeners would show a facilitation for the discrimination of piano notes that were high versus low probability given the preceding melodic context and further that they would show a clear differentiation in their ratings for notes that were high versus low probability in the explicit task (Pearce et al., 2010). Further, we predicted that amusic participants' ratings in the explicit task would be less discriminating between the two target categories compared with controls, given the difficulty these individual face when required to detect melodic violations (Ayotte et al., 2002; Peretz et al., 2003). However we hypothesised that, as with acquired amusic, I.R. (Tillmann et al., 2007) amusic individuals may nevertheless show comparable performance to controls in the implicit task: a finding that would suggest that they have implicit musical expectations that do not always reach conscious awareness.

2. Experiment 1: implicit melodic expectation task

2.1. Materials and methods

2.1.1. Participants

A total of 24 participants (12 amusic, 12 control) took part. All participants were recruited via an online assessment based on the scale and rhythm subtest of the MBEA (Peretz et al., 2003) (www.delosis.com/listening/home.html). Each participant took the online test twice and those who consistently achieved a score of 22/30 or below were invited to come in to the laboratory where assessment could take place under controlled conditions. Four MBEA subtests (scale, contour, interval and rhythm subtests) were administered in a sound attenuated booth in order to confirm the presence or absence of amusia. Previous research had shown that amusia is characterised by poor perception in the pitch-based subtests of the MBEA (scale, contour, interval) while only half of them typically show a deficit in the rhythm test (Peretz et al., 2003). Thus we calculated a composite score for the three pitch-based subtests, using 65 as a cut off score (the sum of the published cut offs for each of these three subtests). Individuals were classified as amusic if their composite score fell below this value (Liu, Patel, Fourcin, & Stewart, 2010; Williamson et al., 2010). Table 1 provides background information on the two groups in terms of age, gender, number of years of formal education and number of years of musical education. Table 2 provides scores on the MBEA subtests and psychophysically measured pitch change detection and pitch direction discrimination thresholds that we include as an additional background measure (see Liu et al., 2010 for procedural details).

2.1.2. Stimuli

The melodies of 58 hymns, randomly selected and transcribed from a Church of England hymnal (Nicholson, Knight, Dykes, & Bower, 1950) were played in their original keys and rendered as MIDI files using the grand piano acoustic instrument of a Roland sound canvas (SC-88) MIDI synthesizer. In order to focus specifically on pitch expectations, the rhythmic structure of the melodies was removed in a musically sensitive manner by a skilled musicologist so that each note had the same duration and equivalent inter-onset interval of 700 ms. This note duration was chosen to give participants sufficient time to make their judgments and reorient to the ongoing melody. Although English hymnals do not usually contain tempo markings, the current IOI is within the normal range for this musical style. The melodies varied in length from 32 to 64 notes (47 melodies of 32 notes length, 9 melodies of 48 notes length and 2 melodies of 64 notes length). The average pitch across all melodies was 68.60 in MIDI number (~440 Hz) and there was a mean range within melodies of 11.83 semitones.

The probability of individual notes occurring at a given point in a given melody was objectively defined using a computational model of melodic expectation (Pearce & Wiggins, 2006). Through a process of unsupervised learning, the model generates estimates of the probabilities of known events occurring in a melody given the preceding context. The model is made up of two components: a long-term model exposed to the entire training set (a large corpus of western tonal melody) which simulates long term exposure to music, and a short-term model trained incrementally over each melody which simulates the formation of local expectations during online listening. In this study, the model derived its pitch predictions from a representation of the given note's scale degree, relative to the tonic of the notated key of the melody, as well as the size and direction of the interval preceding it.

In brief, each note in a melody is represented by this pair of values (pitch interval and scale degree), and the long and short-term models each generate estimates for the likelihood of each note, represented as such a pair, given the preceding sequence of notes. The predictions of the long and short-term models are combined to produce a single probability distribution, predicting the pitch of the next note.

Fig. 1 shows the musical notation of a sample melody used in the study along with a profile of the expectedness of all of the notes in the melody as defined by the computational model of melodic expectation. The expectedness of each note in the melody is expressed in units of *information content* (IC) instead of as probabilities as the size of the latter may be vanishingly small. In information theory, the IC (the negative logarithm, to the base 2, of the probability of an event occurring) is the lower bound on the number of bits required to encode an event in context (Mackay, 2003). IC may be thought of as the unexpectedness of a given note in context to the model.

Target notes in the current study comprised those notes in each melody to which participants were required to make a response. Such target notes were pinpointed that were either in the low or high range of the IC profile for each melody with constraints that: (i) selected notes were at least 7 notes after the melody had begun and 7 notes after the previously selected note, in order to allow a sufficiently clear context to be established before the participant had to make a response, and (ii) an equal number of each target-type (low, high probability) occurred at the beginning, middle and end sections of each melody. The number of targets in each melody varied depending on the length of the melody from 2 to 3 probes in 32 note melodies, to as many as 6 probes in the 64 note melodies. The number and position of the target notes in each melody were chosen to be as unpredictable

Table 1
Descriptive statistics and results of *t*-tests comparing amusic and control participant characteristics.

		Age	Gender	Yrs. of musical training	Yrs. of education
Amusic	Mean	53.67	10F	1.17	15
	SD	9.27	2M	3.16	2.22
Control	Mean	49.42	10F	1.94	15.67
	SD	13.83	2M	4.41	1.72
t-Tests	*t*	0.88		−0.49	−0.82
	p	0.39		0.63	0.42

Table 2
Descriptive statistics and results of *t*-tests comparing performance of amusic and control participants on subtests of the Montreal Battery of Evaluation of Amusia (MBEA) and psychophysically measured pitch thresholds. The maximum score possible on each subtest of the MBEA is 30 while the maximum possible pitch composite score (calculated by summing scores on the scale, contour and interval subtests) is 90. Individuals were classified as amusic if their pitch composite score fell below a cut off score of 65 (the sum of the published cut offs for each of these three subtests).

