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RESEARCH ARTICLE

Individuals with congenital amusia remember music they like

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Abstract
Music is better recognized when it is liked. Does this association remain evident when music perception and memory are severely impaired, as in congenital amusia? We tested 11 amusic and 11 matched control participants, asking whether liking of a musical excerpt influences subsequent recognition. In an initial exposure phase, participants—unaware that their recognition would be tested subsequently—listened to 24 musical excerpts and judged how much they liked each excerpt. In the test phase that followed, participants rated whether they recognized the previously heard excerpts, which were intermixed with an equal number of foils matched for mode, tempo, and musical genre. As expected, recognition was in general impaired for amusic participants compared with control participants. For both groups, however, recognition was better for excerpts that were liked, and the liking enhancement did not differ between groups. These results contribute to a growing body of research that examines the complex interplay between emotions and cognitive processes. More specifically, they extend previous findings related to amusics' impairments to a new memory paradigm and suggest that (1) amusic individuals are sensitive to an aesthetic and subjective dimension of the music-listening experience, and (2) emotions can support memory processes even in a population with impaired music perception and memory.

Keywords Music · Amusia · Recognition · Memory · Emotion

Introduction

Although associations between emotion and memory have been studied for more than a century (Tait, 1913), numerous questions remain regarding the mechanisms underlying their reciprocal influences. It is well established that emotional events are better remembered than nonemotional events across different modalities and stimulus types (Bennion et al., 2013; Talmi, 2013; LaBar & Cabeza, 2006, for a review of brain correlates supporting emotional memory). Musical stimuli are particularly useful for this type of research because of their potential to engage cognitive resources (Krumhansl, 1990; Tillmann, 2012), and their ability to evoke complex emotional responses (Hunter et al., 2008), seemingly without effort.

The effect of emotion on memory appears to be mediated by arousal and valence. For example, high-arousing musical stimuli are likely to boost attention, which facilitates information processing and encoding (Eschrich et al., 2005; Samson et al., 2009), and positively valenced music is recognized better than negatively valenced music (Eschrich et al., 2008). Nevertheless, controlling the number of musical events negates the arousal effect on memory for happy music in comparison to neutral and sad music, and valence cannot explain enhanced memory for fearful excerpts over sad ones after accounting for arousal (Aubé et al., 2013). In short, associations between emotions and memory for music are not reducible to effects of arousal and/or valence.

Indeed, the full, emotional experience of music listening cannot be explained solely by stimulus-dependent features, including but not limited to arousal and valence (Cowen et al., 2020). Emotional responses to music are personal and subjective, and these listener-dependent processes also might

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influence memory. Such subjective influences are evident not only in the music domain (Ferreri & Rodriguez-Fornells, 2022), but also in the marketing domain, when advertisements that are liked lead to increased recall, recognition, or purchases (Thorson & Reeves, 1986; Youn et al., 2001).

In one study (Stalinski & Schellenberg, 2013), participants listened to a set of unfamiliar excerpts of music and rated how much they liked each excerpt. After a delay, they heard the same excerpts again, intermixed with foils, and judged whether each excerpt was presented in the liking phase. Participants recognized better the excerpts they liked initially compared with those they had disliked or felt neutral about. In follow-up experiments, other extraneous factors were controlled (e.g., order of liking and recognition judgments, familiarity with the music), yet the observed association was replicated in all instances. Moreover, in another study (Ferreri & Rodriguez-Fornells, 2017), participants heard a set of musical excerpts and rated how rewarding each excerpt was. One day later, excerpts that were previously experienced as more rewarding were also better recognized and remembered.

Associations between emotions and memory for music have also been reported for patients with pathologies that include impaired memory. In Alzheimer's disease (AD), for example, higher levels of familiarity are observed for happy- than for sad-sounding music after eight sessions of exposure to the stimuli (Samson et al., 2009), indicating an improvement of episodic memory due to the presence of positive emotion at encoding. Music also enhances recall of autobiographical memories for patients with AD (El Haj et al., 2012), particularly when the participants can select music that they like. Although music recognition declines in healthy aging, emotions continue to benefit music recognition, as they do for younger listeners (Alonso et al., 2015).

