sempre: Society for Education, Music and Psychology Research

MUSIC & SCIENCE

Music and Mental Imagery – Research Article

Music & Science
Volume 6: 1–16

DOI: 10.1177/20592043231166332
journals.sagepub.com/home/mns
SAGE

Earworms in the Amusic Mind? Questionnaire Investigation in Congenital Amusia

Barbara Tillmann[1,2], Lesly Fornoni[1], Agathe Pralus[1], Caliani Hoarau[1], Philippe Albouy[1,3] and Anne Caclin[1]

Abstract

Involuntary musical imagery, colloquially known as "earworms", is a phenomenon hypothesized to reflect involuntary rehearsal of long-term memory representations. Here we investigated musical earworms with a questionnaire adapted from Halpern and Bartlett (2011, Music Perception, 28(4), 425–432), both in typical individuals and in participants with congenital amusia. Congenital amusics have impaired short- and long-term musical memory, yet with evidence for preserved implicit processing of music. Almost all participants in both groups reported experiencing musical earworms, however less frequently so in amusics than in controls. In both groups, musical earworms were reported being mostly familiar music with lyrics, and consisted of music liked by the participants. Some features distinguished earworms in amusics and controls, with more limited familiarity effects in amusics. Moreover, amusics were deploying less voluntary strategies to stop the earworms, in keeping with less stable music memories in this group. In addition, we investigated verbal earworms in the same participants. Verbal earworms occurred less frequently than musical earworms, and were more frequent in amusics than in controls. However, the two types of earworms showed similar features and their frequencies of occurrence were correlated, suggesting they rely in part on domain-general processes. Implications for the understanding of involuntary auditory imagery and congenital amusia are discussed.

Keywords

Implicit processing, memory, musical earworms, musical imagery, tone deafness, verbal earworms

Submission date: 17 October 2022; Acceptance date: 12 March 2023

Introduction

Musical "earworms" refer to the phenomenon of having songs "stuck" in one's head (e.g., Williams, 2015). It is an involuntary musical imagery (INMI) that has the specificity of being repetitive. It can be considered as a form of musical memory, consisting of mentally hearing and repeating (familiar) musical excerpts, often of more recently heard music. It also occurs more often and lasts longer for individuals with enhanced music listening or practice (e.g., singing; Müllensiefen et al., 2014). This is in line with features reported for memory in general, that is, better memory for more recent experiences and after repeated exposure. The scientific investigation of "musical imagery" in general (i.e., also including voluntary imagery) has attracted interest as one means to further our understanding of perception and cognitive functions, such as memory, attention, and consciousness. Interestingly, brain activation during voluntarily imagined music was reported as similar to brain activation during perceived music

[1] Lyon Neuroscience Research Center, CNRS UMR 5292, INSERM U1028, Université Claude Bernard Lyon 1, Bron, France
[2] Laboratory for Research on Learning and Development, LEAD-CNRS UMR 5022, Université de Bourgogne, Dijon, France
[3] CERVO Brain Research Center, School of Psychology, Laval University, Québec, G1J 2G3; International Laboratory for Brain, Music and Sound Research (BRAMS), CRBLM, Montreal, Canada

Corresponding authors:
Barbara Tillmann & Anne Caclin, CNRS UMR5292-INSERM U1028, Lyon Neuroscience Research Center, 69675 Bron Cedex, France.
Email address: Barbara.Tillmann@cnrs.fr & anne.caclin@inserm.fr

Correction (June 2023): The author's name Agathe Pralus was listed as lastname firstname. This has been corrected.

(e.g., Halpern, 1999; Zatorre & Halpern, 2005), in particular involving the activation of frontal and superior temporal regions as well as the supplementary motor areas. For INMI more specifically, Farrugia et al. (2015) revealed a negative relationship between frequency of INMI and cortical thickness of various brain areas, including auditory areas and inferior frontal regions. Their VBM results further revealed a relation between the extent to which participants wished to suppress INMI or considered them helpful, and increased gray matter volume in right temporopolar and parahippocampal cortices, respectively.

Various research methods have been used with the aim to further understand the personal and subjective experience of "earworms" or INMI. Most methods are based on self-reports asking for subjective experiences, such as via interviews, questionnaires, diaries, or experience sampling (contacting participants on mobile phones at random times of the day in everyday lives, e.g., Beaty et al., 2013; Halpern & Bartlett, 2011). Data mining with analyses of reports in social media (e.g., Twitter) are part of this approach (e.g., Liikkanen et al., 2015). Some lab-based experiments have also been conducted, notably, for example, by asking participants to tap the tempo of the earworms (Williamson et al., 2014) or presenting catchy tunes in the lab and observing the potential subsequent occurrence of earworms (e.g., Byron & Fowles, 2015). Some of these findings also revealed that repetition and familiarity increase the likelihood of a song to become an earworm.

Studying a wide corpus of tunes reported as "earworms" has revealed specific features of potential INMI tunes on both time and pitch dimension (Jakubowski et al., 2017). INMI tunes have faster average tempi than non-INMI tunes and have specific melodic contour features (with respect to a reference corpus), such as for example either very common global melodic contours (i.e., patterns of rising and falling of pitches), or highly unusual contour patterns. Interestingly, this analysis also revealed that a given song's popularity and recency (e.g., measured with chart entry date and persistence) is related to the frequency of the song to be reported as INMI, thus confirming links with listeners' long-term memory (e.g., recency, familiarity, see also Byron & Fowles, 2015).

Based on these various characteristics of the phenomenon of INMI and the features of INMI-songs, we were interested in investigating the potential existence of musical earworms in a population for which deficits or alterations along these perceptual and cognitive dimensions as well as its involved neural correlates have been reported. This population is referred to as being affected by congenital amusia, which has been described as a lifelong disorder of music perception and production (for reviews, see Peretz, 2016; Tillmann et al., 2015). This deficit cannot be explained by peripheral hearing loss, brain lesions, or general cognitive or social impairments (Ayotte et al., 2002), and short-term memory for verbal material is intact (including classical digit spans; Albouy, Schulze, et al., 2013; Tillmann et al., 2009; Williamson & Stewart, 2010). The main hypotheses for impairments underlying this condition are impaired fine-grained pitch perception (Ayotte et al., 2002; Foxton et al., 2004; Hyde & Peretz, 2004) and impaired short-term memory for pitch, which is observed even in the absence of elevated pitch discrimination thresholds or when the to-be-processed pitch changes exceed amusics' individual pitch discrimination threshold (Albouy, Mattout, et al., 2013; Gosselin et al., 2009; Tillmann et al., 2009; Williamson et al., 2010; Williamson & Stewart, 2010; review in Tillmann, Lévêque, et al., 2016). The main dimension affected by this disorder is the pitch dimension, as revealed by various tasks requiring pitch processing and memory (Liu et al., 2010), but the time dimension can also be affected (e.g., Foxton et al., 2006; Pfeuty & Peretz, 2010; Van Vugt et al., in progress). Subjective reports as well as questionnaire and experience sampling approaches have revealed at least for a subset of amusics an altered music engagement and appreciation (e.g., McDonald & Stewart, 2008; Omigie et al., 2012). Amusic individuals seem to incorporate music to a lesser degree into everyday activities than do controls. They report to listen less often to music and to sing more rarely than do controls, both in private and in public (e.g., Peretz et al., 2008). Interestingly, not all amusic individuals reflect this limited engagement, some show profiles similar to controls (e.g., McDonald & Stewart, 2008; Omigie et al., 2012). The subjective comments also reflect their memory impairments, both for long- and short-term memory. Regarding long-term memory, amusic participants report their difficulties in recognizing a song without lyrics (e.g., Ayotte et al., 2002), an impairment that is also observed in explicit familiar tune recognition tests (e.g., Omigie et al., 2012; Peretz et al., 2002).When performing short-term memory tasks, amusic participants indicate, for example, that it is difficult to hold on a melody in their mind and that information just disappears (e.g., Albouy, Mattout, et al., 2013). This is clearly reflected in one congenital amusic's comment describing their attempts to keep a short musical phrase in memory, reported by Stewart (2008): "When the music finished the sound was always gone - as though it had never happened. And this bewildered me with a sense of failure, of failure to hold on to what I had just heard. Others told me that if I tried to remember I would. But I never did." (p. 128).

Neurophysiological studies investigating the cerebral underpinnings of congenital amusia have revealed functional and anatomical abnormalities in the auditory cortex, the inferior frontal cortex, in particular in the right hemisphere (Albouy et al., 2019; Albouy, Caclin et al., 2019; Albouy, Mattout, et al., 2013; Hyde et al., 2006, 2007, 2011), together with an abnormal connectivity between these structures (Albouy et al., 2015, 2019; Albouy, Mattout, et al., 2013; Hyde et al., 2011; Lévêque et al., 2016; Loui et al., 2009). Some of these cortical alterations thus occur in areas also associated with the individual differences related to INMI (Farrugia et al., 2015).

In light of this pattern of impairments and anomalies, one might thus wonder whether individuals with congenital amusia could experience the phenomenon of musical earworms, and leads to the hypothesis of missing or decreased INMI in this condition. This hypothesis would fit with the comment of the congenital amusic reported by Stewart (2008): "I have no idea what people mean when they say: 'I have a tune going round in my head.' I have never had a tune tell out its music in my head let alone repeat itself!" (p. 128).

However, alternatively, one could make the hypothesis that INMI might benefit from implicit processing capacities as well as default-network involvement (Farrugia et al., 2015; Lévêque et al., 2016), which would allow also amusic individuals to experience this phenomenon. Indeed, an increasing number of reports have revealed that not all musical processing aspects are impaired, but that some implicit processing seems to remain intact, such as implicit detection of pitch changes (e.g., Peretz et al., 2009; Zendel et al., 2015), implicit processing of tonal structures (e.g., Albouy, Schulze, et al., 2013; Lévêque et al., 2022; Tillmann et al., 2012; Tillmann, Lalitte, et al., 2016), as well as some long-term memory for music, allowing for feeling of familiarity judgments as do controls (even though with somewhat slower access; Tillmann et al., 2014) and the influence of familiarity and liking on memory and pitch deviance detection (e.g., Ayotte et al., 2002; Quiroga-Martinez et al., 2020; Lévêque et al., 2023). To the best of our knowledge, the phenomenon of earworms has not been studied in congenital amusia. Note that when writing this report, a study on voluntary musical imagery in congenital amusia was published, also assessing earworms as part of a larger investigation (Loutrari et al., 2022). In contrast to our study, it used a single measure derived from an earworm questionnaire and observed no significant difference on this single aggregated measure between amusic and control participants.

