Auditory imagery in congenital amusia

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Abstract

Congenital amusia is a neurogenetic disorder affecting various aspects of music and speech processing. Although perception and auditory imagery in the general population may share mechanisms, it is not known whether previously documented perceptual impairments in amusia are coupled with difficulties in imaging auditory objects. We employed the Bucknell Auditory Imagery Scale (BAIS) to assess participants' self-perceived voluntary imagery and a short earworm questionnaire to gauge their subjective experience of involuntary musical imagery. A total of 32 participants with amusia and 34 matched controls, recruited based on their performance on the Montreal Battery of Evaluation of Amusia (MBEA), filled out the questionnaires in their own time. The earworm scores of amusic participants were not statistically significantly different from those of controls. By contrast, their scores on vividness and control of auditory imagery were significantly lower relative to controls. Overall, results suggest that the presence of amusia may not have an adverse effect on generating involuntary musical imagery—at the level of self-report—but still significantly reduces the individual's self-rated voluntary imagery of musical, vocal, and environmental sounds. We discuss the findings in the light of previous research on explicit musical judgments and implicit engagement with music, while also touching on some statistical power considerations.

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Keywords
Bucknell Auditory Imagery Scale, music impairments, earworms, speech, music, environmental sounds

Auditory imagery refers to the generation of auditory objects in the absence of external stimulation (Moseley et al., 2018). Musical imagery can emerge in more or less sophisticated forms, with musically naïve listeners creating auditory imagery for familiar tunes (Halpern & Zatorre, 1999; Kraemer et al., 2005) and musically trained individuals often employing it for practice (Brodsky et al., 2003; Highben & Palmer, 2004) or other purposes (Gregg et al., 2008). In addition, musicians' self-rated imagery can be more vivid even for non-musical auditory objects (Talamini et al., 2022). Episodes of auditory imagery can also emerge involuntarily; they range from hallucinations, whereby the individual genuinely believes that there is an external auditory source (Johns et al., 2002; Saba & Keshavan, 1997), to repetitive instances of musical imagery known as *earworms*, which can be vividly experienced but are not perceived as products of external stimulation (Hemming & Altenmüller, 2012). Earworms are known to remain stuck in one's head in a loop, without allowing control over their recurrence (Beaman & Williams, 2010), but several self-help strategies can have an effect on displacing them (Beaman et al., 2015; Euser et al., 2016; Williamson et al., 2014). They have been also reported to be considerably more disturbing than visual, olfactory, gustatory, and other forms of imagery (Liikkanen, 2008), and to adversely affect quality and duration of sleep (Scullin et al., 2021). Even so, respondents to surveys of auditory imagery often say that they enjoy experiencing earworms (Halpern & Bartlett, 2011; Hyman et al., 2013) and this is especially the case among those who experience them more frequently (Müllensiefen et al., 2014).

To our knowledge, no previous studies have considered the experience of voluntary or involuntary auditory imagery in individuals with a diagnosis of congenital amusia. Congenital amusia (hereafter amusia) is a lifelong condition (Hyde et al., 2011; Patel, 2003; Tillmann et al., 2009) which occurs—by current estimates—in approximately 1.5% of the population and leads to deficits that cannot be traced back to brain injury or lack of environmental stimulation (Peretz & Hyde, 2003; Peretz & Vuvan, 2017). The disorder is diagnosed on the basis of performance on a standardized battery known as the Montreal Battery of Evaluation of Amusia (MBEA) (Peretz et al., 2003).

Conscious processing of music and speech has been studied thoroughly in this population, with pitch perception and often production impairments being documented across the two domains (Ayotte et al., 2002; Foxton et al., 2004; Jiang et al., 2010; Liu et al., 2010; Loui et al., 2008; Lu et al., 2015; Moreau et al., 2009; Nan et al., 2010). More recent evidence also points to difficulties associated with segmental phonological processing (Li et al., 2019; Liu et al., 2015; Sun et al., 2017; Zhang et al., 2017). Notwithstanding the perceptual impairments mentioned above, the results of studies using methods that target implicit processing have pointed to various spared abilities (e.g., Ayotte et al., 2002; Lévêque et al., 2018; Marin et al., 2015; Peretz et al., 2009; Tillmann et al., 2012; Tillmann, Lalitte, et al., 2016). Some such abilities include preserved sensitivity to tonality and harmony (Marin et al., 2015; Peretz et al., 2009; Tillmann et al., 2012; Tillmann, Lalitte, et al., 2016), emotional intensity in music (Lévêque et al., 2018), and melody familiarity (Ayotte et al., 2002; Tillmann et al., 2014). It thus appears that aspects of music processing that do not require explicit judgments can be intact in people with amusia (but see, for example, Zhou et al., 2019 suggesting otherwise). A similar facilitative effect of implicit testing has been also demonstrated for speech prosody

(Pralus et al., 2019). Overall, the use of tasks bypassing conscious awareness has contributed to a more thorough understanding of the disorder.