		MBEA scale	MBEA contour	MBEA interval	MBEA rhythm	Pitch composite	Detection[a] threshold	Direction[a] threshold
Amusic	Mean	18.67	20.58	18.58	24.5	58	0.19	1.23
	SD	2.53	3.03	2.27	4.36	5.83	0.09	1.38
Control	Mean	27.33	28.08	27.67	28.25	83.08	0.13	0.17
	SD	1.50	2.35	2.27	1.54	5.38	0.05	0.10
t-Tests	*t*	−10.2	−6.77	−9.79	−2.81	−11.02	2.10	2.65
	p	<0.001	<0.001	<0.001	0.01	<0.001	0.05	0.02

[a] Detection and direction thresholds: Note data is missing from one amusic and control participant in these tasks. Standard deviation and *t*-tests computed using average threshold (of respective groups) to replace missing data points.

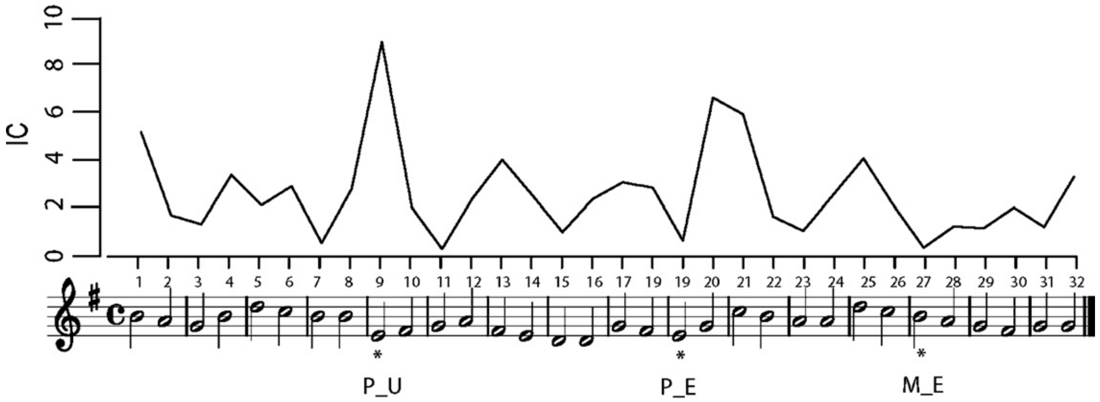

Fig. 1. The musical notation of a sample melody used in the study along with the information content profile of the melody as defined by the computational model of melodic expectation. Asterisks mark the target notes which were an ‘unexpected note’ rendered in piano, an ‘expected note’ rendered in piano and another ‘expected note’ rendered in marimba.

as possible. Fig. 2 shows the distribution of information contents of all the notes in the 58 hymns that were used in the implicit task and the bimodal distribution of the 82 high probability (IC: M = 1.08, SD = 0.45, range = 0.22–1.97) and 82 low probability (IC: M = 4.66, SD = 1.59, range = 2.46–9.39) target notes which differed significantly in their IC values ($p < 0.001$). In the western tonal system the stability of a pitch within a key is related to its position in the tonal hierarchy, and higher ranking/more stable pitches appear more frequently than lower ranking ones (Krumhansl, 1990). In line with this, tonal stability values computed using the empirical key profiles derived from the judgment of expert musicians (Krumhansl & Kessler, 1982), were higher for high than low probability notes (low: M = 4.37,

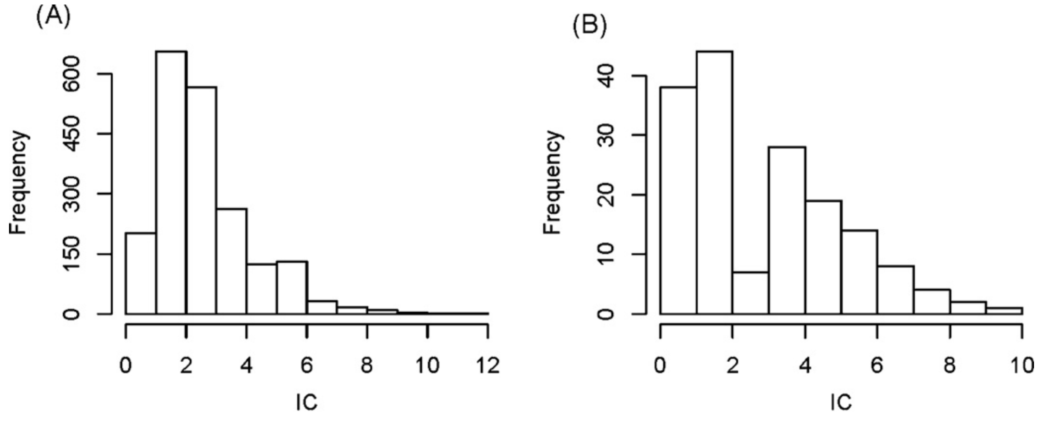

Fig. 2. The distribution of information contents (IC) for notes in the 56 hymns used in the implicit task (A) and the same for the 164 selected target notes alone (B). The bimodal distribution of the target notes reflects their selection from opposite ends of the IC distribution.