We had set out to investigate INMI in individuals with congenital amusia and their matched control participants, who are all rather non-musicians. We started this project in 2011 by translating and adapting the questionnaire introduced by Halpern and Bartlett (2011) into French. As congenital amusia is a rather rare phenomenon (estimated to occur for 1–2% of the general population; Cuddy, 2005; Peretz & Vuvan, 2017; Sloboda et al., 2005), we accumulated the data presented here since then. For consistency with the start of the project, we kept the initial questionnaire without changing to more refined questionnaires or investigation tools of INMI that have been proposed later on (e.g., Floridou et al., 2015). The data reported below are encouraging to further investigate this phenomenon now with more refined tools.

The questionnaire by Halpern and Bartlett (2011) also included questions for potential "verbal earworms". This addition seemed particularly interesting for the population of congenital amusics for which no deficits for verbal processing (e.g., verbal short-term memory, memory span) have been reported, except when pitch information is the only available cue for the required task (e.g., pitch change detection in syllables, Tillmann et al., 2011; or controlled tone language material, e.g., Nan et al., 2010; Nguyen et al., 2009).

Material and Methods

Participants

Starting in 2011, we used a paper version of the questionnaire, and collected data from a first set of participants. In 2017, we implemented an online version of the questionnaire, which allowed us to collect a larger set of data. Data were collected in total from 99 control participants (paper version, $n = 11$; online version, $n = 88$) and 41 amusic participants (paper version, $n = 6$; online version, $n = 35$). Participating in this questionnaire study was proposed to volunteers that came to the lab to participate in behavioral or neuroimaging studies investigating congenital amusia, and thus underwent a full assessment allowing diagnosis of congenital amusia (audiometry, MBEA, PDT, see below for details). To match amusic participants, non-musician control participants were recruited (i.e., participants with mostly no music training outside compulsory courses at school, with some having received limited musical training, as for the amusics, see Table 1). All participants reported no history of neurological or psychiatric disease. Demographic data for the two groups of participants are detailed in Table 1.

Our standard screening session for congenital amusia included: a standard audiometry to exclude moderate to severe hearing loss; the Montreal Battery for the Evaluation of Amusia (MBEA, Peretz et al., 2003); and a Pitch Discrimination Threshold task (Tillmann et al., 2009). To be considered as amusic, participants had to obtain an average score two standard deviations below the average of the normal population on the MBEA. Amusics obtained scores below the cut-off score on the overall MBEA battery (23.4 on average across the six tasks, maximum score = 30) or the three pitch-related subtests (scale, interval, contour, cut-off = 21.7 on average across the three tasks, maximum score = 30; Liu et al., 2010). Pitch discrimination thresholds (PDTs) were determined using a two-alternative forced-choice task with an adaptive tracking, two-down/one-up staircase procedure (see Tillmann et al., 2009, for task and details). MBEA scores and PDT for the two groups, as well as between-group comparisons, are reported in Table 1.

All participants signed a written informed consent prior to behavioral tests, and data collection with the questionnaire followed the appropriate regulation on personal data protection at the time of data collection.

Material

We adapted the questionnaire developed by Halpern & Bartlett (2011), added some extensions and translated it into French. Our French questionnaire (and its English translation) is presented in the Appendix. Various aspects of musical earworms were assessed: frequency of occurrence, features of earworms (musical style, familiarity, liking), subjective experience of musical earworms (pleasantness, ending of the phenomenon, strategies). The same type of questions were then proposed to investigate the phenomenon of verbal earworms.

Table 1. Demographic characteristics of control and amusic participants.

Group	Controls (n = 99)	Amusics (n = 41)	p-value (group comparison)
Age (years)	33 (±13) Min: 18 Max: 74	32 (±13) Min: 18 Max: 59	0.81
Sex	71 women, 28 men	25 women, 16 men	0.23
Education (years)	15 (±2) Min: 10 Max: 18	15 (±2) Min: 10 Max: 20	0.53
Musical education (years)	0.4 (±1.4) Min: 0 Max: 12	0.3 (±1.0) Min: 0 Max: 6	0.74
Handedness	88R, 11L	36R, 5L	1
MBEA Global score (maximum score = 30)	27.1 (±1.3) Min: 24.3 Max: 29.3	21.7 (±1.8) Min: 16.8 Max: 24.5	**<0.001**
MBEA Scale sub-test (maximum score = 30)	27.5 (±2.1) Min: 22 Max: 30	20.9 (±2.8) Min: 14 Max: 25	**<0.001**
MBEA Contour sub-test (maximum score = 30)	28.0 (±1.4) Min: 24 Max: 30	21.0 (±3.0) Min: 15 Max: 26	**<0.001**
MBEA Interval sub-test (maximum score = 30)	26.6 (±2.1) Min: 21 Max: 30	19.6 (±2.8) Min: 13 Max: 26	**<0.001**
MBEA Rhythm sub-test (maximum score = 30)	27.6 (±1.9) Min: 23 Max: 30	24.2 (±3.0) Min: 17 Max: 30	**<0.001**
MBEA Meter sub-test (maximum score = 30)	24.8 (±4.2) Min: 14 Max: 30	19.5 (±4.8) Min: 8 Max: 30	**<0.001**
MBEA Memory sub-test (maximum score = 30)	28.2 (±1.8) Min: 21 Max: 30	24.9 (±3.2) Min: 18 Max: 30	**<0.001**
PDT (semitones)	0.3 (±0.3) Min: 0.007 Max: 2.18	1.4 (±1.2) Min: 0.16 Max: 4.98	**<0.001**

Note: The characteristics of the two groups were compared with Student *t*-tests, except for Sex and Handedness tested with a Fisher Exact test. Bold indicates significant differences.

Statistical Analysis

For each question, we compared between groups the proportion of participants giving the different possible answers using a Fisher's Exact test. We then investigated the potential relation between the occurrence of musical earworms and other relevant variables (occurrence of verbal earworms, age, music memory, musical habits) with Spearman's rank correlations, across all participants and separately in each group.

Results

Results are reported following the order of appearance of the questions in the questionnaire. Subheadings are added for clarity of presentation, but were not included in the questionnaire (see Appendix). Unless otherwise specified, the results were for all participants of both groups (n = 140, see Methods).

Occurrence of Musical Earworms

The first question asked participants whether they knew the expression "avoir une musique dans la tête" [Do you know the expression "having music/song in your head"?], which is the French way of referring to musical earworms. All participants, except for one amusic participant, were familiar with this expression (i.e., responding *yes*). Only four participants (1 control out of 99 and 3 amusics out of 41) reported not experiencing musical earworms (Figure 1A). The proportion of participants not reporting musical earworms was not significantly different between groups (Fisher's Exact test, $p = 0.08$). Among participants who reported musical earworms (98 controls and 38 amusics), the frequencies of occurrence most often reported were "almost daily" and "a few times/week" for controls, whereas they were "a few times/week" and "a few times/month" for amusics (Figure 1B). The frequency of occurrence of musical earworms differed significantly between groups (Fisher's Exact test, $p = 0.02$). Amusics hence reported less frequent musical earworms than did controls.

Features of Musical Earworms

Details about whether musical earworms were always of the same *musical style* (or not) or consisted even of always the same pieces are reported in Table 2. In both groups, the most frequent answer was that musical earworms were of "various musical styles", followed by "various pieces of the same musical style", hence revealing that participants mostly experience a variety of different musical earworms. The distribution across the various options regarding musical style for the musical earworms did not differ significantly between groups (Fisher's Exact test, $p = 0.39$).

For the subsequent questions aiming to further characterize earworms, data were missing for 10 controls and 5 amusics (see Appendix for details about questionnaire implementation and whether or not presenting some questions should be conditioned on answers given to previous questions).

Regarding *familiarity* (Figure 2A), most control participants reported that earworms consisted of familiar music (n = 85 [97%]) rather than unfamiliar music (n = 3 [3%]). This was also the case for amusic participants, but to a lesser extent (n = 28 [85%] for familiar music, vs. n = 5 [15%] for unfamiliar music). The proportion of familiar/unfamiliar responses differed across groups (Fisher's Exact test, p =