It remains to be determined whether amusia is associated with atypical experience of auditory imagery. Both self-report and experimental data suggest a link between weak voluntary mental imagery and poor singing ability (Greenspon et al., 2017; Pfordresher & Halpern, 2013). A relationship between singing and imagery has been also reported for involuntary musical imagery; better self-rated singing ability and a more frequent habit of singing along to music appear to be linked to longer earworms (Beaman, 2018; Müllensiefen et al., 2014). These findings, considered along with evidence showing impaired singing abilities in amusia (Ayotte et al., 2002; Dalla Bella et al., 2009; Liu et al., 2013; Loutrari et al., 2022; Tremblay-Champoux et al., 2010), lend support to the hypothesis that people with amusia may have an atypical experience of voluntary and involuntary imagery. It is of note that most people with amusia display a normal compensatory response to vocal feedback known as the pitch-shift reflex (Hutchins & Peretz, 2013). They also appear able to reproduce pitch contours correctly even when they cannot perceptually judge their direction (Loui et al., 2008). However, these spared areas of pitch production may not be of particular relevance to singing. While people with amusia can reproduce pitch contours, their imitation is imprecise (Loui et al., 2008). Also, the pitch-shift reflex is an automatic response to auditory feedback (Hutchins & Peretz, 2013), not comparable to the vocal production tasks used in the studies by Greenspon et al. (2017) and Pfordresher and Halpern (2013). Evidence also suggests that perception and auditory imagery have shared mechanisms (Kraemer et al., 2005; Vlek et al., 2011; Yoo et al., 2001; Zatorre et al., 1996), although it is of note that the complexity of the stimulus may affect the degree of overlap (Schaefer et al., 2013). By the same token, this relationship between perception of auditory object features and imagery suggests that people with amusia, who, as outlined earlier, have poor pitch perception, should report more limited voluntary imagery.

An analogous prediction could be made about earworms. The melodic structure of a song is one of the factors thought to determine whether it will be experienced as an earworm episode (Jakubowski et al., 2017). The poor pitch perception of people with amusia may translate into decreased sensitivity to melodic motives commonly considered catchy and, as a result, to fewer earworms. Furthermore, self-rated vividness of imagery is known to relate to working memory representations in neurotypical individuals, where less vivid voluntary imagery results from manipulations that interfere with the relevant working memory processes and storage (Baddeley & Andrade, 2000). In a similar vein, the experience of earworms seems to hinge on both auditory memory and long-term memory representations, with the elements that comprise an earworm (e.g., the melody) being both familiar and relatively short in duration (Beaman & Williams, 2010). People with amusia have preserved short-term memory for words (Tillmann et al., 2009), a normal digit span (Williamson & Stewart, 2010), intact memory recognition of voices and environmental sounds (Ayotte et al., 2002; Peretz et al., 2002), and perhaps preserved short-term memory for changes of loudness (Graves et al., 2019), but display short- and long-term memory deficits for musical material (Albouy et al., 2013; Gosselin et al., 2009; Graves et al., 2019; Marin et al., 2012; Tillmann et al., 2009; Tillmann, Lévêque, et al., 2016; Williamson & Stewart, 2010). In addition, although it may not be musicianship in itself that results in differences in earworm scores (Beaman & Williams, 2010; Floridou et al., 2012), more frequent and longer earworms have been associated with music training in some studies (Beaty et al., 2013; Hyman et al., 2013; Moeck et al., 2018). Hence, all things considered, people with amusia might be expected to report less vivid musical imagery and fewer earworms, but typical imagery of voices and environmental sounds.

However, in counterpoint to a hypothesis of impaired imagery in people with amusia is the finding that pitch discrimination ability does not seem to be associated with self-reported imagery (Pfordresher & Halpern, 2013), which suggests that impaired pitch discrimination ability does not necessarily imply poor imagery. Put differently, people with amusia could still report typical imagery despite their difficulties with pitch discrimination. Furthermore, imagery does not solely consist of pitch. In addition to melodic contours, musical timbre can also be imagined (Crowder, 1989; Halpern et al., 2004; Pitt & Crowder, 1992). People with amusia have intact timbre discrimination ability (Marin et al., 2012) and can rely on timbre to judge emotion in music, in conjunction with temporal features of the music (Gosselin et al., 2015), but see Marin et al. (2012) on compromised short-term memory for timbre in people with amusia.

As another example of non-pitch-related imagery, this time of the involuntary kind, it has been shown that, under experimental conditions, the presence of lyrics can result in earworm experiences (Floridou et al., 2012; Liikkanen, 2009), and it could be that people with amusia experience earworms triggered by verbal material regardless of how they encode melodic and rhythmic patterns. Another strand of research with potential relevance to musical imagery is that of everyday engagement with music. Participants with amusia in McDonald and Stewart (2008)'s research self-reported more limited music appreciation in comparison to neurotypical individuals, although cases of typical engagement with music also appeared in their amusic sample. Cluster analysis in a diary study by Omigie et al. (2012) including questions on music appreciation, listening motivation, effect on mood and context of music listening showed that, although more than half of the amusic participants and a minority of controls displayed an atypical profile, a relatively large proportion of amusic participants had a profile similar to the majority of controls. In another study, no significant differences were found between a group of individuals with amusia and matched controls in terms of liking and aversion to music (Marin et al., 2012). Finally, more recent studies, partly based on questionnaires used in previous research, found that, on average, amusic respondents reported typical emotional experiences in relation to music in everyday life (Gosselin et al., 2015; Lévêque et al., 2018). Taken together, these findings imply that conscious music perception, as assessed by the MBEA, may not necessarily be a prerequisite for meaningful engagement with music; in turn, everyday engagement with music could be expected to pave the way for normal musical imagery formation.