In the present study, we investigated whether associations between emotion and memory for music remain evident when the ability to process and memorize music is selectively impaired. *Congenital amusia* is characterized by poor performance in discriminating tones and musical excerpts, and in particular by poor memory for music, even though general cognitive abilities (including verbal memory) are intact and the disorder cannot be attributed to hearing impairment or cerebral damage (Ayotte et al., 2002; Peretz & Hyde, 2003; Tillmann et al., 2016). Although impaired short-term memory for music and other nonverbal sounds (i.e., timbre) has been observed for individuals with congenital amusia in numerous studies (Tillmann et al., 2009, 2016; Williamson & Stewart, 2010), far fewer studies have examined long-term memory. Congenital amusics recognize familiar songs (without lyrics) above chance levels, but their performance is impaired relative to controls (open-set naming in Ayotte et al., 2002; closed-set naming in Graves et al., 2019). Specifically, compared with controls, the ability of amusic participants to identify a familiar melody based on its pitch contour is impaired, as is recognition based on brightness or loudness contours (Graves et al., 2019). In other words, mental representations of musical features seem to be impaired in congenital amusics' long-term memory, which could lead to impairments in melodic familiarity and recognition when participants are asked to make old-new judgments (Ayotte et al., 2002). Congenital amusic individuals also perform poorly on the Incidental Memory subtest from the Montreal Battery of Evaluation of Amusia (MBEA; Peretz et al., 2003; Jiang et al., 2013; Lévêque et al., 2018), which tests recognition of computer-generated melodies that were heard five times previously.

Despite having impaired long-term memory for music, congenital amusics exhibit feelings of familiarity for instrumental music that are similar to those of controls when evaluated with a less direct (i.e., *implicit*) approach (Tillmann et al., 2014), which suggests that some aspects of musical information have been stored in memory. Thus, congenital amusics' long-term memory appears to retain a musical lexicon, even though it may be deficient or difficult to access. For example, amusic individuals take longer than controls to respond when they are asked to provide familiarity judgements (Tillmann et al., 2014).

Previous research that investigated musical *emotions* in congenital amusia reports equivocal findings. According to two surveys (McDonald & Stewart, 2008; Omigie et al., 2012), approximatively half of amusic participants reported not liking music and/or feeling few emotions when listening to music (Ayotte et al., 2002; Peretz et al., 2002). Nevertheless, some experimental studies found no differences between amusic and control participants in their ability to recognize emotions in music (Ayotte et al., 2002; Gosselin et al., 2015; Jiang et al., 2017) or in speech prosody (Ayotte et al., 2002; Hutchins et al., 2010). In one instance (Lévêque et al., 2018), amusics had impaired recognition of specific emotions expressed by music, even though they were similar to controls when asked to evaluate emotional *intensity*. This type of result across tasks was also observed for judgments of emotions in speech prosody (Pralus et al., 2019).

In short, although amusics' performance on music perception and cognition tasks is impaired, their musical feelings in daily life and emotional judgments of musical excerpts may be preserved (Lévêque et al., 2018; McDonald & Stewart, 2008). This hypothesis is consistent with previous reports showing that a brain-damaged (acquired) amusic patient (I.R.) experiences musical emotions and provides normal emotional judgments for musical excerpts, even though she cannot discriminate the same excerpts or identify well-known excerpts, or detect an obvious melodic error (Peretz et al., 1998a; Peretz & Gagnon, 1999). Other individuals show the opposite pattern, with intact music-cognition skills but impaired emotional responding to music, as in congenital or acquired *anhedonia* (Mas-Herrero et al., 2014; Satoh et al., 2011). Additional evidence of partial independence between music cognition and emotion comes from the general populations, whose music-discrimination skills correlate weakly with their emotion-perception abilities (Fuentes-Sánchez et al., 2021). Moreover, performance on music-perception tasks is often correlated positively with music training (Schellenberg & Weiss, 2013), whereas performance on tasks that measure emotional responding, such as ratings of tension or emotionality of music, as well as physiological measurements of emotion responding, can be independent of training (Steinbeis et al., 2006).

In the present study, we tested the hypothesis that liking music—an emotional evaluation—influences memory for music. Liking might boost subsequent recognition because of greater activation of the reward system, in congenital-amusic participants as well as controls (Ferreri & Rodriguez-Fornells, 2022; Miendlarzewska et al., 2016*).* The potential benefit of liking on memory has parallels with previously observed benefits of tonal structures, which improve musical memory in congenital amusia (Albouy et al., 2013b; Lévêque et al., 2022). Amusics' memory traces for music, which fade easily due to memory load, interference, or time (Williamson et al., 2010; Williamson & Stewart, 2010; Gosselin et al., 2009), could be enhanced by beneficial influences of other features, such as liking and tonality. Musical memory might thus benefit from its interaction with other functional networks, such as those underlying emotions or implicit knowledge of musical structure (tonality). For instance, joyful music improves visual attention in congenital amusia (Fernandez et al., 2021), which suggests a potential influence of musical emotions on cognition.