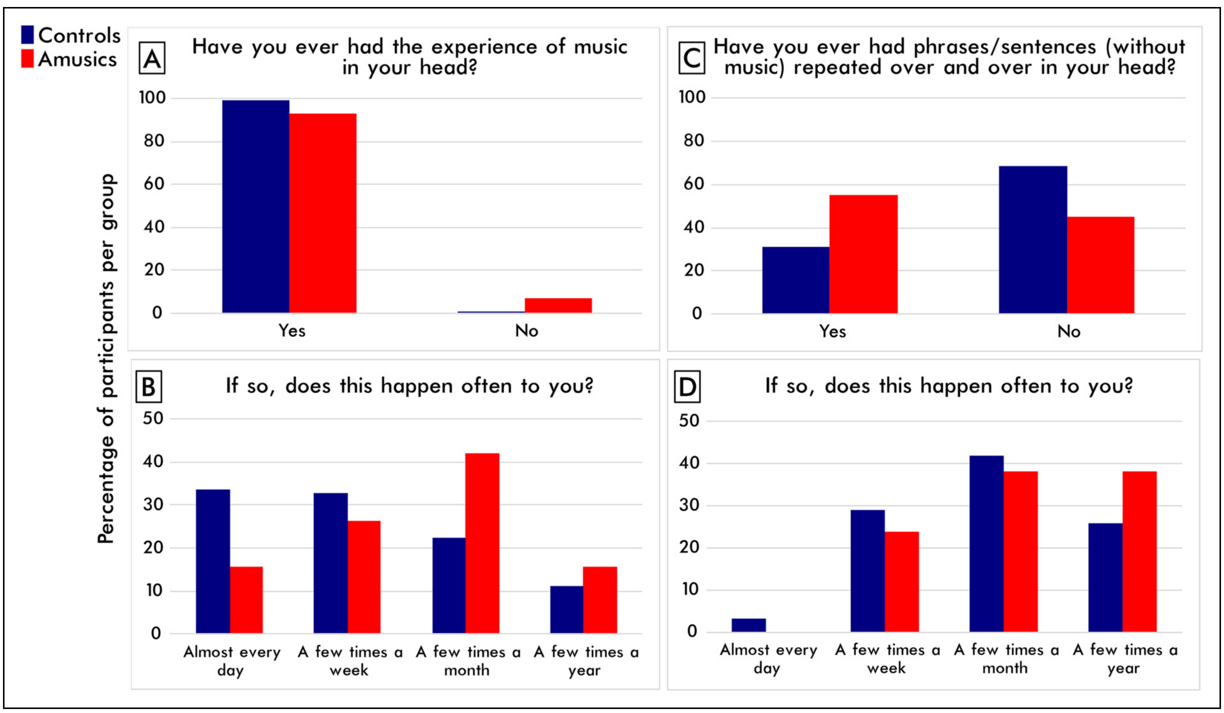

Figure 1. *Occurrence of musical and verbal earworms in control (n = 99) and amusic (n = 41) participants.* A. Percentages of participants in each group that report experiencing musical earworms. B. For participants who experience musical earworms (98 controls and 38 amusics), percentages of participants in each group that report a given frequency of occurrence of musical earworms. C. Percentages of participants in each group that report experiencing verbal earworms (missing data from one amusic participant). D. For participants who experience verbal earworms (31 controls and 22 amusics), percentages of participants in each group that report a given frequency of occurrence of musical earworms (missing data from one additional amusic participant). Blue bars on the left for controls, red bars on the right for amusics.

Table 2. Nature of musical and verbal earworms.

	Musical		Verbal	
	Controls	Amusics	Controls	Amusics
The type of *music/language* you hear may be very different	70 (71.4%)	27 (71.1%)	10 (33.3%)	7 (33.3%)
The type of *music/language* is always the same but the *musical pieces/words or sentences* are different	15 (15.3%)	6 (15.8%)	10 (33.3%)	7 (33.3%)
It is always the same *musical pieces* that are repeated/ The same *words* are repeated very frequently	9 (9.2%)	4 (10.5%)	7 (23.3%)	4 (19.0%)
The same *piece of music/words is/are* repeated all the time	4 (4.1%)	1 (2.6%)	3 (10.0%)	3 (14.3%)

Note. The values reported are the number of participants that choose this response option followed by the percentage of participants per group in brackets. *Musical earworms*: data from 98 control participants and 38 amusics who reported experiencing musical earworms. *Verbal earworms*: Data from 30 controls and 21 amusics who reported experiencing verbal earworms (missing data from one participant per group).

0.03). Most participants reported that earworms were *music with lyrics* (Figure 2B), both in the control group (n = 78 [89%] for music with lyrics, vs. n = 10 [11%] for music without lyrics), and in the amusic group (n = 30 [91%] for music with lyrics, vs. n = 3 [9%] for music without lyrics). The proportion of the two response options did not differ significantly between groups (Fisher's Exact test, p = 0.44). Finally, most participants reported that earworms consisted of music they appreciated (Figure 2C), both in the control group (n = 67 [77%] for *music they like*, n = 15 [17%] for neutral music, and n = 5 [6%] for music they dislike, missing data for an additional control participant) and in the amusic group (n = 24 [73%] for music they like, n = 7 [21%] for neutral music, and n = 2 [6%] for music they dislike; the proportion of the three responses did not differ significantly between groups, Fisher's Exact test, p = 0.62).

The musical styles of the pieces that participants indicated hearing as earworms are presented for both groups in Figure 3A, with pop, rock, and summer hit being the most frequent answers in both groups (note that participants could give several answers).

Subjective Experience of Musical Earworms

Hearing musical earworms can be a positive, a negative, or a neutral experience. In controls, the most frequent answer was that it is a negative experience (n = 39 [40%] for negative, n = 34 [35%] for positive, and n = 25 [25%] for neutral). In amusics, the most frequent answer was that it is a neutral

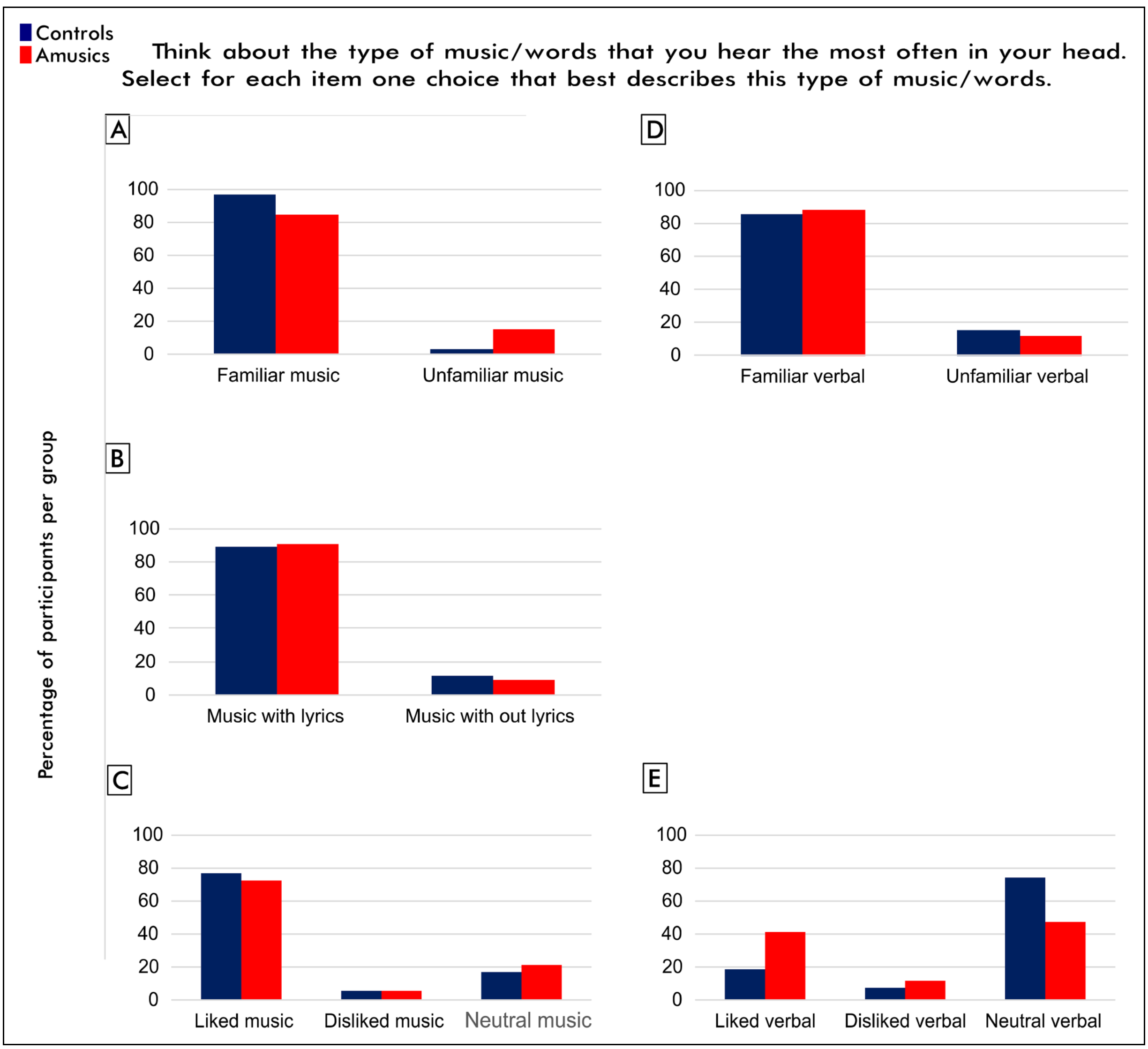

Figure 2. *Features of musical and verbal earworms in control and amusic participants.* A. Percentages of participants in each group who reported that musical earworms consisted mostly of familiar or unfamiliar music. B. Percentages of participants in each group who reported that musical earworms consisted mostly of music with or without lyrics. C. Percentages of participants in each group who reported that musical earworms consisted mostly of music they liked, neutral music, or music they disliked. D. Percentages of participants in each group who reported that verbal earworms consisted mostly of familiar or unfamiliar content. E. Percentages of participants in each group that report that verbal earworms consisted mostly of liked, neutral, or disliked content.

experience (n = 15 [41%] for neutral, n = 11 [31%] for positive, and n = 10 [28%] for negative, missing data for 2 participants). The proportion of these three responses differed significantly between groups (Fisher's Exact test, p = 0.009).