In summary, voluntary auditory imagery and perception seem to share partly overlapping mechanisms (Kraemer et al., 2005; Yoo et al., 2001; Zatorre et al., 1996). Poorer voluntary imagery has been associated with worse pitch production ability (Greenspon et al., 2017; Pfordresher & Halpern, 2013), and the vividness of imagery may be reduced due to interference with working memory (Baddeley & Andrade, 2000). Apart from pitch, timbre can be also imagined voluntarily (Crowder, 1989; Halpern et al., 2004; Pitt & Crowder, 1992). As for earworms, an involuntary form of musical imagery, it has been reported that music training and better self-rated singing ability are associated with more frequent and/or longer episodes (Müllensiefen et al., 2014). As reviewed above, the melodic structure of a tune (Jakubowski et al., 2017) and its lyrics (Floridou et al., 2012; Liikkanen, 2009) can also lead to earworms. Finally, the occurrence of earworm episodes also seems to depend on short- and long-term memory representations (Beaman & Williams, 2010). Hence, two contradictory hypotheses can be formulated regarding both voluntary and involuntary auditory imagery in amusia: first, people with amusia will experience atypical engagement with imagery due to their poor pitch perception, degraded memory for pitch, and difficulties with pitch production; second, they may self-report typical imagery due to their intact abilities including timbre discrimination, music emotion intensity perception, and often typical engagement with music. The lack of a significant correlation between self-reported imagery vividness and pitch discrimination ability lends some weight to the second hypothesis in the case of voluntary imagery, although this is only negative evidence.

To address the above hypotheses, we employed three self-report measures: a short earworm questionnaire (Beaman & Williams, 2013) and the Bucknell Auditory Imagery Scale (BAIS; Halpern, 2015), comprising two subscales measuring vividness (BAIS-V) and control of imagery (BAIS-C). The BAIS-C captures a more dynamic form of auditory imagery relative to the BAIS-V, but the two are correlated (Halpern, 2015), which affords the opportunity to also determine whether the same trend is borne out in people with amusia.

Methods

Participants

A total of 66 Mandarin-speaking participants (32 with amusia and 34 matched controls) were recruited through advertisements in the bulletin board systems of universities in Shanghai, China. Amusia was diagnosed using the Montreal Battery of Evaluation of Amusia (MBEA) (Peretz et al., 2003), based on the cut-off scores of 65 on the pitch composite score (Liu et al., 2010), 78% correct on the global score (Peretz et al., 2003), and 1.23 using *d'* (Henry & McAuley, 2013; Pfeifer & Hamann, 2015). Table 1 summarizes participants' demographic data and MBEA results. None of the participants reported having speech or hearing problems, or neurological or psychiatric disorders. None received extracurricular musical training. Participants' hand dominance was assessed by the Edinburgh Handedness Inventory (Oldfield, 1971). Ethical approval was obtained from the research ethics committees at the University of Reading and Shanghai Normal University. Written informed consent was given by all participants prior to the commencement of the study.

Materials

For voluntary auditory imagery, we employed the Bucknell Auditory Imagery Scale (BAIS; Halpern, 2015), consisting of two components: Vividness (BAIS-V) and Control (BAIS-C). BAIS-V comprises 14 questions requiring participants to rate the vividness of auditory images on a Likert-type scale. A rating of 1 corresponds to a complete absence of imagery, while 4 corresponds to a relatively vivid image, and 7 to a degree of vividness reminiscent of the actual sound. Items on this scale can be musical (e.g., a trumpet beginning a piece), vocal (e.g., the voice of a teacher), environmental (e.g., waves crashing against rocks), or a combination of different sounds (e.g., imagining driving a car while listening to a rock song). BAIS-C also includes 14 items, again using a 7-point scale, and requires respondents to mentally control a transition to a new sound. For example, respondents have to self-assess their ability to mentally control a change in timbre (e.g., the sound of a trumpet is heard but then a violin carries the tune). As in BAIS-V, combinations are included. For instance, participants are asked to imagine the sound of a car radio song being masked by the sound of the car grinding to a halt. A rating of 1 corresponds to a total absence of imagery, while a rating of 4 implies that the individual can imagine the change, albeit with some effort, and a rating of 7 suggests that the change is extremely easy to imagine. The total score per type of sound (musical, vocal, environmental) corresponded to the sum of ratings divided by the number of items.

A condensed version (Beaman & Williams, 2013) of an earlier earworms questionnaire (Beaman & Williams, 2010) was used to assess participants' involuntary imagery experience.

Table 1. Characteristics of participants with amusia and controls.