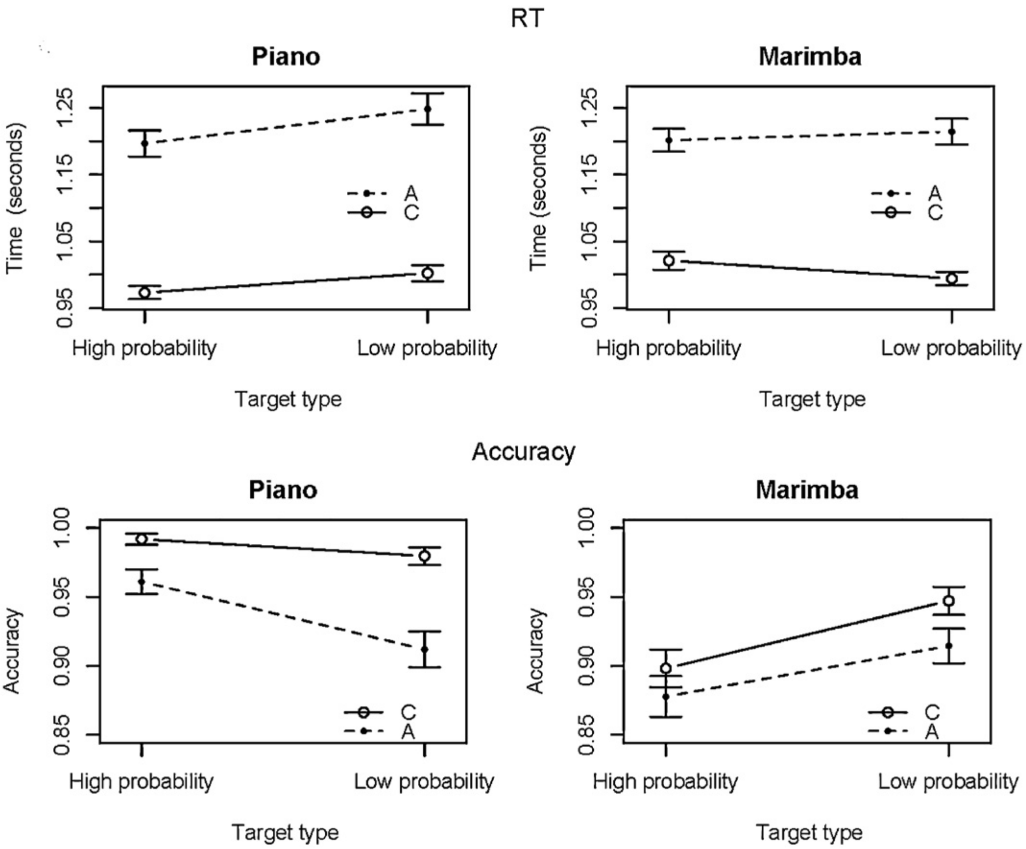

Fig. 3. Mean response times and accuracy in the implicit task presented as a function of target-type (high probability and low probability) and group (amusic and control) for piano and marimba target notes. C stands for controls and A stands for amusics. RT stands for response times.

SD = 1.20, range = 2.29–6.35, high: M = 5.00, SD = 1.06, range = 2.88–6.35, $p < 001$). Furthermore, consistent with previous reports that large interval sizes are relatively more rare in melodies (Huron, 2001), low probability notes tended to follow larger interval jumps than high probability ones (low: M = 4.03, SD = 2.58, range = 0–4, high: M = 1.44, SD = 0.8, range = 0–12, $p < 001$). Once selected, half of the high probability and low probability target notes were altered to a deviant marimba timbre using Anvil studio (Freeware MIDI sequencer), to create the required second timbre category for the timbral discrimination task. Speeded judgments were therefore made on four types of targets: high probability and low probability notes rendered in piano (constituting the main targets of interest) and high probability and low probability notes rendered in marimba (constituting the task foils).

2.1.3. Procedure

Participants gave written consent to participate and the study was approved by the Ethics Committee at Goldsmiths, University of London. All experiments were conducted in a sound-attenuated booth and controlled by a Java program running on a Dell laptop. Participants were asked to listen carefully to melodies presented over headphones (Sennheiser HD 202) while remaining vigilant for the appearance of a visual response cue. The cue comprised an analogue clock, the hand of which counted down to the target, in time with the melody, pointing in turn to the 3, 6, 9 and finally 12 O'Clock positions on the clock. The participants were instructed to respond to the auditory event whose onset time coincided with the hand of the clock returning to 12. In particular, participants were required to indicate whether the note heard was played in the piano timbre (same as previous notes) or in the marimba timbre. These responses were made using the 1 and 2 number keys on a laptop keyboard.

Participants were instructed to respond as quickly and as accurately as possible. Two practice trials were provided to familiarise them with the experimental set-up. Once participants were confident that they understood the task requirements, the testing phase, which took approximately 45 min to complete, commenced. This was comprised of 56 melodies, the order of which was randomised across participants. Since veridical memory representations of familiar stimuli, as well as generic expectations (based on one's acquired knowledge of melodic structure) can contribute to the formation of expectations (Bharucha, 1994), participants were required to indicate at the end of each melody whether the melody that they had just heard was familiar to them using a drop down menu at the bottom of the screen. This additional information could then be used a covariate in the subsequent analysis to control for any differences that may arise between levels of familiarity reported by the two groups.

2.2. Results

Based on previous melodic priming data (e.g. Marmel & Tillmann, 2008), facilitation in speed of response to those targets that were the same timbre as the prime context (the piano notes) was taken as evidence for the formation of pitch expectations. However for the sake of completeness, we also present data from targets rendered with the marimba tone. Also, following previous research (e.g. Bharucha & Stoeckig, 1986) additional analysis probing performance accuracy is reported.