A majority of participants reported that it was difficult to get rid of musical earworms, both for controls (n = 68 [69%] having difficulties, vs. n = 30 [31%] having no such difficulties), and for amusics (n = 24 [63%] having difficulties, vs. n = 14 [37%] having no such difficulties; the proportion of the two responses did not differ significantly between groups, Fisher's Exact test, p = 0.09). When asked how the earworm terminates, control participants mostly reported that it goes away by itself (n = 76 [78%]), whereas some deploy voluntary strategies to stop it (n = 19 [19%]), and a few reported that it is almost impossible to stop it (n = 3 [3%]). Almost all amusics reported the earworm goes away by itself (n = 31 [86%]), with only few amusic participants reporting to deploy a voluntary strategy to stop it (n = 3 [8%]) or that it is almost impossible to stop it (n = 2 [6%], missing data for 2 participants, the proportion of these three responses differed significantly between groups, Fisher's Exact test, p = 0.01). Some participants provided descriptions of the strategies to get rid of the earworms, which we could sort into three categories: listening to or singing the original musical piece (n = 11 controls for listening, n = 2 controls for singing; n = 1 amusic

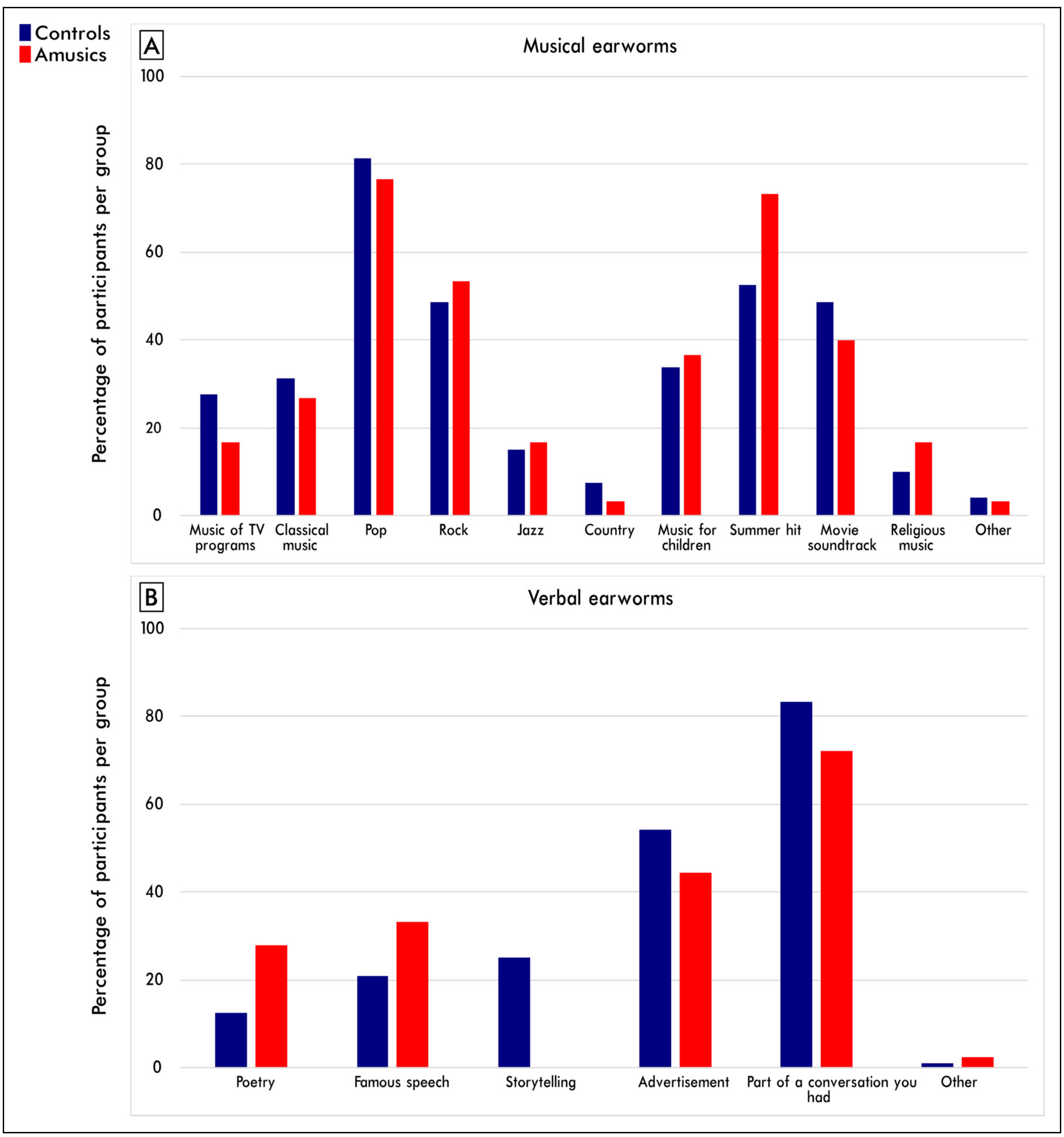

Figure 3. *Types of musical and verbal earworms in control and amusic participants.* Participants could select one or several items describing the types of musical (A) or verbal (B) earworms they are experiencing. The percentage of participants in each group that selected a given type is depicted. Blue bars on the left for controls, red bars on the right for amusics.

for listening); listening to other musical pieces (n = 4 controls, n = 1 amusic); switching to a different activity (n = 1 control, n = 1 amusic).

Occurrence of Verbal Earworms

The second part of the questionnaire investigated verbal earworms, defined as verbal information (e.g., phrases, sentences) repeating over and over in one's head (one amusic participant did not respond to this part of the questionnaire). Only one third of the control participants reported experiencing verbal earworms, whereas more than half of the amusic participants did so (Figure 1C, the proportion of participants experiencing verbal earworms differed significantly between groups, Fisher's Exact test, $p = 0.006$). Amongst the participants who reported verbal earworms (31 controls out of 99 and 22 amusics out of 40, missing data for the verbal part of the questionnaire for one amusic participant), the frequency of occurrence most often reported was "a few times/month" (Figure 1D, the frequency of occurrence did not differ significantly between groups, Fisher's Exact test, $p = 0.12$). Hence, amusics reported having verbal earworms more than did controls, but the frequency of occurrence of these earworms (in participants who experienced verbal earworms) was similar in the two groups.

Features of Verbal Earworms

Details about the nature of these verbal earworms are reported in Table 2. In the two groups, verbal earworms were most often described as being of different types (e.g., poetry, famous speech, advertisement), or as being always of the same type, but made of different sentences. The proportion of the four response choices (see Table 2) did not differ significantly between the groups (Fisher's Exact test, $p = 0.17$).

Further questions aimed at characterizing verbal earworms (missing data for 4 controls and 5 amusics, see Appendix for details). For *familiarity* (Figure 2D), participants in both groups reported that verbal earworms were mostly familiar: for controls, n = 23 [85%] for familiar, vs. n = 4 [15%] for unfamiliar; for amusics, n = 15 [88%] for familiar, vs. n = 2 [12%] for unfamiliar; the proportion of the two responses did not differ significantly between groups (Fisher's Exact test, $p = 0.22$). For *liking* (Figure 2E), participants in both groups reported that verbal earworms were mostly neutral material: for controls, n = 20 [74%] for neutral, n = 5 [19%] for dislike, and n = 2 [7%] for like; for amusics, n = 8 [47%] for neutral, n = 7 [41%] for dislike, and n = 2 [12%] for like; the proportion of the three responses did not differ significantly between the groups (Fisher's Exact test, $p = 0.08$).

The type of sentences heard as verbal earworms are presented for both groups in Figure 3B, with "Part of a conversation you had" and "Advertising" being the most frequent answers in both groups (note that participants could give several answers).

Subjective Experience of Verbal Earworms

Control participants who reported having verbal earworms reported these earworms as a neutral (n = 14 [47%]) or a negative (n = 13 [43%]) experience, and only rarely a positive experience (n = 3 [10%], missing data for one participant). Amusic participants reported equally verbal earworms as a negative (n = 8 [36%]), a neutral (n = 7 [32%]), or a positive (n = 7 [32%]) experience (the proportion of the three responses differed significantly between groups, Fisher's Exact test, $p = 0.01$).

When asked how the verbal earworm terminates, control participants mostly reported that it goes away by itself (n = 23 [77%]), yet a few deploy a voluntary strategy to terminate it (n = 4 [13%]) or report that it is almost impossible to get rid of it (n = 3 [10%], missing data for one participant). Almost all amusic participants reported that it goes away by itself (n = 19 [90%]), a few deploy a voluntary strategy to terminate it (n = 2 [10%]), none reported that it is almost impossible to get rid of it (missing data for one participant). The proportion of the three responses differed significantly between groups, Fisher's Exact test, $p = 0.04$. Among the six participants who reported using a voluntary strategy to get rid of the verbal earworm, two controls reported changing activity (e.g., switching on the TV), two amusics to think about something else (e.g., to-do list), and two controls to reflect on the repeating words (described as ruminations).

Correlations Between Musical and Verbal Earworms

To assess the link between musical and verbal earworms, we created a score for each material (musical or verbal), with 0 for participants who reported not experiencing earworms, and 1 to 4 for participants who reported experiencing earworms, coding their frequency of occurrence with 1 meaning "a few times/year" and 4 meaning "almost daily" (taken directly from the second question of the questionnaire, see Appendix). The correlation between these two "frequency report scores" for musical and verbal earworms was assessed across all participants (n = 99 controls and n = 40 amusic, missing data for the verbal part of the questionnaire for one amusic participant), and separately in each group, using Spearman's rank correlations. The correlation between musical and verbal earworms was significant across all participants ($r_s(137) = 0.320$; $p < .0001$), for controls ($r_s(97) = 0.297$; $p = .003$), and for amusics ($r_s(38) = .591$, $p < .0001$), see Table 3.

Correlations Between Musical Earworms and age, Music Memory, or Music Listening

Using the "frequency report scores" for musical earworms (i.e., frequency of occurrence of musical earworms: from 0: never, to 4: almost daily), we assessed the link between musical earworms and age, as well as music-related variables, across all participants and separately in each group, using Spearman's rank correlations (Table 3).

Age correlated negatively with earworms, across all participants ($r_s(138) = -0.325$, $p < .0001$), for controls ($r_s(97) = -0.320$, $p = .001$), and for amusics ($r_s(39) = -.398$, $p < .001$), suggesting that the older the participants, the fewer earworms were experienced.

To assess the link between musical earworms and musical memory, we used the MBEA pitch score (average performance on the first three subtests of the battery, which are delayed-matching-to-sample tasks with pitch changes, Liu et al., 2010) as a measure of melodic (pitch) short-term memory ability, and the MBEA incidental memory score (performance on the last sub-test of the battery, which tests whether participants recognize the melodies used in the other 5 subtests) as a measure of melodic long-term memory. MBEA pitch score correlated with musical earworm occurrence across all participants ($r_s(138) = .217$, $p = .01$), but not within groups (for controls, $r_s(97) = 0.032$, $p = .75$; for amusics, $r_s(39) = .085$, $p = .60$). MBEA incidental memory score correlated with musical earworm occurrence across all participants ($r_s(138) = 0.296$, $p = .0004$), and separately for amusics ($r_s(39) = .381$; $p = .01$), but failed to reach significance for controls ($r_s(97) = .178$, $p = .078$).