Participant characteristics	Amusic participants	Controls	t	p
Gender	23F, 9M	26F, 8M	N/A	N/A
Handedness	2L, 30R	0L, 34R	N/A	N/A
Age	22.81 (2.01)	22.00 (2.22)	1.56	.12
Education (in years)	16.25 (1.46)	16.50 (1.02)	0.80	.42
MBEA scale	18.13 (2.21)	27.68 (1.72)	19.51	<.001
MBEA contour	19.94 (3.54)	27.91 (1.82)	11.41	<.001
MBEA interval	16.94 (1.64)	27.26 (1.69)	25.13	<.001
MBEA rhythm	22.03 (3.55)	28.06 (1.70)	8.70	<.001
MBEA meter	19.19 (4.07)	26.29 (3.43)	7.64	<.001
MBEA memory	22.16 (3.49)	28.44 (1.65)	9.24	<.001
MBEA pitch composite	55.00 (3.88)	82.85 (3.40)	30.93	<.001
MBEA global	65.76 (4.95)	91.94 (3.23)	25.27	<.001

F: female; M: male; L: left; R: right; MBEA: Montreal Battery of Evaluation of Amusia (Peretz et al., 2003).
Note: The second and third columns from the left report on mean MBEA scores, with SDs in round brackets. The pitch composite score refers to the sum of the first three MBEA subtests and the MBEA global score is the average percentage of correct responses across all subtests. Two-tailed two-sample Welch's *t*- tests were conducted to compare the two groups.

Questions here touch on earworm frequency and duration, effects on behavior, possible interference with everyday activities and ability to displace earworms. This questionnaire includes a combination of numerical answers and alphabetical options. Alphabetical options are scored in an ordinal manner (that is, A corresponds to 1, B to 2, etc.), but the reverse pattern holds for the last question (A is scored as 5, B as 4, etc.). There are also two items to be rated on a 7-point scale. The total earworm score was the sum of all items. A higher score indicated a greater effect of earworms on the individual's everyday life. For more details about the questionnaires, please see Supplementary Materials.

Procedure and data analysis

The two questionnaires were made available on the survey platform JISC and participants completed them in their own time and without supervision.

Statistical analyses were conducted using R (R Core Team, 2019; version 4.0.3). Linear mixed effects models with type of sound and group as fixed effects and participant ID as a random effect were fitted to the BAIS-V and BAIS-C data using R. Model assumptions were tested through residual and normal probability plots. The lmerTest (Kuznetsova et al., 2017) and lme4 (Bates et al., 2015) packages were employed for significance testing and the *emmeans* package with Holm's correction for multiple comparisons was used for post-hoc tests (Lenth, 2019). For the earworm data, a two-tailed independent samples *t*-test was run using the *t*-test command in R. The tab_corr function of the sjPlot package (Lüdecke, 2021) was used to generate correlation matrices.

Using the powerSim function of the simr package (Green & Macleod, 2016), it was estimated that for each mixed model with a group × type of sound interaction including averaged observations for the three types of sound, a total sample of $N = 66$ would correspond to a slope difference (effect size of the interaction) of .45, reaching a power of 70%, $\alpha = .05$, based on 1,000

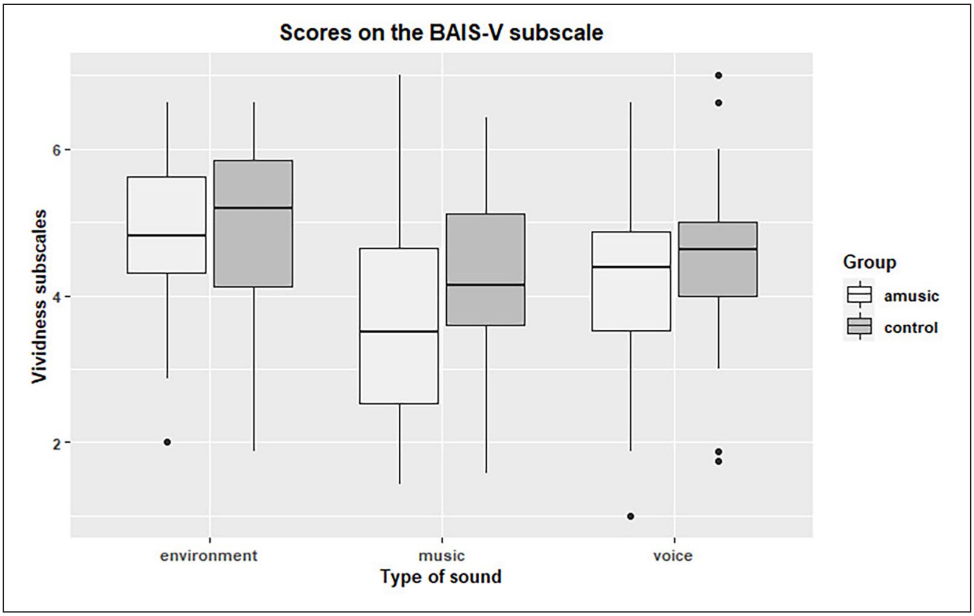

Figure 1. Participants' scores on BAIS-V broken down by type of sound and group. The thick horizontal lines represent median values; black dots represent outliers. Higher scores imply more vivid imagery, with the maximum obtainable score per type of sound being 7.

simulations. Using the pwr package (Champely, 2007) in R, the total sample size required for a two-tailed independent samples *t*-test for earworm scores was found to be $N = 60$ in order to detect an effect size of $d = .65$, power = .70, $\alpha = .05$. We selected these parameter values to achieve an acceptable, if suboptimal, level of power because of the low prevalence of amusia and the realistic constraints of recruiting participants with amusia in large numbers.