Our goals were to evaluate (1) congenital amusics' ability to recognize a musical excerpt heard in a preceding experimental phase, and (2) the potential benefit of liking on musical long-term memory. As in Stalinski and Schellenberg (2013), the procedure had an initial experimental phase in which participants made liking ratings for musical excerpts, followed by a second experimental phase that asked for recognition ratings. The musical stimuli were unfamiliar but excerpted from real-world musical recordings. Instead of encoding one melody and intentionally keeping it in memory for a couple of seconds (as in a same/different task emphasizing short-term memory; Tillmann et al., 2016), memory was tested across two experimental phases, with excerpts potentially encoded unintentionally in long-term memory during the first phase, when participants provided liking judgements. Incidental encoding was chosen to keep in line with the protocol of Stalinski and Schellenberg (2013), and because implicit processing mechanisms seem to be better preserved in amusia than explicit, conscious mechanisms (Omigie et al., 2012; Tillmann et al., 2012). It also has the advantage of reflecting ecological listening conditions when musical memories are created by mere exposure.

We predicted that overall music recognition would be lower for amusic participants compared with controls, based on their impaired long-term memory for melodies (Ayotte et al., 2002; Peretz et al., 2003). A second, novel prediction was that amusics would better recognize music that they liked, demonstrating an influence of personal musical appreciation on memory, even in individuals with musical impairments. This second prediction was motivated by amusics' preserved ability to perceive emotional intensity in music (Lévêque et al., 2018), and from prosodic cues in speech (Pralus et al., 2019).

Method

Participants

Eleven amusic participants (7 women) and 12 control participants (8 women) provided written, informed consent to participate in the study. All participants received token remuneration. One control participant was excluded because of a difference between recognition scores for old and new excerpts (indicating successful recognition) that was more than two *SD*s below the average of the control group and lower than any score in the amusic group. Thus, the final sample comprised 11 participants in both groups. As shown in Table 1, the two groups did not differ significantly in terms of age, education, and music training. Mean MBEA scores are presented in Table 1. As expected, amusic participants had lower scores than controls on all MBEA subtests evaluating pitch perception, as reflected in the composite "MBEA Pitch" score (McDonald & Stewart, 2008), as well as in the incidental memory subtest. This last subtest—the only test involving long-term memory and implicit encoding in the MBEA—evaluates recognition of melodic sequences that were heard in the preceding subtests. As shown in Table 1, the amusic group also had a higher (worse) mean Pitch Discrimination Threshold (PDT) and a lower Musical Emotion score (see below for details).

Materials and stimuli

Participants were first tested in a separate session with an audiometry, the MBEA with its six subtests (Peretz et al., 2003) and an adaptive pitch-discrimination threshold (PDT) test (two-down/one-up staircase procedure, following Tillmann et al., 2009). The audiometry revealed normal peripheral hearing in all participants (loss <25dB at 250, 500, 1000, 2000, 4000, 6000, and 8000 Hz in either ear). To be classified as amusic, participants had to obtain an average score on the MBEA at least two *SD*s below norms (i.e., cutoff score of 23, maximum score = 30; Peretz et al., 2003).

Before the experimental session and as part of the general screening procedure, participants completed a questionnaire

Table 1 Descriptive statistics (mean ± SD) and group comparisons (*t*-tests) for age, years of education, years of music training, pitch discrimination threshold (PDT), musical emotion scores, and MBEA scores. The maximum MBEA score was 30 (Chance = 15)

	Amusics ($n = 11$)	Controls ($n = 11$)	*t*-test *p*-value
Age (yr)^	34.1 ± 14.1	30.4 ± 8.0	0.457
Education (yr)	15.5 ± 2.2	14.4 ± 2.2	0.214
Music training (yr)	0.27 ± 0.9	0.36 ± 0.8	0.806
PDT (semitones)	0.73 ± 0.5	0.26 ± 0.2	0.013
Musical emotion score*^	3.27 ± 0.7	3.95 ± 0.4	0.024
MBEA			
Global	21.1 ± 1.5	26.9 ± 1.7	< .001
Pitch	19.3 ± 2.5	26.6 ± 2.3	< .001
Rhythm	24.3 ± 3.8	26.8 ± 2.7	.092
Meter	21.3 ± 3.1	26.3 ± 3.0	<.001
Incidental memory	23.1 ± 3.1	28.6 ± 1.1	< .001