Finally, to assess the link between musical earworms and music listening habits, we took advantage of a questionnaire about musical experience and participants' relation to music (based on questionnaires of McDonald & Stewart, 2008; Peretz et al., 2009; Sloboda et al., 2005) that participants had filled out as part of our general screening procedure. Fifty-four participants (35 controls and 19 amusics) responded to this questionnaire. Among more than 90 questions, this questionnaire included questions that are relevant based on previous research investigating INMIs: Participants ranked on a 1-to-5 scale (1: never, 5: very often) how often they listen to music intentionally, how often they listen to music alone, how often they listen to music with company, how often they sing when they are alone, and how often they sing in public. Across all participants, the occurrence of musical earworms was correlated with the frequency of listening to music intentionally ($r_s(52) = 0.369$, $p = .006$), with the frequency of listening to music alone ($r_s(52) = 0.418$, $p = .002$), and with the frequency of singing alone ($r_s(52) = 0.275$, $p = .04$; for other correlations $p > .22$). None of these correlations reached significance in controls ($p > .24$), but the first two were significant in amusics (listening to music intentionally, $r_s(17) = 0.741$, $p = 0.0003$; listening to music alone, $r_s(17) = 0.649$, $p = 0.0003$) and the third one was marginally significant in amusics (singing alone, $r_s(17) = 0.444$, $p = .06$; for other correlations $p > .17$), see Table 3 for details.

Discussion

We investigated musical and verbal earworms in non-musician control participants and amusic participants with a questionnaire adapted from Halpern and Bartlett (2011), in a large-scale study with a total of 140 participants. In the following, we first discuss how the data from non-musician controls replicated and extended previous findings on musical earworms in populations with various musical backgrounds (e.g., Liikkanen et al., 2015; Müllensiefen et al., 2014; see Liikkanen & Jakubowski, 2020, for a review), and then we discuss the data of our amusic participants and show how musical earworms further also our understanding of the phenomenon of congenital amusia. Finally, we discuss the potential relationship between musical and verbal earworms.

Experience of Musical Earworms in the General Population

All control participants (n = 99) reported knowing the expression "having music/song in your head", and all but

Table 3. Correlations (Spearman's r) between musical earworms and verbal earworms, age, MBEA pitch Score, MBEA incidental memory score, and music listening habits (with (a) how often they listen to music intentionally, (b) how often they listen to music alone, (c) how often they listen to music with company, (d) how often they sing when they are alone, and (e) how often they sing in public).

	All participants			Controls			Amusics		
	r	df	*p*	r	df	*p*	r	df	*p*
Musical earworms – Verbal earworms	.320	137	**<.0001**	.297	97	**.003**	.591	38	**<.0001**
Musical earworms									
– age	-.325	138	**<.0001**	-.320	97	**.001**	-.398	39	**<.001**
– MBEA pitch	.217	138	.0099*	.032	97	.750	.085	39	.598
– MBEA incidental memory	.296	138	**.0004**	.178	97	.078	.381	39	.014*
– how often listen intentionally	.369	52	**.006**	.086	33	.622	.741	17	**.0003**
– how often listen alone	.418	52	.002*	.203	33	.242	.649	17	**.0003**
– how often listen with company	.172	52	.215	-.044	33	.803	.325	17	.174
– how often sing alone	.275	52	.044*	.003	33	.986	.444	17	*.057*
– how often sing in public	.169	52	.222	.162	33	.353	.080	17	.744

Note: Correlations are reported for all participants across the two groups as well as for control participants and amusic participants separately, with degrees of freedom (df) and *p*-values (*p*). Uncorrected significant correlations are indicated with *. Correlations that remained significant after Bonferroni correction are indicated in bold. Corrections were made for nine tested correlations, separately for each concerned participant pool (i.e., threshold was corrected to *p* = .006).

one indicated having experienced earworms. This observation is in agreement with Halpern and Bartlett's report (2011) that all participants (n = 18) had already had the experience of music playing over and over in their mind. Our control participants reported experiencing this phenomenon "almost daily" or "a few times a week" for about 66%, which is comparable to Halpern and Bartlett (2011), indicating 72% of their participant pool to choose these two response options. Musical earworms were of various musical styles for most participants (71%), as reported by 66% of participants in Halpern and Bartlett (2011). Responses also indicated that earworms were mostly familiar music with lyrics, as in Halpern and Bartlett (2011). This observation also fits with other findings, for example that INMIs are three times more often familiar rather than unfamiliar songs (Hyman et al., 2015), and that more earworms were reported for music with lyrics than for instrumental music (e.g., Liikkanen & Jakubowski, 2020, Beaman, 2018). Beaman (2018) confirms this latter observation in an experimental setting, notably by using the same tunes as either lyrical or instrumental version. This finding suggests that the observation of tunes with lyrics as frequently experienced INMIs cannot be explained solely by some enhanced mere exposure for tunes with lyrics than instrumental music.

Most of our control participants reported that earworms consisted of music they did appreciate, rather than dislike or neutral. In contrast to Halpern and Bartlett (2011), where 16 out of 18 participants reported that the experience was typically pleasant or mixed/neutral, our participants referred to earworms almost as frequently as negative experience (40%) than as positive experience (35%). This variation integrates into the different patterns of experience previously reported in the literature, with Beaty et al. (2013) reporting it as mostly positive experience (N = 190), Williamson et al. (2014) as neutral or pleasant (N = 1046), while Liikkanen et al. (2015) as a more negative experience (exploiting over 80,000 tweets).

While most control participants reported that it was difficult to get rid of musical earworms, they also acknowledged that earworms also go away by themselves (78%), as in Halpern and Bartlett (2011; 67%). Interestingly, the strategies reported by both amusics and controls are similar to those that have been previously reported, such as listening to or singing the target piece or other pieces and/or switching activities (see for example Williamson et al., 2014, for Finnish and English participants).

Across all participants, the occurrence of musical earworms was correlated with the frequency of listening to music intentionally or alone and the frequency of singing alone (albeit not reaching significance after correction for multiple comparisons). However, none of these correlations reached significance in controls separately (but see below for amusics), thus only partially confirming Müllensiefen et al. (2014)'s observation that INMI are occurring more often and last longer for individuals with enhanced music listening or practice. However, our controls were mostly non-musicians, while Müllensiefen et al. (2014)'s participants of their online study included a wide spread of musical background, including musician participants, which might also include enhanced variability regarding music listening or singing behavior.

Regarding individual differences of INMI, Liikkanen and Jakubowski (2020) review that only a weak negative relationship was observed between age and INMI frequency, with data suggesting a mediating factor of musical practice. In our study, mostly non-musicians were tested, confirming a significant negative relationship (see also Liikkanen, 2012); the older they were, the weaker the reported frequency of occurrence of INMI.

We also assessed the link between INMI and long-term memory capacity, notably by taking advantage that all participants had been tested with the MBEA (to ascertain absence of amusia). In particular, we used the MBEA subcomponent testing for incidental memory to investigate the potential link between INMI and long-term memory capacity. Across all participants, the incidental memory score of the MBEA correlated significantly with musical earworm occurrence, further supporting the link between INMI and memory (e.g., Byron & Fowles, 2015). The correlation with the MBEA pitch score, which reflects short-term memory capacity, did not reach significance when corrected for multiple comparisons. To further address this difference, we took advantage that 16 participants of our present participant pool (7 amusics, 9 controls) had also participated in a previous study investigating both short-term memory and long-term memory (with a familiar melody identification task) (Graves et al., 2019). For the present purpose, we averaged performance across conditions for short-term and long-term memory tasks, respectively, and correlated these performance with the musical earworm occurrence. Congruently with the results observed here with the MBEA scores, performance correlated significantly with the long-term memory performance ($r = .631$, $p = .009$, $df = 14$), but not the short-term memory performance ($r = .438$, $p = .090$, $df = 14$). Because of the relatively small overlap in participants between the two studies, we combined control and amusic participants for the present additional analyses. Future research should now further investigate the differential link between INMI and short-term versus long-term memory capacity, respectively.

In sum, the present data provided converging evidence with previous reports regarding INMI, but here with a French (non-musician) population, which was rather understudied up to now, as most data sets stem from Australia, India, Finland, the UK, and USA (see Liikkanen & Jakubowski, 2020, for a review).

Experience of Musical Earworms in Congenital Amusia

While all but one amusic participants reported knowing the expression "having music/song in your head", they almost all reported experiencing this phenomenon, yet significantly less frequently than controls (weekly or monthly rather than daily or weekly). As for controls, musical earworms were of various musical styles for most amusic participants (71% in both groups). Also as for controls, earworms were mostly familiar music with lyrics, even though the difference between familiar and unfamiliar music response options was less pronounced for amusics. This response pattern is in agreement with previous data showing that also amusic individuals might have a mental musical lexicon; they can experience feelings of familiarity and also somewhat recognize songs, even though the access might take more time, be related to a feeling of uncertainty and lead to weaker recognition scores (e.g., Graves et al., 2019; Tillmann et al., 2014). Interestingly, the distribution across the different musical style categories looked very similar for amusics and controls, with pop music being reported as the most frequent category, an observation keeping with Halpern and Bartlett (2011; Experiment 2).

Like for control participants, amusic participants reported that earworms consisted of music they did appreciate, rather than music that was judged neutral or music they disliked. This might be related to some preserved emotional processing for music in the amusic population. Indeed, Gosselin et al. (2015) reported normal recognition of emotions in musical clips for amusic individuals, albeit with a reduced use of cues related to change of mode in comparison to controls. And even though amusics showed a deficit to explicitly label the emotion expressed by music in a different study using real recordings of orchestral music, their emotional intensity judgments are similar to controls, thus pointing again to rather preserved implicit processing (Lévêque et al., 2018), which thus might contribute to the observed response pattern here too.