Results

BAIS-V scores

The analysis detected a significant main effect of group, $F(1, 191.99) = 13.83$, $p < .001$, $\eta_p^2 = .07$, with the control group reporting more vivid imagery than amusic participants, and type of sound, $F(2, 132.57) = 47.49$, $p < .001$, $\eta_p^2 = .42$. Post hoc pairwise comparisons with Holm's correction showed that both groups of participants reported higher vividness scores for environmental sounds in comparison to music, $t(133) = 9.70$, $p < .001$, $d = .84$, and voice, $t(133) = 5.60$, $p < .001$, $d = .48$, sounds. Voice-related items were reported to be more vivid than music-related items, $t(133) = 4.11$, $p < .001$, $d = .35$. No significant interaction was observed between group and type of sound, $F(2, 132.57) = 1.19$, $p = .30$, $\eta_p^2 = .02$. Boxplots broken down by group and type of sound are presented in Figure 1.

BAIS-C scores

Again, the model detected a main effect of group, $F(1, 191.92) = 8.21$, $p = .004$, $\eta_p^2 = .04$, with controls reporting having better control over imagery albeit with a small effect size, and type of

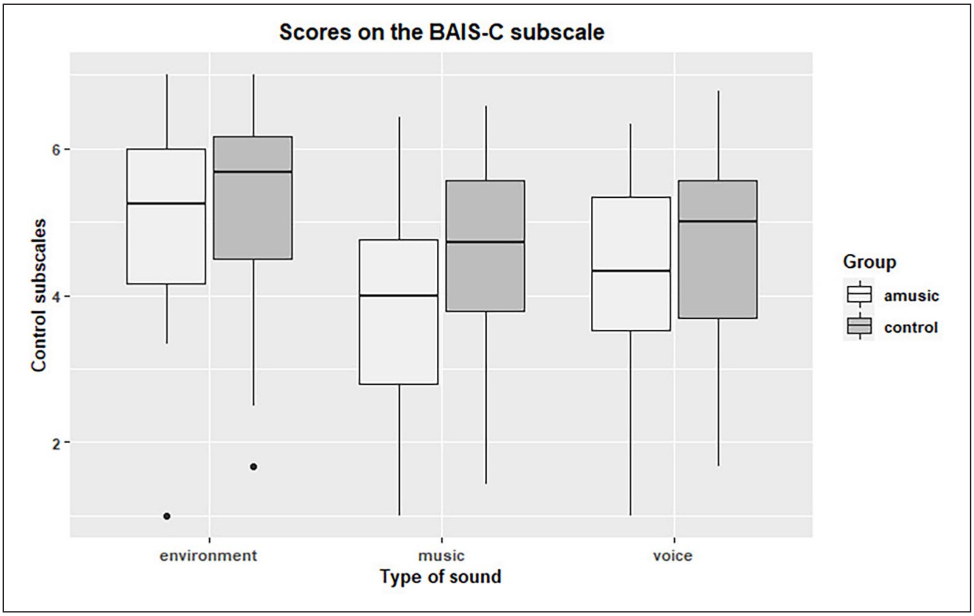

Figure 2. Scores on BAIS-C across amusic participants and controls. The thick horizontal lines represent median values; black dots represent outliers. Higher scores indicate better mental control of imagery, with the maximum obtainable score per type of sound being 7.

sound, $F(2, 132.82) = 37.05$, $p < .001$, $\eta_p^2 = .35$. Post hoc pairwise comparisons with Holm's correction revealed higher self-reported scores for environment versus music, $t(133) = 8.41$, $p < .001$, $d = .72$, and voice, $t(133) = 5.77$, $p < .001$, $d = .50$, sounds. Control over voice-related items was better than music items, $t(133) = 2.63$, $p = .02$, $d = .22$. No significant group × type of sound interaction was seen, $F(2, 132.82) = 2.07$, $p = .13$, $\eta_p^2 = .03$. The results are shown in Figure 2.

Earworms

A two-tailed independent samples *t*-test was run to compare earworm scores obtained from the two groups. No significant difference was detected between groups, $t(64) = 1.60$, $p = .11$, $d = .40$. The results are shown in Figure 3.

Correlations

Correlations were computed across measures using Holm's correction for multiple comparisons. MBEA scores and pitch composite scores (the sum of scale, contour, and interval subtests) did not correlate with either voluntary or involuntary imagery in controls, but an intercorrelation between BAIS-V and BAIS-C was observed ($r = .76$, $p < .001$).

MBEA scores did not significantly correlate with voluntary imagery in participants with amusia, but an intercorrelation between BAIS-V and BAIS-C was observed ($r = .81$, $p < .001$). These intercorrelation coefficients were not themselves significantly different between the groups (Fisher's *r*-to-*z* = .50, $p = .30$), suggesting that the relationships between the voluntary vividness and control of auditory imagery were similar across the two groups.