Participants gave timbre discrimination responses for almost all trials (amusics: 99.5%, controls: 99.8%). Fig. 3 shows the accuracy with which amusics and controls made all responses as well as the length of time it took them to make correct responses, presented as a function of target-type (high probability, low probability) and timbre (piano, marimba). Table 3 presents descriptive statistics for the same measures sorted by target-type, timbre and group. An independent samples *t*-test indicated that amusic participants reported familiarity with a significantly fewer melodies than controls (amusics: 5.95%, controls: 19.05%, $t(1,22) = -3.12$, $p < 0.01$). For this reason, preliminary analyses were run to examine the influence of familiarity on accuracy and response times. Proportion of correct responses and correct response times (logarithmically transformed) were submitted to separate repeated measures ANCOVA models with group (amusic, control) as between-subjects factor, timbre (piano, marimba) and target-type (high probability, low probability) as within-subject factors, and familiarity as covariate. This analysis revealed no influence of familiarity on either of these measures either when all notes were considered (accuracy:

Table 3
Descriptive statistics of accuracy and response times in the implicit task presented as a function of target-type, timbre and group.

				High probability	Low probability
Accuracy	Amusic	Piano	Mean	0.96	0.91
			SD	0.19	0.28
		Marimba	Mean	0.88	0.91
			SD	0.33	0.28
	Control	Piano	Mean	0.99	0.98
			SD	0.09	0.14
		Marimba	Mean	0.90	0.95
			SD	0.30	0.22
RT (s)	Amusic	Piano	Mean	1.20	1.25
			SD	0.42	0.49
		Marimba	Mean	1.20	1.21
			SD	0.36	0.41
	Control	Piano	Mean	0.97	1.00
			SD	0.21	0.27
		Marimba	Mean	1.02	0.99
			SD	0.28	0.21

$p = 0.11$, speed: $p = 0.64$) or when only piano notes were considered (both $p > 0.1$). Thus, in order to increase the power of statistical analyses addressing the study's main hypotheses, familiarity was not included as a covariate in subsequent analyses.

2.2.1. *Response time*

Response times for accurate trials were logarithmically transformed and submitted to a 2 by 2 by 2 repeated measures ANOVA with group (amusic, control) as a between-subjects factor and timbre (piano, marimba) and target-type (high probability, low probability) as within-subject factors. The main effect of group was significant: $F(1,22) = 7.01$, $p < 0.05$, indicating that amusic participants were slower to respond than control participants. There was a tendency for participants to respond faster to high probability compared with low probability notes but the main effect of target-type failed to reach significance, $F(1,22) = 4.10$, $p = 0.06$. There were no other significant main effects or interactions (all $p > 0.05$) apart from a significant interaction between target-type and timbre: $F(1,22) = 5.6$, $p = 0.03$, which is investigated below.

Follow up 2 by 2 ANOVAs (factors: group, target-type) were run separately for trials where piano notes were the target and trials where marimba notes were the target. Starting with the ANOVA for trials where piano notes were the target, a main effect of group was observed, indicating that amusic participants responded more slowly than controls, $F(1,22) = 6.97$, $p = 0.02$. A main effect of target-type was also observed, indicating that participants responded more quickly to high probability than to low probability notes: $F(1,22) = 6.13$, $p = 0.02$. The absence of a significant interaction of group and target-type showed that this tendency was similar for both groups: $F(1,22) = 0.74$, $p = 0.40$, and this was supported by follow up *t*-tests which showed comparable *t* values in both groups (amusics: $t(11) = -1.84$, $p = 0.09$, controls: $t(11) = -1.94$, $p = 0.08$). The ANOVA pertaining to trials where marimba notes were the target revealed a main effect of group, reflecting the fact that amusics responded more slowly than controls: $F(1,22) = 5.99$, $p = 0.02$. There was no main effect of target-type but there was a significant interaction between target-type and group, $F(1,22) = 5.13$, $p = 0.03$. Paired *t*-tests revealed that while there was no difference in the speed with which amusic participants responded to high probability and low probability marimba notes, $t(11) = -1.10$, $p = 0.29$, controls responded faster to low probability than high probability marimba notes, $t(11) = 2.15$, $p = 0.05$.

2.2.2. *Accuracy*

The proportion of correct responses were submitted to a 2 by 2 by 2 repeated measures ANOVA with group (amusic, control) as a between-subjects factor and timbre (piano, marimba) and target-type (high probability, low probability) as within-subject factors. This resulted in a significant main effect of group, indicating that control participants were more accurate in their responses than amusics, $F(1,22) = 5.4$, $p = 0.03$. A significant main effect of timbre was also obtained, reflecting the fact that accuracy was higher for identification of notes rendered with piano rather than marimba tone, $F(1,22) = 48.76$, $p < 0.001$. Finally, there was a significant interaction between target-type and timbre, $F(1,22) = 27.86$, $p < 0.0001$.

To investigate the significant interaction between target-type and timbre further, follow up 2 by 2 ANOVAs (factors: group, target-type) were run separately for trials where piano notes were the target and trials where marimba notes were the target. Starting with the ANOVA for trials where piano notes were the target, a main effect of group was found indicating that amusics were less accurate than controls, $F(1,22) = 9.4$, $p < 0.01$, and a main effect of target-type showed that high probability notes were more accurately identified as piano notes compared with low probability ones, $F(1,22) = 5.37$, $p = 0.03$. The failure of the group × target-type interaction to reach significance suggested that both groups showed the same pattern of performance in terms of responding more accurately to high probability notes, $F(1,22) = 1.93$, $p = 0.18$, although follow up paired *t*-tests revealed that the significant effect of target-type in the main ANOVA was driven by the amusic group (amusic: $t(11) = 2.15$, $p = 0.05$, controls: $t(11) = 0.92$, $p = 0.38$)).