Some of our results showed differences between earworms of control participants and of amusic participants. These differences can be linked to characteristics observed in congenital amusia and to the involvement of memory in the phenomenon of INMI. Indeed, even though both populations judged similarly that it is difficult to get rid of musical earworms (63% of amusics and 69% of controls reported having such difficulties), amusics' responses suggest that the INMI are less persistent than for controls: amusics reported to rely less on voluntary strategies than did controls (8% of amusics, 19% of controls) and that the phenomenon stops rather by itself (reported by 86% of amusics, but 78% of controls).

These subjective reports suggesting more volatile INMI in amusics than in controls can be linked to previous reports showing that musical memory traces are less well established in amusia (e.g., Albouy et al., 2016; Gosselin et al., 2009; Tillmann et al., 2014). One could argue that this difference in volatility might be related to the difference in reported subjective experience, notably with amusics reporting it mostly as neutral, followed by positive and then only negative, while the most frequent answer in controls was negative, followed by positive and then neutral (with, for example, the involuntary or uncontrollable aspect that might be experienced as negative). Future research will need to further investigate this potential link, also with more detailed questionnaires allowing for responses including more precise estimates of frequency of occurrence, for example.

A link with memory and musical engagement is also suggested by participants' responses to our general musical questionnaire, namely listening to music intentionally or alone is correlated to the frequency of INMI in amusia. Furthermore, the MBEA incidental memory score, an indicator for individuals' long-term memory capacity, correlated with musical earworm occurrence (even though not reaching significance in the amusic group when corrected for multiple testing), further revealing the link between INMI and memory. For amusics only, this correlation with musical earworm occurrence was not significant for the MBEA pitch score, which relies on short-term memory only, further suggesting a link with long-term memory and INMI. Note that, as for controls, age was negatively correlated with frequency of INMI.

In sum, our amusic participants' data reveal that despite their condition, they experience INMI, even though less frequently and less persistently than controls. Amusics' INMI experience reflect certain characteristics that can be linked to their condition, such as their decreased memory for musical material, for example, or less frequent intentional music listening or singing.

While surprising that even amusics might have INMI, this observation is in agreement with a very recent report that came out while writing our manuscript. Loutrari et al. (2022) reported no difference in a global earworm score between controls and amusics. The more detailed responses of our questionnaire (adapted and extended from Halpern & Bartlett, 2011) revealed some alterations in amusics' INMI that can be connected to other characteristics of amusic individuals (e.g., memory impairments).

The observation that also amusics can experience INMI can be linked to other recent findings showing that amusic individuals have still some implicit capacity to process musical material (e.g., Tillmann et al., 2012; Tillmann, Lalitte, et al., 2016). Indeed, one might argue that musical earworms are less explicit than inner singing for rehearsal or finding a melody in one's mind. It could be referred to as "spontaneous recall", thus not requiring explicit search or effort. INMI might thus benefit from implicit processing, which has also shown its power in the amusic population, notably for pitch processing or tonal structure processing (e.g., Omigie et al., 2013; Tillmann et al., 2012; Zendel et al., 2015). The amusic individuals might also benefit from other dimensions in the "earworm material", notably they might benefit from the lyrics associated to it. Consequently, one might wonder whether amusics are able to report musical earworms because of the memory of verbal information, and even more so as amusic individuals also report verbal earworms (see below).

Regarding the neural correlates, INMI might benefit from the default-network involvement. Indeed, Farrugia et al. (2015) reported a negative correlation between the frequency of INMI episodes and cortical thickness in two regions of the DMN (in particular, AG and ACC), providing evidence of shared mechanisms with other forms of self-generated thoughts. For congenital amusia, resting-state brain activation analyses have revealed not only altered connectivity between auditory cortices and auditory and frontal networks, but also showed an overconnectivity between Heschl's gyri and the core areas of the DMN (notably, medial prefrontal cortex, posterior cingulate cortex, and temporo-parietal junctions; Lévêque et al., 2016), which might perhaps allow amusic individuals to experience this phenomenon of INMI. However, future research of the potentially involved brain correlates and their potential deficit are needed.

Musical and Verbal Earworms

In addition to musical earworms, the questionnaire we used here (adapted from Halpern & Bartlett, 2011) includes an inquiry about verbal earworms. Interestingly, both control and amusic participants reported verbal earworms, while the proportion of amusics who did so was higher than that of controls. In comparison to musical earworms, the frequency of verbal earworms is decreased, with "a few times a month" being the most chosen category, in keeping with Halpern and Bartlett (2011), and did not differ between the two groups. Participants who experienced verbal earworms reported them to be either of different types (e.g., poetry vs. famous speech, 33%) or of the same type but with different sentences/words (33%), somewhat in line with Halpern and Bartlett (2011), where verbal earworms were mostly reported being of different types (67%; note, however, that only 9 participants reported verbal earworms in this earlier study). For both groups of participants, the verbal material was reported being mostly familiar and emotionally neutral, often coming from a conversation.

Beyond the observation that the verbal material was mostly familiar, the responses for verbal earworms further revealed some link to memory and some group differences. While both groups reported that the verbal earworms go away by themselves, this was the case for almost all amusic participants, but only 77% of the controls. This suggests that not only for musical but also for verbal earworms, the memory traces seem to be more volatile for amusics. This observation differs from reports for short-term memory results, notably with amusics showing deficits only for musical, but not for verbal material (e.g., Albouy, Schulze, et al., 2013; Tillmann et al., 2009; Williamson et al., 2010; Williamson & Stewart, 2010) and needs to be further investigated. One might also want to further investigate how this pattern evolves for voluntary mental imagery of both verbal and musical materials.

The potential link with more general cognitive processes involved in mental imagery is further supported by the here observed correlation of the frequency of musical and verbal earworms. Across both groups as well as within each of the groups, the two imageries seem related: the more musical earworms one reports, the more verbal earworms are reported too. However, beyond these similarities between musical and verbal earworms, which might be related to the involvement of domain-general processes, amusics reported less frequent musical earworms than did controls, whereas the reverse was observed for verbal earworms. These findings suggest some specificities of musical versus verbal earworms and highlight the need for further research investigating involuntary imagery across domains.

Conclusion and Perspectives

The present questionnaire investigation confirms that musical earworms are a common experience in the general population, even in non-musicians, and extend this finding to the case of congenital amusia, even if musical earworms are less frequent in this population (see also Loutrari et al., 2022). Verbal earworms also occur, but seem to be a less frequent experience. We here replicated a number of earlier findings about musical earworms: INMI are of diverse musical styles and consist mostly of familiar and liked music with lyrics. Although INMI can be quite sticky in memory, they are generally not perceived as a negative experience. Our present findings support a link between musical earworms and long-term memory, not only because of familiarity effects that have been previously described, but because of the differences observed between amusics and controls, and the correlation with the MBEA incidental memory score as well as the link with our previous data (Graves et al., 2019). Our findings with amusic participants also suggest that musical earworms could be related to implicit musical knowledge and processes that are largely spared in congenital amusia.

The present results open new perspectives to benefit from the investigation of the phenomenon of congenital amusia to further our understanding of INMI in general and its links to memory, emotion, consciousness, and voluntary imagery. Our study is a starting point with a first, rather basic questionnaire; the investigation can now benefit from the various other methods that the research domain of INMI has developed, such as in particular more refined questionnaires (e.g., the Involuntary Musical Imagery Scale of Floridou et al., 2015) or lab-based earworm creation or evocation.

Acknowledgements

We thank Jackson Graves for his help in the supplementary analysis combining musical earworm occurrence with short-term and long-term memory performance in a subset of the participants.

Action Editor

Solange Glasser, University of Melbourne, Melbourne Conservatorium of Music.

Peer Review

Karen Wise, Guildhall School of Music and Drama, Department of Music Therapy
One anonymous reviewer

Contributorship

BT, AC, and PA conceived the study. BT, AC, and LF were involved in gaining ethical approval, participant recruitment and data analyses. AP and CH were involved in participant recruitment and behavioral testing for screening. LF implemented the online version of the questionnaire. BT and AC wrote the first draft of the manuscript. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical Approval

Participants signed a written informed consent prior to behavioral tests, and data collection with the questionnaire followed the appropriate regulation on personal data protection at the time of data collection (questionnaire registered with the CIL at the CNRS #13019).

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was conducted in the framework of the LabEx CeLyA ("Centre Lyonnais d'Acoustique", ANR-10-LABX-0060) and of the LabEx Cortex ("Construction, Function and Cognitive Function and Rehabilitation of the Cortex", ANR-11-LABX-0042) of Université de Lyon, within the program "Investissements d'avenir" (ANR-11-IDEX-0007) operated by the French National Research Agency (ANR).

ORCID iDs

Barbara Tillmann https://orcid.org/0000-0001-9676-5822
Lesly Fornoni https://orcid.org/0000-0003-0239-4165

References

Albouy, P., Cousineau, M., Caclin, A., Tillmann, B., & Peretz, I. (2016). Impaired encoding of rapid pitch information underlies perception and memory deficits in congenital amusia. *Scientific Reports*, *6*, 18861.

Albouy, P., Mattout, J., Bouet, R., Maby, E., Sanchez, G., Aguera, P.-E., Daligault, S., Delpuech, C., Bertrand, O., Caclin, A., & Tillmann, B. (2013). Impaired pitch perception and memory in congenital amusia : The deficit starts in the auditory cortex. *Brain: A Journal of Neurology*, *136*(Pt 5).

Albouy, P., Mattout, J., Sanchez, G., Tillmann, B., & Caclin, A. (2015). Altered retrieval of melodic information in congenital amusia : Insights from dynamic causal modeling of MEG data. *Frontiers in Human Neuroscience*, *9*, 20.

Albouy, P., Peretz, I., Bermudez, P., Zatorre, R. J., Tillmann, B., & Caclin, A. (2019). Specialized neural dynamics for verbal and tonal memory : FMRI evidence in congenital amusia. *Human Brain Mapping*, *40*(3), Art. 3.