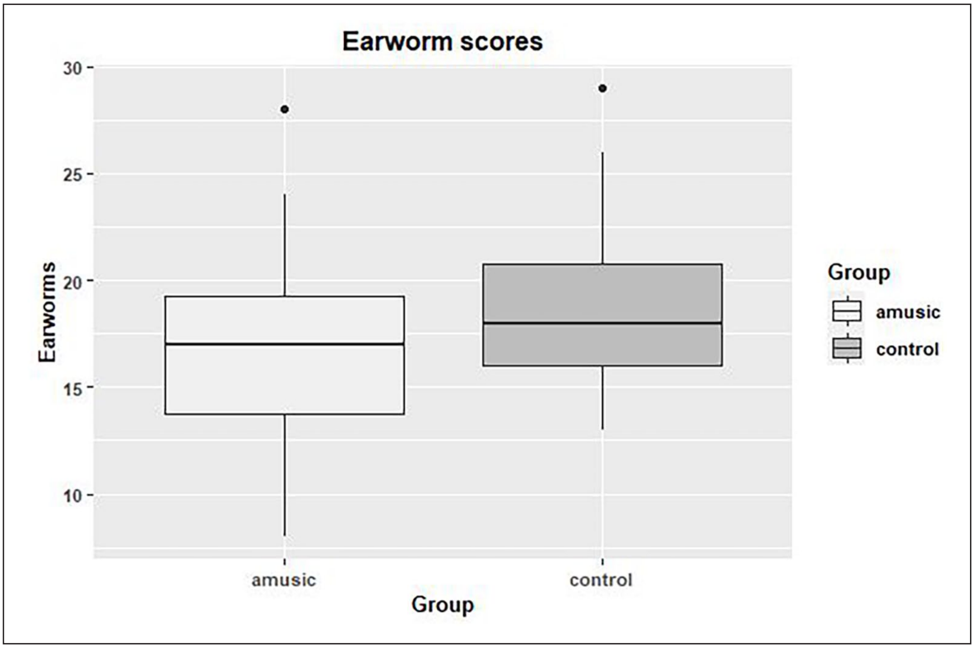

Figure 3. Self-reported earworm scores for amusic participants and controls. The horizontal lines in each box represent median values; black dots represent outliers. Higher scores indicate a larger effect of earworms on participants' everyday life, with the maximum obtainable score being 37.

Self-reported scores from the earworm questionnaire correlated with the scores of participants with amusia on MBEA global ($r = .62$, $p < .001$). The correlation coefficient between earworms and MBEA global was significantly different between amusic participants and controls (Fisher's r-to-$z = 2.55$, $p = .01$). The results are presented in more detail in Tables 2 and 3.

Discussion

This study set out to explore whether individuals with congenital amusia experience voluntary and involuntary imagery differently from neurotypical controls. This is, to the best of our knowledge, the first investigation of auditory imagery in this population. Group differences emerged when voluntary auditory imagery—including musical imagery—was considered; the scores of amusic participants were found to be significantly lower for vividness (BAIS-V) and mental control of imagery (BAIS-C) than those of controls. An intercorrelation between the two imagery subscales was observed not only in controls, in line with a previously established trend (Halpern, 2015), but also in amusic participants, pointing to an association between imagining vivid sounds and exerting mental control over sound transitions in both samples. Results showed that self-reported earworm ratings in amusic participants did not differ significantly from controls but, as discussed at the end of this section, this result should be interpreted with caution due to possibly insufficient power. A significant correlation between earworms and MBEA global was seen in the amusic sample but not in the control group. This may reflect less variability in the MBEA global scores among the control group than among the participants with amusia.

Table 2. Pearson correlations for amusic participants' performance across measures with Holm's correction for multiple comparisons.

	Scale	Contour	Interval	Rhythm	Meter	Memory	Pitch composite	MBEA global	BAIS-V	BAIS-C	Earworms
Scale											
Contour	–.33 (1.00)										
Interval	.05 (1.00)	–.01 (1.00)									
Rhythm	–.46 (.32)	.33 (1.00)	.11 (1.00)								
Meter	.004 (1.00)	–.11 (1.00)	–.11 (1.00)	.16 (1.00)							
Memory	.07 (1.00)	.29 (1.00)	.03 (1.00)	.25 (1.00)	.19 (1.00)						
Pitch Composite	.28 (1.00)	.71** (<.001)	.44 (.54)	.08 (1.00)	–.14 (1.00)	.32 (1.00)					
MBEA Global	–.03 (1.00)	.50 (.144)	.20 (1.00)	.61* (.01)	.53 (.10)	.72** (<.001)	.53 (.10)				
BAIS-V	.17 (1.00)	.09 (1.00)	–.20 (1.00)	–.08 (1.00)	.11 (1.00)	.02 (1.00)	.09 (1.00)	.06 (1.00)			
BAIS-C	.26 (1.00)	–.10 (1.00)	–.15 (1.00)	–.04 (1.00)	.07 (1.00)	.21 (1.00)	–.01 (1.00)	.09 (1.00)	.81** (<.001)		
Earworms	.12 (1.00)	.31 (1.00)	.02 (1.00)	.35 (1.00)	.29 (1.00)	.49 (.188)	.36 (1.00)	.62* (.005)	.17 (1.00)	.18 (1.00)	

MBEA: Montreal Battery of Evaluation of Amusia; BAIS-V: Bucknell Auditory Imagery Scale-Vividness; BAIS-C: Bucknell Auditory Imagery Scale-Control.
Note: The only perception-imagery correlation that remained significant after correction was that between earworms and MBEA Global. The intercorrelation between BAIS-V and BAIS-C also remained significant.
$^*p \leq .01$, $^{**}p \leq .001$.