*Data missing for one amusic and two control participants

^Unequal variances *t*-test

“Global” is the average of correct answers on all six subtests of the MBEA. “Pitch” corresponds to the average of correct answers on the three pitch subtests of the MBEA. “Rhythm” and “Meter” are subtests 4 and 5. “Incidental Memory” is the final subtest of the MBEA

about their musical experiences and their relationship with music. This questionnaire, also used in Lévêque et al. (2018), was based on others used previously (McDonald & Stewart, 2008; Peretz et al., 2009; Sloboda et al., 2005). Among more than 90 questions, 14 asked about personal experiences of musical emotions (9 positive, 5 negative; e.g., *Certain music can sometimes motivate or excite me*). On a scale from 1 to 5, participants indicated their agreement with each statement (1: *Completely disagree*, 5: *Completely agree*). One amusic and two control participants did not fill out the questionnaire. Following Lévêque et al. (2018), the ratings of the 14 “emotion” items were averaged for each participant (reverse coding negative items) to compute a Musical-Emotion score (Table 1). Higher scores indicated stronger emotional reactivity to music.

The experimental stimuli were 48 music excerpts, with 32 taken from Stalinski and Schellenberg (2013), which came originally from Hunter et al. (2008). We added 16 new excerpts, because informal pilot testing suggested that 16 of the 48 excerpts used by Stalinski and Schellenberg (2013) were at risk of being recognized by our French participants. These were thus replaced by lesser-known excerpts, according to the same design constraints regarding style, mode, tempo, length, and instrumentation. All excerpts were taken from commercial recordings (Hunter et al., 2008; Appendix for the 16 new excerpts). All had a duration of 15 s and were instrumental (i.e., without vocals), encompassing a wide variety of musical genres. Excerpts were paired by composer/artist or genre and by valence and arousal, so that we could form two stimulus lists (List A and List B), both with 24 excerpts with one from each pair in each list, such that valence and arousal were counterbalanced. In both lists, 6 excerpts were happy sounding (fast tempo, major mode), 6 were sad (slow and minor) and 12 were mixed (fast and minor, or slow and major). *Presentation* software (Neurobehavioral systems, Albany, CA) was used to present the stimulus excerpts and record responses.

Procedure

The experiment took place in a sound-attenuating booth. The testing session included two phases: an exposure phase when participants listened to target musical excerpts and provided a liking rating for each excerpt, and a test phase when participants listened to target and foil musical excerpts and provided a recognition rating for each one.

In the initial exposure phase, participants listened to 24, 15-s excerpts (List A or List B). After each, they provided a subjective liking rating using a scale from 1 (*dislike a lot*) to 5 (*like a lot*). Presentation of the 24 trials was self-paced. The presentation of list A or list B was counterbalanced, with trials in a different random order for each participant. Participants were unaware that their recognition would be tested subsequently. A delay of 5 to 10 min followed, when participants filled out a demographic questionnaire. For a subset of participants (5 from the amusic group, 8 from the control group), we also asked whether they knew any of the music excerpts. If they answered positively, we asked them to provide details about the “recognized” pieces. Most responses (8 of 13) suggested no recognition at all or were vague (e.g., *I think I recognized some classical music*; *sounds familiar*). No artist, composer, or title of the musical piece was identified, except for one artist who was identified by one control participant.

In the subsequent test phase, participants heard all 48 musical excerpts (24 old, 24 new) presented in a different random order for each participant. For each, they rated how confident they were that they heard the excerpt in the exposure phase, using a scale from 1 (*sure I heard it*) to 7 (*sure I did not hear it*).