Albouy, P., Caclin, A., Norman-Haignere, S. V., Lévêque, Y., Peretz, I., Tillmann, B., & Zatorre, R. J. (2019). Decoding task-related functional brain imaging data to identify developmental disorders: The case of congenital amusia. *Frontiers in Neuroscience*, *13*, 1165.

Albouy, P., Schulze, K., Caclin, A., & Tillmann, B. (2013). Does tonality boost short-term memory in congenital amusia? *Brain Research*, *1537*, 224–232.

Ayotte, J., Peretz, I., & Hyde, K. (2002). Congenital amusia: A group study of adults afflicted with a music-specific disorder. *Brain: A Journal of Neurology*, *125*(Pt 2), Art. Pt 2.

Beaman, C. P. (2018). The literary and recent scientific history of the earworm: A review and theoretical framework. *Auditory Perception & Cognition*, *1*(1–2), 42–65.

Beaty, R. E., Burgin, C. J., Nusbaum, E. C., Kwapil, T. R., Hodges, D. A., & Silvia, P. J. (2013). Music to the inner ears: Exploring individual differences in musical imagery. *Consciousness and Cognition*, *22*(4), 1163–1173.

Byron, T. P., & Fowles, L. C. (2015). Repetition and recency increases involuntary musical imagery of previously unfamiliar songs. *Psychology of Music*, *43*(3), 375–389.

Cuddy, L. L. (2005). Musical difficulties are rare : A study of "tone deafness" among university students. *Annals of the New York Academy of Sciences*, *1060*(1), 311–324.

Farrugia, N., Jakubowski, K., Cusack, R., & Stewart, L. (2015). Tunes stuck in your brain: The frequency and affective evaluation of involuntary musical imagery correlate with cortical structure. *Consciousness and Cognition*, *35*, 66–77.

Floridou, G. A., Williamson, V. J., Stewart, L., & Müllensiefen, D. (2015). The involuntary musical imagery scale (IMIS). *Psychomusicology: Music, Mind, and Brain*, *25*(1), 28–36.

Foxton, J. M., Dean, J. L., Gee, R., Peretz, I., & Griffiths, T. D. (2004). Characterization of deficits in pitch perception underlying « tone deafness ». *Brain: A Journal of Neurology*, *127*(Pt 4), Art. Pt 4.

Foxton, J. M., Nandy, R. K., & Griffiths, T. D. (2006). Rhythm deficits in "tone deafness". *Brain and Cognition*, *62*(1), 24–29.

Gosselin, N., Jolicoeur, P., & Peretz, I. (2009). Impaired memory for pitch in congenital amusia. *Annals of the New York Academy of Sciences*, 1169, 270–272.

Gosselin, N., Paquette, S., & Peretz, I. (2015). Sensitivity to musical emotions in congenital amusia. *Cortex*, *71*, 171–182.

Graves, J. E., Pralus, A., Fornoni, L., Oxenham, A. J., Caclin, A., & Tillmann, B. (2019). Short- and long-term memory for pitch and non-pitch contours: Insights from congenital amusia. *Brain and Cognition*, *136*, 103614.

Halpern, A. R. (1999). When that tune runs through your head: A PET investigation of auditory imagery for familiar melodies. *Cerebral Cortex*, *9*(7), 697–704.

Halpern, A. R., & Bartlett, J. C. (2011). The persistence of musical memories: A descriptive study of earworms. *Music Perception*, *28*(4), 425–432.

Hyde, K. L., Lerch, J. P., Zatorre, R. J., Griffiths, T. D., Evans, A. C., & Peretz, I. (2007). Cortical thickness in congenital amusia: When less is better than more. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *27*(47), Art. 47.

Hyde, K. L., & Peretz, I. (2004). Brains that are out of tune but in time. *Psychological Science*, *15*(5), Art. 5.

Hyde, K. L., Zatorre, R. J., Griffiths, T. D., Lerch, J. P., & Peretz, I. (2006). Morphometry of the amusic brain: A two-site study. *Brain: A Journal of Neurology*, *129*(Pt 10), Art. Pt 10.

Hyde, K. L., Zatorre, R. J., & Peretz, I. (2011). Functional MRI evidence of an abnormal neural network for pitch processing in congenital amusia. In *Cerebral Cortex* 1991), 21(2), Art. 2.

Hyman, I. E., Cutshaw, K. I., Hall, C. M., Snyders, M. E., Masters, S. A., Au, V. S. K., & Graham, J. M. (2015). Involuntary to intrusive: Using involuntary musical imagery to explore individual differences and the nature of intrusive thoughts. *Psychomusicology: Music, Mind, and Brain*, *25*(1), 14–27.

Jakubowski, K., Finkel, S., Stewart, L., & Müllensiefen, D. (2017). Dissecting an earworm: Melodic features and song popularity predict involuntary musical imagery. *Psychology of Aesthetics, Creativity, and the Arts*, *11*(2), 122–135.

Lévêque, Y., Fauvel, B., Groussard, M., Caclin, A., Albouy, P., Platel, H., & Tillmann, B. (2016). Altered intrinsic connectivity of the auditory cortex in congenital amusia. *Journal of Neurophysiology*, *116*(1), Art. 1.

Lévêque, Y., Lalitte, P., Fornoni, L., Pralus, A., Albouy, P., Bouchet, P., Caclin, A., & Tillmann, B. (2022). Tonal structures benefit short-term memory for real music: Evidence from non-musicians and individuals with congenital amusia. *Brain and Cognition*, *161*, 105881.

Lévêque, Y., Schellenberg, G., Fornoni, L., Bouchet, P., Caclin, A., & Tillmann, B. (in press). Individuals with Congenital Amusia Remember Music They Like. *Cognitive, Affective, and Behavioral Neuroscience*.

Lévêque, Y., Teyssier, P., Bouchet, P., Bigand, E., Caclin, A., & Tillmann, B. (2018). Musical emotions in congenital amusia: Impaired recognition, but preserved emotional intensity. *Neuropsychology*, *32*(7), Art. 7.

Liikkanen, L. A. (2012). Musical activities predispose to involuntary musical imagery. *Psychology of Music*, *40*(2), 236–256.

Liikkanen, L. A., & Jakubowski, K. (2020). Involuntary musical imagery as a component of ordinary music cognition : A review of empirical evidence. *Psychonomic Bulletin & Review*, *27*(6), 1195–1217.

Liikkanen, L. A., Jakubowski, K., & Toivanen, J. M. (2015). Catching earworms on Twitter. *Music Perception*, *33*(2), 199–216.

Liu, F., Patel, A. D., Fourcin, A., & Stewart, L. (2010). Intonation processing in congenital amusia: Discrimination, identification and imitation. *Brain*, *133(6)*, 1682–1693.

Loui, P., Alsop, D., & Schlaug, G. (2009). Tone deafness: A new disconnection syndrome? *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *29*(33), Art. 33.

Loutrari, A., Ansell, K., Philip Beaman, C., Jiang, C., & Liu, F. (2022). Auditory imagery in congenital amusia. *Musicae Scientiae*, 102986492211228.

McDonald, C., & Stewart, L. (2008). Uses and functions of music in congenital amusia. *Music Perception*, *25*(4), 345–355.

Müllensiefen, D., Fry, J., Jones, R., Jilka, S., Stewart, L., & Williamson, V. J. (2014). Individual differences predict patterns in spontaneous involuntary musical imagery. *Music Perception*, *31*(4), 323–338.

Nan, Y., Sun, Y., & Peretz, I. (2010). Congenital amusia in speakers of a tone language: Association with lexical tone agnosia. *Brain*, *133*(9), 2635–2642.

Nguyen, S., Tillmann, B., Gosselin, N., & Peretz, I. (2009). Tonal language processing in congenital amusia. *Annals of the New York Academy of Sciences*, *1169*(1), 490–493.

Omigie, D., Müllensiefen, D., & Stewart, L. (2012). The experience of music in congenital amusia. *Music Perception: An Interdisciplinary Journal*, *30*(1), Art. 1.

Omigie, D., Pearce, M. T., Williamson, V. J., & Stewart, L. (2013). Electrophysiological correlates of melodic processing in congenital amusia. *Neuropsychologia*, *51*(9), 1749–1762.

Peretz, I. (2016). Neurobiology of congenital amusia. *Trends in Cognitive Sciences*, *20*(11), Art. 11.

Peretz, I., Ayotte, J., Zatorre, R. J., Mehler, J., Ahad, P., Penhune, V. B., & Jutras, B. (2002). Congenital amusia: A disorder of fine-grained pitch discrimination. *Neuron*, *33*(2), Art. 2.

Peretz, I., Brattico, E., Järvenpää, M., & Tervaniemi, M. (2009). The amusic brain: In tune, out of key, and unaware. *Brain: A Journal of Neurology*, *132*(Pt 5), Art. Pt 5.

Peretz, I., Gosselin, N., Tillmann, B., Cuddy, L. L., Gagnon, B., Trimmer, C. G., Paquette, S., & Bouchard, B. (2008). On-line identification of congenital amusia. *Music Perception*, *25*(4), 331–343.

Peretz, I., & Vuvan, D. T. (2017). Prevalence of congenital amusia. *European Journal of Human Genetics*, *25*(5), 625–630.

Pfeuty, M., & Peretz, I. (2010). Abnormal pitch—time interference in congenital amusia: Evidence from an implicit test. *Attention, Perception, & Psychophysics*, *72*(3), 763–774.

Quiroga-Martinez, D. R., Tillmann, B., Brattico, E., Cholvy, F., Fornoni, L., Vuust, P., & Caclin, A. (2020). Listeners with congenital amusia are sensitive to context uncertainty in melodic sequences. *bioRxiv*, 2020.07.07.191031.

Sloboda, J. A., Wise, K. J., & Peretz, I. (2005). Quantifying tone deafness in the general population. *Annals of the New York Academy of Sciences*, *1060*(1), 255–261.