Table 3. Pearson correlations for controls' performance across measures with Holm's correction for multiple comparisons.

	Scale	Contour	Interval	Rhythm	Meter	Memory	Pitch composite	MBEA global	BAIS-V	BAIS-C	Earworms
Scale											
Contour	–.05 (1.00)										
Interval	.27 (1.00)	.17 (1.00)									
Rhythm	–.02 (1.00)	–.10 (1.00)	.06 (1.00)								
Meter	.32 (1.00)	–.06 (1.00)	.27 (1.00)	.04 (1.00)							
Memory	–.12 (1.00)	–.28 (1.00)	–.14 (1.00)	.23 (1.00)	.05 (1.00)						
Pitch Composite	.61* (.006)	.58* (.01)	.74** (<.001)	–.03 (1.00)	.26 (1.00)	–.28 (1.00)					
MBEA Global	.45 (.33)	.30 (1.00)	.50 (.09)	.23 (1.00)	.68** (<.001)	.25 (1.00)	.64** (.001)				
BAIS-V	.05 (1.00)	.18 (1.00)	.01 (1.00)	.19 (1.00)	.15 (1.00)	–.23 (1.00)	.12 (1.00)	.10 (1.00)			
BAIS-C	.24 (1.00)	–.006 (1.00)	.15 (1.00)	.11 (1.00)	.20 (1.00)	–.30 (1.00)	.19 (1.00)	.06 (1.00)	.76** (<.001)		
Earworms	–.14 (1.00)	.18 (1.00)	–.12 (1.00)	–.10 (1.00)	.21 (1.00)	–.08 (1.00)	–.03 (1.00)	.07 (1.00)	.31 (1.00)	.13 (1.00)	

MBEA: Montreal Battery of Evaluation of Amusia; BAIS-V: Bucknell Auditory Imagery Scale-Vividness; BAIS-C: Bucknell Auditory Imagery Scale-Control.
Note: Controls' music perception scores did not correlate with any type of imagery. A significant correlation was observed between BAIS-V and BAIS-C.
$*p \leq .01$, $**p \leq .001$.

The self-reported ability of amusic participants to generate earworms, as seen in this study, may be the result of alternative forms of learning and engaging with music. Previous data indicate that some people with amusia (Loutrari & Lorch, 2017; McDonald & Stewart, 2008; Omigie et al., 2012), if not the majority of them (Gosselin et al., 2015; Lévêque et al., 2018; Marin et al., 2012), can engage with music meaningfully in alternative ways. It may be that the earworm experience taps into implicit forms of learning acquired through everyday exposure to music. Nonetheless, open questions remain as to why amusic participants' less efficient music memory and poor pitch perception do not appear to have had a major impact on their experience of earworms. People with amusia report difficulties in recognizing familiar tunes (Ayotte et al., 2002), and recent evidence suggests that they do not store melodies in long-term memory as efficiently as controls (Graves et al., 2019). It is also surprising that less efficient auditory imagery control scores do not result in more frequent or more intrusive self-reports of earworms. Weaker long-term memory traces for music may be the result of short-term music memory difficulties also present in amusia (Albouy et al., 2013; Gosselin et al., 2009; Marin et al., 2012; Tillmann et al., 2009; Tillmann, Lévêque, et al., 2016; Williamson & Stewart, 2010), or perceptual impairments (Jiang et al., 2013). Regardless of the origin of these memory impairments, since forming earworms is believed to draw on auditory memory and long-term memory mechanisms (Beaman, 2018; Beaman & Williams, 2010), one would expect the degraded long-term memory for tunes of people with amusia to lead to considerably fewer occurrences of earworms. Also, considering that certain melodic patterns in music appear to give rise to earworms (Jakubowski et al., 2017), one would expect reduced sensitivity to melodic structure to be coupled with difficulty to generate earworms. Finally, earworm frequency is known to correlate with various aspects of musical behavior, such as music practice (Floridou et al., 2015; Liikkanen, 2012) and music training (Beaty et al., 2013; Hyman et al., 2013; Moeck et al., 2018). As these characteristics are not typically associated with amusia, the reasons behind the present results are not conclusive.

A few possible explanations hold for the earworm findings. Firstly, there is evidence that people with amusia are able to form long-term music memory traces (Tillmann et al., 2014), which in turn seem to help them imitate familiar song segments better than novel ones (Loutrari et al., 2022). Even if their long-term memory for music is not comparable to that of controls (Graves et al., 2019), it may be good enough to be conducive to some form of earworm experience. Secondly, given that earworms can be triggered by lyrics (Floridou et al., 2012; Liikkanen, 2009), it could be that they are initiated more frequently by verbal material in the amusic brain. Thirdly, as our results are based on self-reports rather than experimental gauging of imagery, it may be that pitch or rhythmic sequences may be reactivated as earworms even if they are originally encoded in a degraded form. To address these outstanding questions, more research on amusia and the nature of the earworm experience *per se* is needed.