The ANOVA pertaining to trials where marimba notes were the target revealed a significant effect of target-type, reflecting the fact that high probability notes were less accurately identified as marimba notes compared with low probability ones, $F(1,22) = 17.2$, $p < 0.001$). There was no significant effect of group (paired *t*-tests confirmed the effect of probe-type was largely present in both groups (amusic: $t(11) = -2.05$, $p = 0.06$, controls: $t(11) = -4.71$, $p < 0.05$)) and no interaction between group and target-type.

2.3. *Discussion*

In Experiment 1, we investigated whether the response made to a target note in an implicit melodic priming task was influenced by the note's probability as estimated by a computational model of melodic expectation. Participants were required to make speeded timbral discriminations for notes that were high or low in terms of their probability, given the preceding melodic context. The precise points in the melody where a judgement was required were indicated to the participants using a visual cue as the melody unfolded. Faster processing time for highly probable notes presented in the same timbre as the context was taken as evidence of a melodic priming effect.

Results showed that amusics were generally slower and less accurate than controls in their timbre discrimination responses but, like controls, were facilitated in terms of response time for high probability relative to low probability piano notes. Additional analysis showed that amusic individuals were also, like controls, more accurate in identifying high probability notes.

With regard to the observed divergence in the patterns of responding to piano and marimba notes, our findings are similar to the results of other musical priming experiments which demonstrate that when the target of the irrelevant task maintains the same parameters as the context (for example an in-tune chord following an in-tune context, or a piano note following a piano context) the effects of the musical manipulation are clear in showing a facilitation effect for more expected events. In contrast, when the target deviates in some way (e.g., in tuning or timbre), processing accuracy and speed may show no facilitation effects (e.g. Tillmann et al., 2006, 2007) or even a reverse facilitation effect whereby processing of the unexpected event is quicker than that of the expected

(Bharucha & Stoeckig, 1986; Bigand & Pineau, 1997; Marmel & Tillmann, 2008; Tillmann et al., 1998).

In the current study, the controls showed a reverse facilitation effect whereby they responded more quickly to low than high probability notes. The reverse priming effect observed in intonation judgment tasks has been attributed to congruency effects similar to those found in linguistic priming tasks (Marmel & Tillmann, 2008; Tillmann et al., 2006), and in the context of a timbral discrimination task, to a disruption of the acoustical surface and subsequently of the context effect that permits normal expectancy formation (Marmel & Tillmann, 2008; Tillmann et al., 2006). Observing similar results to those seen in the current control sample, Marmel and Tillmann (2008) proposed that strategic biases may result when a target is perceived as discontinuous with the context, such that a target which is mismatched both in the timbre and pitch domain may actually become easier to identity.

It is therefore interesting to note that such a pop out effect, believed to be due to the segregation of the deviant timbre from the auditory stream (Bregman, 1990) was not observed in the amusic sample. The fact that target notes that were mismatched in terms of both pitch and timbre were not more salient for amusics is in line with their generally longer timbre discrimination response times and poorer performance accuracy. Nevertheless, based on the facilitation effects shown in terms of accuracy and response time, we suggest that the present results may be taken as indication that that amusic individuals are able to form melodic pitch expectations, at least when probed at an implicit level, in turn suggesting that they have assimilated regularities concerning melodic structure over a lifetime of incidental listening.

3. Experiment 2: explicit melodic expectation task

Experiment 1 showed an influence of melodic pitch expectations on both the accuracy and the speed with which amusic individuals made a speeded timbral discrimination judgement. Experiment 2 investigated the extent to which this evidence of intact implicit processing of pitch probability was accompanied by explicit awareness of melodic pitch expectations. In this experiment, participants gave explicit ratings regarding the expectedness of cued notes in the context of the preceding melody.

3.1. Materials and methods

3.1.1. Participants

The same 12 amusic and 12 control participants as in Experiment 1 took part in this experiment.

Table 4
Descriptive statistics of ratings given in the explicit task as a function of target-type and group.

		High probability	Low probability
Amusic	Mean	2.04	2.53
	SD	1.70	1.87
Control	Mean	1.96	3.22
	SD	1.16	1.77

3.1.2. Stimuli

32 hymns (27 melodies of 32 notes length, 4 melodies of 48 notes length and 1 melody of 64 notes length) were selected from the same Church of England hymnal and treated in the same way as melodies in Experiment 1 (rendered as MIDI files and altered so that each note had the same duration and equivalent inter-onset interval of 700 ms). These melodies were distinct from those used in Experiment 1 but were characterised by similar information content distributions. The average pitch across all melodies was 68.28 in MIDI number ($\sim$415.3 Hz) and there was a mean range within melodies of 11.98 semitones.

Target notes were selected to be as similar in IC range as those used in Experiment 1, whilst following the same constraints regarding relative distance between target notes and the positioning of the two types of target notes at both the beginning and end of the melodic stimuli. Fig. 4 shows the distribution of information contents for the 30 hymns used in the experimental phase and the bimodal distribution of the 43 high probability (IC: M = 1.18, SD = 0.42, range = 0.33–2.08) and 43 low probability (IC: M = 4.88, SD = 1.50, range = 2.40–9.76) notes selected to act as targets in the explicit task which differed significantly in their IC values ($p < 0.001$). As with those in the implicit task, low and high probability notes in this experiment differed significantly in tonal stability (low: M = 4.12, SD = 1.33, range = 2.33–6.35, high: M = 4.96, SD = 1.09, range = 2.88–6.35, $t = 6.61$, $p < 0.001$) and size of preceding intervals (low: M = 3.56, SD = 2.31, range = 0–12, high: M = 1.3, SD = 0.71, range = 0–2). Importantly, however, they did not differ in these respects from the corresponding stimulus categories used in experiment 1 (all $p > 0.05$).