Results

Recognition ratings

Recognition ratings were averaged for each participant, separately for old and new musical excerpts. Preliminary analyses revealed no main effect of list (A or B) on recognition ratings and no interactions involving list and liking or group. List was not considered further. Data are illustrated in Fig. 1 (response frequencies) and Fig. 2 (mean comparisons). Both groups were above chance level, as measured by a paired t-test comparing "old" and "new" ratings (Controls: $t(10) = 16.27$, $p < 0.001$; Amusics: $t(10) = 7.36$, $p < 0.001$). A mixed-design Analysis of Variance (ANOVA), with excerpt type (old or new) as a repeated measure and group (amusic or control) as a between-subjects factor, revealed no main effect of group, $F < 1$. There was a significant main effect of excerpt type, $F(1, 20) = 227.22$, $p < 0.001$, partial $\eta^2 = 0.919$, which was qualified by a two-way interaction with group, $F(1, 20) = 7.58$, $p = 0.012$, partial $\eta^2 = 0.275$. The difference between old and new ratings was smaller for amusics than for controls, confirming impaired recognition for amusics, as predicted (Fig. 2). More detailed analyses identified that old ratings (i.e., correct recognition) were higher for controls than amusics, $p = 0.045$, but there was no group difference for new ratings (i.e., incorrect recognition or false alarms), $p = 0.140$ (Fig. 2).

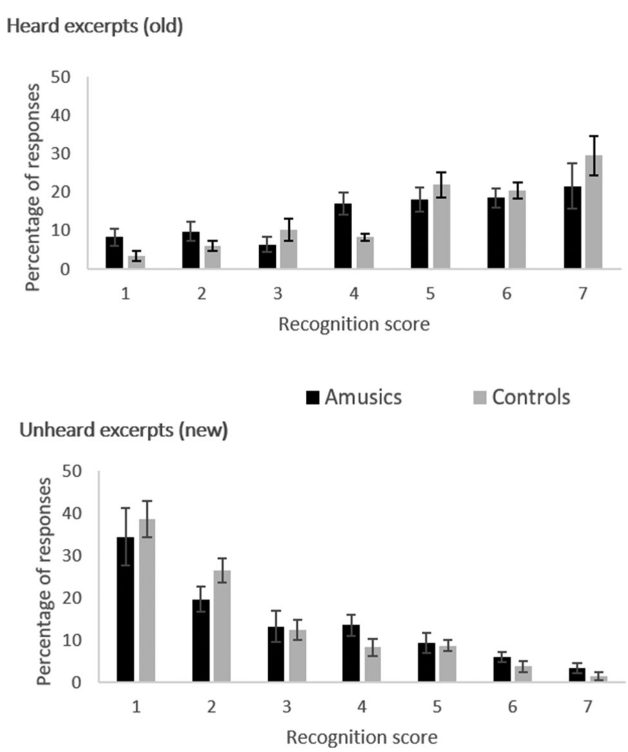

Fig. 1 Distribution of recognition scores for "old" (upper panel) and "new" (middle panel) musical excerpts, separately for amusics and controls. Error bars represent standard errors

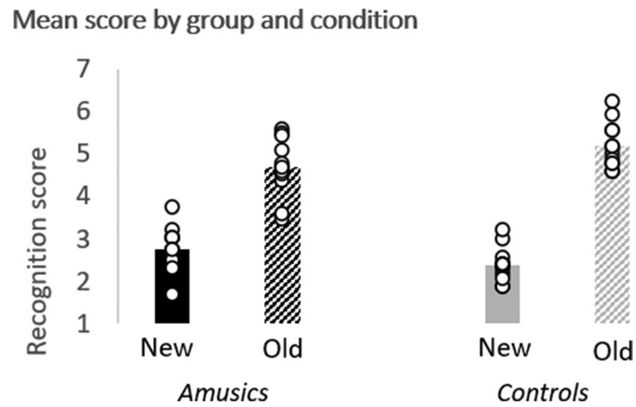

Fig. 2 Mean recognition scores, averaged by Group and Excerpt type (old or new). Circles represent individual data

Liking and recognition

As in Stalinski and Schellenberg (2013), liking ratings for the 24 excerpts heard in the first phase were divided into three categories. Excerpts were considered "disliked" if they were rated 1 or 2, "neutral" if rated 3, and "liked" if rated 4 or 5. The number of liking ratings in each category could thus vary from participant to participant depending on how much they appreciated the musical stimuli. For example, some participants may have disliked 6 of the 24 excerpts in the liking phase, whereas others may have disliked 8. Response proportions are provided in Table 2. Every participant liked, disliked, or felt neutral about some excerpts.