The significantly lower scores of amusic participants on BAIS-V and BAIS-C seem to be more aligned with their profile, at least in terms of the musical component of the subscales. Perceiving and imaging an auditory stimulus are believed to rely on shared processing mechanisms (Kraemer et al., 2005; Vlek et al., 2011; Yoo et al., 2001; Zatorre et al., 1996), and a large body of literature points to pitch perception and production impairments in amusia (Ayotte et al., 2002; Dalla Bella et al., 2009; Foxton et al., 2004; Jiang et al., 2010; Liu et al., 2010, 2013; Loui et al., 2008; Lu et al., 2015; Moreau et al., 2009; Nan et al., 2010; Tremblay-Champoux et al., 2010). Poor voluntary mental imagery—as measured by the BAIS scale—has been associated with poor singing (Greenspon et al., 2017; Pfordresher & Halpern, 2013). *Ergo*, the present findings concur well with previous work where the same imagery tool was employed. What remains unclear is why amusic participants also performed worse on vocal and environmental imagery items. Previous studies suggest that the recognition of vocal and environmental sounds is spared in people with amusia (Ayotte et al., 2002; Peretz et al., 2002). As no significant interaction was observed between group and type of sound, the present results suggest that it was not only musical imagery that was associated with amusic participants' poorer scores. More research on non-musical sound perception is warranted to reconcile these two strands of evidence and determine whether poorer imagery of non-musical sounds can be traced back to hitherto unexplored non-musical deficits in amusia. In particular, independent verification of these findings is required to increase confidence in any null results (see also discussion on statistical power at the end of this section).

It is of note that this is not the first time a dissociation between voluntary and involuntary imagery has been reported in an atypical population. A similar dissociation was observed in a recent study with autistic participants; their BAIS self-ratings were found to be lower than controls in contrast to their earworm scores (Bacon et al., 2020). In fact, their earworm scores were slightly higher than those of their neurotypical counterparts. The current findings provide further evidence that voluntary auditory imagery and involuntary musical imagery are dissociated.

This work also adds nuances to the discussion of explicit versus implicit music processing in amusia. Previous studies show that while people with amusia manifest pronounced explicit processing impairments (e.g., Ayotte et al., 2002; Foxton et al., 2004; Jiang et al., 2010; Liu et al., 2010; Nan et al., 2010), implicit processing can remain intact under various experimental conditions (Ayotte et al., 2002; Lévêque et al., 2018; Marin et al., 2015; Peretz et al., 2009; Tillmann et al., 2012; Tillmann, Lalitte, et al., 2016). Overall, the study of implicit engagement with music has been manifold: recording electrophysiological responses (Peretz et al., 2009), using priming (Tillmann et al., 2012), experience sampling (Omigie et al., 2012), and even comparing the performance of people with amusia on familiar to unfamiliar music tasks (Ayotte et al., 2002). Methodological differences aside, all these paradigms have revealed areas of intact music processing that do not hinge on direct awareness. This account can be further expanded by considering the specificity of a given response, regardless of whether it is based on self-report. Although this remains speculative until further researched, the specificity of the auditory scenarios put to our amusic participants in the BAIS questionnaire may explain why their ratings were lower; it is not known whether less specific questions would bear out the same trends. The earworm questionnaire draws on broader reflection on everyday life rather than specific instances that may require a rather more explicit access to an imaged sound. Amusic participants' earworm scores may reflect their ability to engage with music in everyday life regardless of how accurately—or vividly—music snippets are encoded and how they reoccur as earworms.

As alluded to previously, insufficient power could account for the statistically non-significant difference between groups on earworms and the non-significant interactions between group and type of sound in the BAIS scales. Interaction effects are not infrequently underpowered because of the multiple sources of noise involved. Visual inspection of the earworm graph suggests a trend of lower scores in the amusic group, but statistical analysis reveals this to be within the bounds of what might easily happen by chance even if there was no such trend in the population. Whether there is a strict or a blurred dichotomy between involuntary and voluntary imagery in amusia remains to be settled. It should be noted parenthetically that similar concerns, not only about false negative results but also false positives, apply to other areas of research in amusia and other low-prevalence conditions given the small samples typically recruited in the field. Future studies could remedy such limitations by adopting a Many Labs approach, conducive to testing the robustness of reported findings. Moreover, preregistration may lead to null results being reported more often, thus contributing to a more accurate picture of the impairments—and abilities—of people with amusia. Given some heterogeneity in amusia (Omigie et al., 2012), such approaches may not only show whether a given effect holds across studies but also elucidate specific patterns of variability.

In conclusion, this study has made an original contribution to the amusia literature by delving into amusic participants' subjective experience of voluntary and involuntary imagery. The present findings point to a possible difference between these two types of imagery in amusia, suggesting that music perception deficits, as diagnosed by the MBEA, may not have a major effect on the experience of involuntary imagery, whereas the impact on voluntary imagery appears pronounced. The mechanisms that give rise to the present pattern of self-perceived imagery remain in need of further investigation.

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Supplemental material

Supplemental material for this article is available online.

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