Stewart, L. (2008). Fractionating the musical mind: Insights from congenital amusia. *Current Opinion in Neurobiology*, *18*(2), 127–130.

Tillmann, B., Albouy, P., & Caclin, A. (2015). Congenital amusias. *Handbook of Clinical Neurology*, *129*, 589–605.

Tillmann, B., Albouy, P., Caclin, A., & Bigand, E. (2014). Musical familiarity in congenital amusia: Evidence from a gating paradigm. *Cortex; a Journal Devoted to the Study of the Nervous System and Behavior*, *59*, 84–94.

Tillmann, B., Gosselin, N., Bigand, E., & Peretz, I. (2012). Priming paradigm reveals harmonic structure processing in congenital amusia. *Cortex*, *48*(8), 1073–1078.

Tillmann, B., Lalitte, P., Albouy, P., Caclin, A., & Bigand, E. (2016). Discrimination of tonal and atonal music in congenital amusia: The advantage of implicit tasks. *Neuropsychologia*, *85*, 10–18.

Tillmann, B., Lévêque, Y., Fornoni, L., Albouy, P., & Caclin, A. (2016). Impaired short-term memory for pitch in congenital amusia. *Brain Research*, *1640*(Pt B), Art. Pt B.

Tillmann, B., Rusconi, E., Traube, C., Butterworth, B., Umiltà, C., & Peretz, I. (2011). Fine-grained pitch processing of music and speech in congenital amusia. *The Journal of the Acoustical Society of America*, *130*(6), Art. 6.

Tillmann, B., Schulze, K., & Foxton, J. M. (2009). Congenital amusia: A short-term memory deficit for non-verbal, but not verbal sounds. *Brain and Cognition*, *71*(3), Art. 3.

Williams, T. I. (2015). The classification of involuntary musical imagery: The case for earworms. *Psychomusicology: Music, Mind, and Brain*, *25*(1), 5–13.

Williamson, V. J., Liikkanen, L. A., Jakubowski, K., & Stewart, L. (2014). Sticky tunes: How do people react to involuntary musical imagery? *PLoS ONE*, *9*(1), e86170.

Williamson, V. J., McDonald, C., Deutsch, D., Griffiths, T. D., & Stewart, L. (2010). Faster decline of pitch memory over time in congenital amusia. *Advances in Cognitive Psychology*, *6*, 15–22.

Williamson, V. J., & Stewart, L. (2010). Memory for pitch in congenital amusia: Beyond a fine-grained pitch discrimination problem. *Memory (Hove, England)*, *18*(6), Art. 6.

Zatorre, R. J., & Halpern, A. R. (2005). Mental concerts: Musical imagery and auditory cortex. *Neuron*, *47*(1), 9–12.

Zendel, B. R., Lagrois, M.-E., Robitaille, N., & Peretz, I. (2015). Attending to pitch information inhibits processing of pitch information: The curious case of amusia. *Journal of Neuroscience*, *35*(9), 3815–3824.

APPENDIX

1. Connaissez-vous l'expression « avoir une musique/chanson dans la tête » ?*[Do you know the expression "having music/song in your head"?]*

◯ OUI ◯ NON *[Yes/No]*

2. Avez-vous déjà eu de la musique dans la tête? [Have you ever had the experience of music in your head?]

◯ OUI ◯ NON*[Yes/No]*

si oui, cela vous arrive-t-il souvent(choisissez une seule proposition) *[If so, does this happen often to you? Choose one response option.]*

◯ Quelques fois par an *[A few times a year]*
◯ Quelques fois par mois *[A few times a month]*
◯ Quelques fois par semaine *[A few times a week]*
◯ Presque tous les jours *[Almost daily]*

3. Quelle proposition décrit le mieux la musique que vous entendez dans votre tête? (choisir une seule proposition)*[Which statement best describes the music you hear in your head (choose one)?]*

◯ Le type de musique que vous entendez peut être très différent (par exemple, du rock ou de la musique classique) *[The type of music you hear may be very different (for example, rock or classical music)]*
◯ Le type de musique est toujours le même mais les morceaux sont différents *[The type of music is always the same but the musical pieces are different]*
◯ Ce sont toujours les mêmes morceaux qui se répètent *[Always the same musical pieces are repeated]*
◯ Le même morceau de musique se répète presque tout le temps *[The same piece of music is repeated almost all the time]*

4. Si vous avez coché les propositions 2, 3 ou 4 de la question 3[1], pensez au type de morceau de musique que vous entendez le plus souvent dans votre tête. Sélectionnez une proposition pour chaque item qui décrit le mieux ce type de musique: *[If you checked 2, 3 or 4 of question 3, think about the type of music that you hear the most often in your head. Select for each item one choice that best describes this type of music:]*

a. Musique familière__ Musique non familière__ *[Familiar music … Unfamiliar music]*
b. Musique avec des paroles __ Musique sans paroles___ *[Music with lyrics … Music without lyrics]*
c. Musique que vous appréciez__ Musique que vous n'appréciez pas__ Musique neutre__ *[Music that you like … Music that you do not like … Neutral music]*
d. Type de musique (choisissez un ou plusieurs items): *[Type of music (choose one or several options):]*

◯ Musique de programme télévisé *[Music of TV programs]*
◯ Musique classique *[Classical music]*
◯ Pop *[Pop]*
◯ Rock *[Rock]*
◯ Jazz *[Jazz]*
◯ Country *[Country]*
◯ Musique pour enfant *[Music for children]*
◯ Tube de l'été *[Summer hit]*
◯ Musique de film *[Movie soundtrack]*
◯ Morceau religieux *[Religious music]*
◯ autres (précisez): …. *[Other (specify):]*

e. Le cas échéant, pouvez-vous écrire le nom du morceau de musique que vous avez le plus souvent entendu dans votre tête: *[If applicable, can you write down the name of the musical piece that you have heard most often in your head:]*

5. Quand un air de musique persiste dans votre tête, vous trouvez cette expérience *[When a tune lingers in your head, do you find this experience]*

◯ agréable *[pleasant]*
◯ désagréable *[unpleasant]*
◯ neutre *[neutral]*

6. Lorsque vous avez de la musique dans la tête, est-il difficile de vous en séparer (musique/chanson persistante dans la tête)? *[When you have music in your head, is it difficult for you to separate yourself from it (music/song lingering in your head)?]*

◯ OUI ◯ NON *[Yes/No]*

7. Comment cela se termine en général? *[How does it usually end?]*

◯ la musique s'en va toute seule, sans que vous ne fassiez d'efforts particuliers *[the music goes away by itself, without you making any particular effort]*
◯ il est très difficile, si ce n'est impossible de l'arrêter *[it is very difficult, if not impossible to stop it]*
◯ Vous adoptez une stratégie particulière pour l'arrêter, si oui pouvez-vous la décrire …………
…………………………………………………………

………………… *[You adopt a particular strategy to stop it, if so, can you describe it]*

8. Avez-vous déjà eu des phrases (sans musique) se répétant sans cesse dans votre tête? *[Have you ever had phrases/sentences (without music) repeated over and over in your head?]*

◯ OUI ◯ NON *[Yes/No]*

si oui, cela vous arrive-t-il souvent(choisissez une seule proposition) *[If so, does this happen often to you? Choose one response option.]*

○ Quelques fois par an *[A few times a year]*
○ Quelques fois par mois *[A few times a month]*
○ Quelques fois par semaine *[A few times a week]*
○ Presque tous les jours *[Almost daily]*

9. Quelle proposition décrit le mieux les mots/phrases que vous entendez dans votre tête? *[Which statement describes best the words/sentences you hear in your head?]*

○ Le type de langage que vous entendez dans votre tête est différent (par exemple de la poésie, et des contes) *[The type of language you hear in your head is different (e.g., poetry, and stories)]*
○ Le type de langage est toujours le même mais les mots/phrases changent *[The type of language is always the same but the words/sentences change]*
○ Les mêmes mots sont répétés très fréquemment *[The same words are repeated very frequently]*
○ Les mêmes mots sont répétés tout le temps *[The same words are repeated all the time]*

10. Si vous avez coché les propositions 2, 3, 4 de la question 9[2], pensez au type de mots que vous entendez le plus souvent dans votre tête *[If you checked off 2, 3, 4 in question 9, think of the type of words you hear most often in your head]*

a. Mots familiers__ Mots non familiers__ *[Familiar words …. Unfamiliar words]*

b. Mots que vous aimez__ mots que vous n'aimez pas__ mots neutre__ *[Words that you like … Words that you do not like …. Neutral words]*

c. Type: *[Type]*
○ Poésie *[Poetry]*
○ Discours célèbre *[Famous speech]*
○ Conte *[Storytelling]*
○ Publicité *[Advertisement]*
○ Partie d'une conversation que vous avez eue *[Part of a conversation you had]*
○ Autre (décrivez)… *[Other (describe)]*

11. Quand ces phrases/mots persistent dans votre tête, vous trouverez cette expérience? *[When these phrases/ words persist in your head, you will find this experience]*

○ agréable *[pleasant]*
○ désagréable *[unpleasant]*
○ neutre *[neutral]*

12. Comment cela se termine en général*[How does it usually end?]*

○ Les phrases (/mots) s'en vont toutes seules, sans que vous ne fassiez d'efforts particuliers *[The sentences (/words) go away by themselves, without any particular effort]*
○ Il est très difficile si ce n'est impossible de l'arrêter *[It is very difficult if not impossible to stop it]*
○ Vous adoptez une stratégie particulière pour l'arrêter, si oui pouvez-vous la décrire …………………… ………………………………………………………… …………….. *[You have a particular strategy to stop it, if so can you describe it ?]*

Notes

1. For this question and for question 10, our online version had an error in the implementation (i.e., not choosing the same options from question 3 for some participants and still allowing for responding to the options a)–e) afterwards). We also noted that in the paper version, participants did not respect this restrictions. It turned out that these responses were quite valuable, irrespective of the answer to question 3. We thus recommend for future implementations to remove the condition ("if you checked …") and ask these questions to every participant.
2. See footnote 1.