Recognition ratings were averaged separately for liked, neutral, and disliked excerpts. Descriptive statistics are illustrated in Fig. 3. A mixed-design ANOVA with liking as a within-subject factor (liked, neutral, disliked) and group as a between-subjects factor (amusic, control) revealed a main

Table 2 Percentage of excerpts in each liking category for each group

	Disliked	Neutral	Liked
Amusics	38.1%	25.7%	36.2%
Controls	34.6%	23.1%	42.3%

effect of liking, $F(2, 40) = 13.47$, $p < 0.001$, partial $\eta^2 = 0.402$, but no main effect of group, $p = 0.097$, and no interaction between liking and group, $p = 0.408$. In other words, the liking effect on recognition did not differ significantly between amusics and controls. As in Stalinski and Schellenberg (2013), Bonferroni-corrected pairwise comparisons confirmed that liked excerpts were recognized better than neutral and disliked excerpts, $ps \leq 0.001$, which did not differ, $p = 0.882$.

A final analysis used Bayesian statistics (JASP 0.16.3, JASP Team, 2022, default priors) to examine further the null group effect (i.e., no interaction between liking and group), and whether it was likely to be a Type II error. For each participant, a *liking effect* score was calculated as the difference between recognition ratings for liked and disliked excerpts. A Bayesian independent-samples *t*-test asked whether the observed data were more likely under the alternative (control > amusic) or null (control = amusic) hypotheses. The results revealed that the data were 5.2 times more likely under the *null* hypothesis, which provided substantial support for the null two-way interaction between group and liking reported above.

Correlations: Recognition, liking, and musical ability

The next set of analyses determined whether recognition accuracy and the association between recognition accuracy and liking could be predicted by other musical abilities. *Recognition accuracy* was calculated as the difference between old and new recognition ratings. Recognition accuracy and the liking effect were not correlated significantly, $r = -0.260$, $N = 22$, $p = 0.243$.

Correlations with PDT, Musical Emotions, and MBEA scores (MBEA Global, Pitch, and Incidental Memory) are provided in Table 3. For both groups considered jointly, significant positive correlations with recognition accuracy were observed for MBEA Global, Pitch, and Incidental Memory scores. By contrast, the liking effect was associated negatively with only one variable, Emotional Responding, but this correlation was influenced by a single amusic outlier who had a high liking-effect score and a low musical-emotion score (see Fig. A in supplemental material). Removing this participant made the correlation non-significant, $r = -0.271$, $N = 21$, $p = 0.277$. Correlations conducted separately for the two groups are also provided in Table 3, but should be interpreted with caution because of the small sample sizes.

Discussion

The present study investigated recognition memory and its association with liking in a sample of individuals with congenital amusia by using a two-phase recognition paradigm and ecologically valid musical material. Our findings revealed impaired long-term musical memory in the amusic group compared with the control group, as predicted. We also observed a liking effect on music recognition that

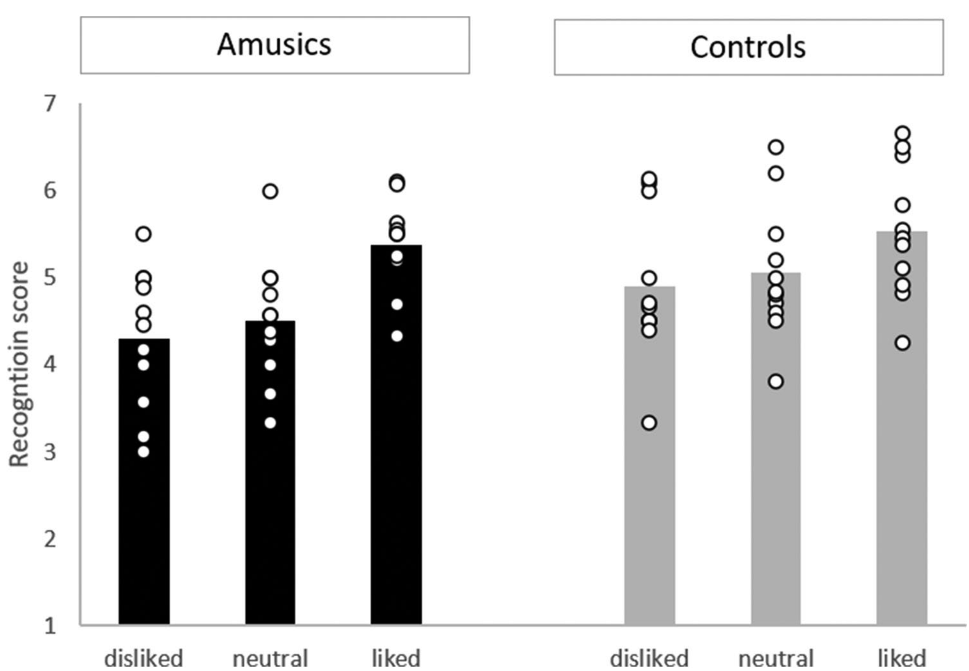

Fig. 3 Mean recognition scores as a function of liking ratings, separately for amusics and controls. Circles represent individual data