3.1.3. Procedure

As in experiment 1, participants were cued to make a response using a visual cue (analogue clock countdown). Participants made rating judgments, on a scale of 1–7, indicating how expected they found the cued notes to be, where 1 was 'Very expected' and 7 was 'Very unexpected'. Participants were encouraged to make their responses using the whole rating scale. At the end of each melody, participants indicated whether the melody that they had just heard was familiar or not. Two practice trials were given to familiarise them with the task before the testing phase, lasting approximately 30 min, commenced.

3.2. Results

Participants made judgements on almost all trials (amusics: 98.7%, controls: 99.8%). Table 4 shows the mean and standard deviations of ratings given by each group to high probability and low probability notes and Fig. 5 presents mean ratings as a function of target-type. An independent samples t-test showed that there was no difference in the levels of familiarity reported by the two groups (amusics: 8%, controls: 14%, $t(1,22) = -1.03$,

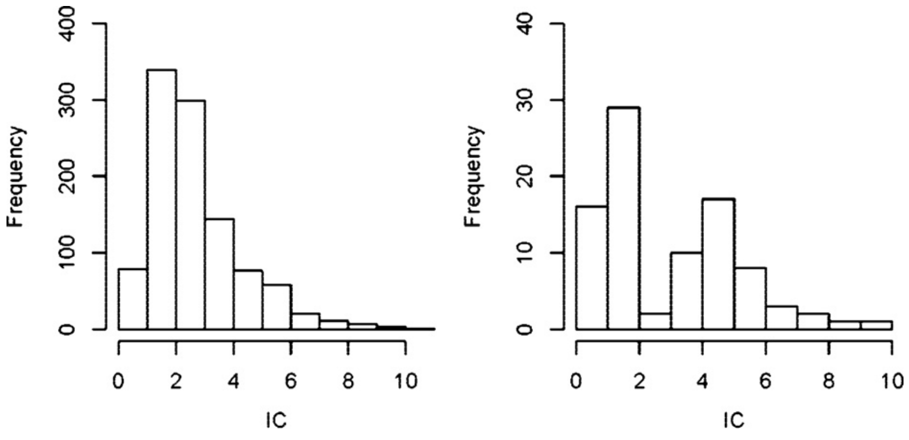

Fig. 4. The distribution of information contents for the notes in the 30 hymns used in the explicit task (A) and the same for the selected target notes alone (B). The bimodal distribution of the target notes reflects their selection from opposite ends of the distribution.

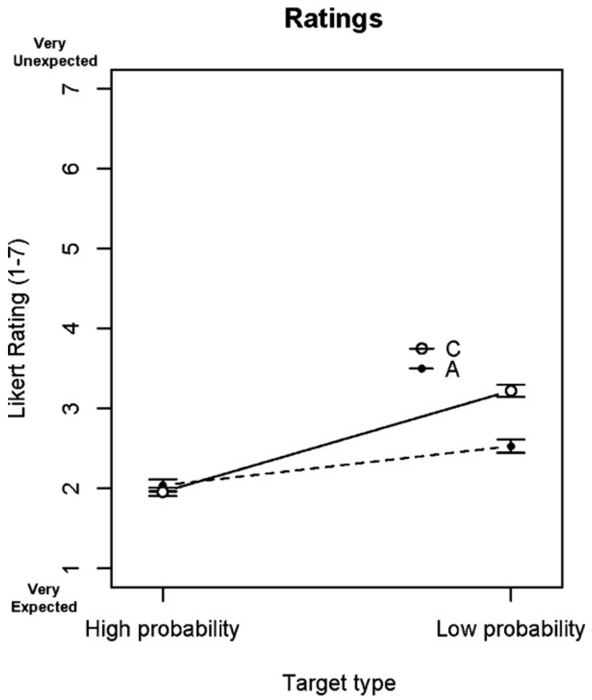

Fig. 5. Mean ratings presented as a function of target type for control and amusic groups. C stands for Controls and A stands for Amusics.

$p = 0.31$) and a repeated measures ANCOVA with group (amusic, controls) as a between-subjects factor, target-type (high probability, low probability) as within-subject factors and familiarity as covariate revealed that any within-group influence of familiarity on ratings was not significant ($p > 0.05$). Familiarity was therefore not included as a covariate in subsequent analyses.

Ratings were submitted to a 2 by 2 ANOVA with group as a between-subjects factor and target-type as a within-subjects factor. There was no effect of group: $F(1,22) = 0.48$, $p = 0.49$, indicating that there was no difference in the way the two groups used the scale, however a significant main effect of target-type was observed indicating that participants rated high probability notes as more expected than low probability ones, $F(1,22) = 61.72$, $p < 0.001$. There was also a significant interaction between group and target-type, $F(1,22) = 11.82$, $p < 0.01$. Further analysis was carried out to investigate the effect of target-type in each group separately. Paired t-tests revealed that although both groups rated high probability notes as more expected compared with low probability notes (amusics: $t(11) = -3.17$, $p < 0.01$; controls $t(11) = -7.86$, $p < 0.001$), this effect was stronger in controls than in amusics (effect sizes: controls: $r = 0.92$, amusics: $r = 0.69$).

A further question of interest was whether performance on the implicit and explicit tasks could be predicted by performance on the MBEA scale subtest, or psychophysically measured pitch thresholds. The former constitutes a measure of sensitivity to musical violations and may thus be predicted to correlate with the ability to form expectations, while the latter have been implicated as underlying the disordered musical perception that is seen in individuals with congenital amusia. The difference between accuracy for high and low probability piano notes, as well as the difference between response times to high and low probability piano notes, served as measures of the strength of implicit expectations. Similarly the difference between ratings to high and low probability notes served as a measure of the ability to make explicit responses regarding melodic structure. As individuals showed differences in average response time, timbre discrimination ability and also in the way the rating scale was used, values on each trial were individually normalized to z scores to focus on the individual difference in response across the two categories.

The only significant correlation found was between the pitch detection thresholds of the amusic sample and their accuracy on the explicit rating task ($r = -0.67$, $p = 0.02$). However further analysis revealed that this relationship was driven by a single amusic participant who gave higher unexpectedness ratings to high probability notes than to low probability notes and the effect did not hold when this individual was removed from the analysis ($p = 0.34$).

3.3. Discussion

Experiment 2 investigated the extent to which the explicit expectedness ratings of amusics and matched controls reflect the varying probability of pitches in the context of the preceding melody. As in the previous implicit task the precise points in each melody where a judgement was required were indicated using a visual cue, and were selected to be high or low in probability in the context of what had gone before. However, in contrast to the implicit task of Experiment 1 where only automatic processing was investigated, the current task assessed the ability of participants to consciously reflect on the perceived expectedness of target pitches given the melodic context.

Our analysis revealed that amusic participants were significantly worse than controls at this task. This is in contrast to the implicit task of experiment 1 where, even though amusics were slower and less accurate in discriminating target timbres, they showed equivalent facilitation compared with controls in terms of the speed which with which they responded to high versus low probability targets rendered in the piano timbre (as well as an effect of target type on performance accuracy).

The current findings demonstrate that a different pattern of performance may be seen, depending on whether melodic expectations are probed at an implicit or explicit level. Such a finding parallels the work of Tillmann et al. (2007) who showed similar results in a single acquired amusic individual. Patient I.R. showed a harmonic priming effect equivalent to matched controls in both a phoneme identification and timbre discrimination task but was deficient, relative to controls when required to explicitly judge how well a final chord completed a sequence of chords. Tillmann et al. (2007) suggested that this demonstrates preserved musical knowledge in I.R. despite her inability to report it.

However it is important to note that despite the impairment amusic individuals showed relative to controls in the explicit task, they were nevertheless able to distinguish between low and high probability notes using their ratings. In this regard they differ from patient I.R. (Tillmann et al., 2007), for whom completion judgments for related sequences did not significantly differ from completion judgments for less related sequences. The conscious processing of subtle variations in musical structure shown here by amusic individuals lies in stark contrast to their performance on the scale subtest of the MBEA where they fail to observe gross musical deviants in the form of out of key notes.

4. General discussion

An extensive experimental literature has shown that expectations influence the way we perceive events in our environment (Bubic et al., 2010). The act of listening to music involves not only hearing a series of sounds but also making predictions about future ones. For typical listeners, these predictions are formed on the basis of long-term schematic knowledge, gained over a lifetime of exposure to music (Tillmann et al., 2000). The present study investigated whether or not individuals with congenital amusia generate normal schematic pitch expectations implicitly, even if they are impaired in consciously reporting them. In doing so, it also provided a test of the extent to which formation of auditory predictions, depend on, or can dissociate from, conscious awareness.

With regard to methodology, the current study was unique in two ways. It was the first to use real melodies to investigate the formation of musical expectations in amusic individuals. It was also the first to assess these musical expectations in a dynamic manner. The current paradigm, which employed a visual cue that allowed participants to make responses without the melody being paused, represents a significant extension on existing musical priming paradigms that typically only assess musical expectations for final events (e.g. Bharucha & Stoeckig, 1986; Marmel & Tillmann, 2008). Such paradigms are necessarily limited in merely measuring listeners' perception of how a probed event 'closes' a musical sequence and empirical evidence suggests that expectations regarding closure differ from the expectations made as music unfolds (Aarden, 2003; Toiviainen & Krumhansl, 2003).

Implicit expectations have been shown to influence the speed and accuracy with which typical listeners process the acoustic properties of an incoming pitch (Lynch & Eilers, 1992; Margulis & Levine, 2006; Marmel et al., 2008, 2010; Marmel & Tillmann, 2008). While we anticipated that the amusic cohort would be impaired in their ability to explicitly report musical expectations given previously reported deficits; we hypothesised that their performance on an implicit task may nevertheless reveal the possession of intact expectations which are not fully available to conscious awareness (Tillmann et al., 2007). This original hypothesis was confirmed. Analysis revealed equivalent levels of facilitation between groups in terms of response time in the implicit task for high probability relative to low probability piano notes while performance in the explicit task revealed a significant difference between the two groups in terms of how they responded to contrasting target types.

A surprising finding, however, was that amusic individuals, while impaired relative to controls, nevertheless showed a relatively high level of competence in explicitly distinguishing between high and low probability notes. This is particularly striking given the subtle differences that exist between such notes in the natural melodies used in the current experiment. Considering that a previous study showed a complete lack of explicit musical knowledge in an acquired amusic individual (Tillmann et al., 2007), this suggests that those with the congenital form of the disorder are either less severely impaired than acquired patient I.R. and/or the phenomenology of the congenital versus the acquired form of amusia can differ. However, it is worth noting that expectations regarding closure differ from the expectations made as music unfolds (Aarden, 2003) and one possibility is that the judgments of completion task used in the study from Tillmann and colleagues tapped into different strategies from the current task. Yet another possibility is that harmonic expectations rely on distinct cognitive and neural substrates to melodic expectations (Koelsch & Jentschke, 2010). In any case, evidence of conscious processing of musical structure in congenitally amusic participants reveals a competence not previously observed in these individuals and suggests that the difference between congenitally amusic and typical individuals in terms of conscious access to musical knowledge may not be a purely categorical one.