Table 3 Pearson correlations between outcome variables (recognition accuracy, liking effect) and other music-related variables for all participants ($N = 22$) and for both groups separately (ns = 11)

	Recognition accuracy			Liking effect		
	All	Amusics	Controls	All	Amusics	Controls
PDT	−0.011	0.341	0.540	0.081	−0.148	0.043
Musical emotions	0.390	0.177	0.179	**−0.501**	−0.380	−0.321
MBEA						
Global	**0.569***	**0.617**	−0.181	−0.321	−0.104	−0.118
Pitch	**0.517**	0.245	0.026	−0.414	−0.419	−0.163
Incidental memory	**0.584***	0.510	−0.389	−0.175	0.252	−0.297

Bold font indicates a significant correlation, $p < 0.05$

*Significant correlations after Bonferroni correction lowering the significance threshold to 0.01. The music-related variables were significantly correlated with each other ($rs > 0.4$, $ps < 0.03$), except the PDT, which was not significantly correlated with the Musical Emotions score ($r = -0.31$, $p = 0.20$), or the Incidental Memory score ($r = -0.28$, $p = 0.21$)

was similar for amusics and controls. This effect, which was demonstrated previously in a sample of undergraduates with various musical backgrounds (Stalinski & Schellenberg, 2013), is notable for being evident in a sample of participants with very little musical training, and even more remarkable for being evident among amusic participants. In short, favorable emotional responding improves nonmusicians' as well as amusics' memory for music, despite their impairments in pitch processing and music recognition.

Musical memory in congenital amusia

Evidence of amusics' deficits in musical *short-term* memory comes from behavioral and neuroimaging studies (Tillmann et al., 2016), which typically use same/different discrimination tasks, such that standard and comparison stimuli are separated by a few seconds. Poor performance on these tasks appears to be rooted in an impaired, primarily right-hemisphere, fronto-temporal network (Albouy et al., 2013a). When the to-be-remembered material involves pitch variations, encoding, retention, and retrieval processes—all of which are involved in short-term memory—are affected. In the present study, we examined music recognition across two experimental phases, such that the focus was on long-term rather than short-term memory.

In congenital amusia, frequent complaints from affected individuals indicate that they cannot recognize popular songs without lyrics. Such anecdotes are consistent with findings from laboratory-based studies. Although performance is above chance levels, amusics do poorly compared to controls in naming songs or judging their familiarity when the stimuli are well-known tunes presented without lyrics (Ayotte et al., 2002; Graves et al., 2019). Our results extend these findings by providing experimental evidence of poor long-term memory (compared to controls) for music, using an implicit procedure (no intentional encoding), and unfamiliar, but real-world music. In daily life, the general population is exposed to music frequently and involuntarily (e.g., in films, airplanes or department stores), such that listeners make no effort to remember it. Even infants remember lullabies and their pitch level simply through passive listening (Volkova et al., 2006). Adult and adolescent listeners also recognize hits played on the radio, which are initially unfamiliar but subsequently stored in the musical lexicon with remarkable detail, again simply as a consequence of passive listening (Schellenberg et al., 1999). In fact, listeners with no music training remember melodies heard initially in the lab a full week later (Schellenberg & Habashi, 2015). Such implicit learning, which is evident in the general population, is altered in amusia (Peretz et al., 2012; see Omigie & Stewart, 2011, for contrasting data).

Whereas our stimulus excerpts had multiple instruments and harmonic structures (more than one note sounded simultaneously) and a single previous exposure, the incidental-memory subtest of the MBEA tests long-term memory for piano melodies that are monophonic (one note at a time) and computer-generated. This incidental-memory subtest—at the end of the battery—asks listeners whether they recognize melodies that they heard at least four times in the earlier subtests. Poor long-term memory in this final subtest is predicted by poor pitch-based short-term memory in the earlier subtests (Peretz et al., 2003). In the present study, we extended this finding to real-world music heard previously a single time. Our findings also confirmed associations between poor short-term memory (as quantified by four subtests of the MBEA) and poor recognition performance.