Not withstanding the evidence of present, if diminished, conscious processing of musical structure in amusic individuals, the findings from the current study extends previous work showing that congenital amusia may be better characterised as a disorder of awareness rather than perception (Peretz, Brattico, Jarvenpaa, & Tervaniemi, 2009). A previous study by Peretz et al. (2009) used electrophysiological methods to examine the sensitivity of the amusic brain to *out-of-tune* and *out-of-key* notes in the context of a melody. These authors found an increased early negativity (termed the N200) for out-of-tune notes that the amusic sample had failed to report, leading the authors to suggest that amusic individuals may be able to process fine-grained pitch differences outside of conscious awareness (this same dissociation was not seen in response to out-of-key notes, leading the authors to suggest that amusic individuals lack knowledge of the tonal hierarchy). In contrast to the afore-mentioned study, which sought to determine whether those with amusia could detect out of tune or out of key deviants, the current study asked whether those with amusia could make a more subtle distinction, distinguishing between notes that were relatively likely versus unlikely to occur, given the preceding melodic context. Critically, the low probability notes were not inserted deviants, rather they were points within an existing melody which were identified by a computational model as relatively unexpected, given the preceding melodic context.

The conception of amusia as a disorder of awareness rather than perception has found support in previous observations of individuals with a developmental disorder known as *Tune Deafness*, which whilst diagnosed using a different diagnostic test to the MBEA may be related to congenital amusia (Braun et al., 2008). Braun et al. (2008) investigated the sensitivity of a cohort of tune deaf individuals to deviants in melodic sequences using electrophysiological methods and observed evidence of one intact electrophysiological index of deviance detection (the P300) in the absence of another (the Mismatch negativity or MMN). The authors proposed a patho-physiological account of the disorder whereby the former electrophysiological marker was taken as evidence of preserved implicit processing, while the absence of the latter was proposed to reflect the absence of conscious awareness of deviations in melodic structure. Importantly, while exact mechanisms remain to be established, the current findings suggest that amusia may be likened to other conditions such as aphasia, alexia and prosopagnosia, in which reports of a discrepancy between implicit and explicit processing have also been made (Avidan & Behrmann, 2008; McKeeff & Behrmann, 2004; Mimura et al., 1996; Young et al., 1988).

In demonstrating that amusic individuals are capable of forming both implicit and explicit pitch expectations, the current findings speak against the characterisation of amusia as a disorder of fine-grained pitch perception (see also Hyde, Zatorre, & Peretz, 2011; Moreau, Jolicoeur, & Peretz, 2009; Peretz et al., 2009), since, in order to perform as well as controls in the implicit task and to the extent they did in the explicit one, amusics must be able to discriminate pitch excursions of differing size. The findings reinforce the suggestion that the performance of amusic individuals on pitch-based tasks may be critically dependent on the way in which knowledge is probed (Liu et al., 2010; Omigie & Stewart, 2011).

Typical listeners learn about the statistical distribution of pitches and pitch intervals in music through incidental exposure in everyday life and we interpret the current findings as confirmation that individuals with congenital amusia have also internalised music's regularities. An alternative explanation is that the observed facilitation which amusics show for high probability events across both tasks (though to varying extents) may be accounted for by general cognitive and perceptual predispositions that are not specific to music processing (Thompson & Schellenberg, 2002; Trehub, 2000). Indeed it has been suggested that innately specified Gestalt principles of grouping might influence the formation of musical expectations without any need for musical enculturation (e.g. Narmour, 1990). According to this view, for example, the fact that pitches preceded by small intervals are more expected is a universal property of the auditory system. However, pitches preceded by small intervals are also more prevalent in music, so one can argue that advantages shown for processing proximate tones are simply a result of the frequency with which they occur in the environment. Indeed, it is very difficult to tease apart whether expectations arise from statistical learning or innate mechanisms and in fact, this has led Schellenberg, Adachi, Purdy, & McKinnon (2002, pg. 533) to suggest that the *effects of nature (a predisposition for gestalt principles) and nurture (exposure to stimuli following these principles) are perfectly confounded*.

In the current study, we supplied our model of statistical sequence learning with representations of scale degree (pitch relative to a tonic) and pitch interval. We used the model to select target types differing in their probability of occurrence, given the preceding context, at a given point in a melody. As a result, our two target types (high and low probability notes) differed in terms of both tonal stability and the size of the preceding interval, such that low probability events were, on average, tonally more unstable and more likely to be preceded by a large interval. While the comparable strength of facilitation shown by the amusic and control participants in the implicit task suggests the influence of both these measures (scale degree and pitch interval) in driving expectations across members of the two groups, such a claim cannot be made based on the current data and we suggest that further studies may seek to control for the effects of pitch interval in order to establish whether amusic individuals are as sensitive to tonal influences on expectation as controls.

In sum, the current study provides evidence that while individuals with amusia differ from controls in their ability to explicitly report musical expectations, they do nevertheless form normal musical expectations at an implicit level. This complements previous studies which demonstrate that amusic individuals are also able to learn about regularities in novel tonal materials in the context of a short-term incidental learning task (Omigie & Stewart, 2011).

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