Despite their impairments, amusics in the present study exhibited long-term memory for the real-world musical excerpts after a single exposure, as evidenced by higher recognition ratings for previously heard compared to novel excerpts. Other studies that used real-world musical stimuli have shown that congenital amusics' familiarity judgments do not differ from those of controls (Ayotte et al., 2002, Tillmann et al., 2014), except that they take longer to respond (Tillmann et al., 2014). Thus, amusia does *not* prevent participants from developing a musical lexicon or feelings of familiarity, even though explicit memory or a direct link with the title or performer is impaired. Protracted response times (Tillmann et al., 2014) could stem from impaired access to the musical lexicon, an impoverished lexicon, and/or a lack of confidence in their abilities (Graves et al., 2019, Omigie & Stewart, 2011). The distribution of recognition responses in the present study (Fig. 1) also suggests more uncertainty in amusics compared to controls, with a greater number of responses of 4 (scale midpoint) for both new and old excerpts.

One limitation of the present study is the small sample size, which restricts generalization of the results, although it is similar to other samples of participants with this rare condition (Gosselin et al., 2015; Lagrois & Peretz, 2019; Williamson et al., 2010; Zendel et al., 2015). Another limitation is that our method does not allow us to distinguish whether amusics' recognition impairment stems from encoding, storage, or retrieval of musical information. Electro- or magnetoencephalography (EEG or MEG, respectively) or fMRI coupled with the present behavioral paradigm, as in studies of short-term memory (Albouy et al., 2013a, 2019), could shed light on this question. Albouy et al. (2013a) demonstrated that musical short-term memory is altered in congenital amusia at the first (encoding) step, with delayed MEG responses in bilateral inferior frontal gyrus (IFG) and superior temporal gyrus (STG). Reduced connectivity within this fronto-temporal network during melodic encoding was subsequently confirmed with fMRI data (Albouy et al., 2019). During the retention phase, which involved maintenance of melodic information in short-term memory, additional functional anomalies in the right dorsolateral prefrontal cortex (DLPFC) and posterior parietal cortex were revealed with MEG (Albouy et al., 2013a). The fMRI data further indicated that maintaining melodic information in memory is accompanied by reduced activation in the right auditory cortex, IFG, and DLPFC for amusics compared to controls, along with reduced connectivity between IFG and DLPFC (Albouy et al., 2019). These previous results for short-term memory motivate a hypothesis that could be tested in the future: impairments in long-term memory for music among congenital amusics arise initially during the encoding phase, adversely affecting subsequent maintenance and retrieval.

Liking and memory

Our most important finding was that liking influenced memory in amusic participants and that this effect was similar to that observed in controls. In fact, the observed data provided support for the null hypothesis (no difference between groups). In absolute terms, liked excerpts were rated, on average, 1.0 point higher than disliked excerpts in the amusic group. For controls, the difference was 0.6 points.

Our use of two counterbalanced lists of musical stimuli ruled out the possibility that some excerpts were inherently more likeable or memorable, which could have biased responding. Moreover, Stalinski and Schellenberg (2013) confirmed that the effect of liking on memory is *not* attributable to drawing participants' attention to liking, to familiarity with the musical excerpts, to similarities between the excerpts and the music participants favor, or to superficial processing of excerpts in the exposure phase. Moreover, the beneficial effect of liking does not extend to foils. In other words, previously unheard excerpts are not falsely recognized simply because they are liked (Stalinski & Schellenberg, 2013). Thus, emotion (or liking) appears to facilitate the processing of information and/or reinforce encoding, which in turn facilitates memory of the same information (Bennion et al., 2013), over the short (Murray & Kensinger, 2012) or long (Kensinger & Corkin, 2003) term.

Ferreri et al. (2021) propose that the link between emotion and memory involves activation of the reward system. Reward responses to music are associated with arousal and emotional modulations generated by the musical features and structures, and extend further to prediction, motivation, and hedonic feelings of the listener (Ferreri & Rodriguez-Fornells, 2017). Dopamine release, which is associated with reward, improves long-term potentiation in the hippocampus, increasing the capacity to store and consolidate new information in long-term memory (Chowdhury et al., 2012; Ripollés et al., 2018). Ferreri and Rodriguez-Fornells (2017) showed that pleasantness ratings predict recollection of musical excerpts 24 hours later, in line with the results of Stalinski and Schellenberg (2013). They also observed that "wanting" a musical excerpt modulated memory performance. Moreover, personal musical hedonia (a measure of sensitivity to music as a reward) was significantly correlated with memory performance. These results were later extended in a study that included a pharmacological intervention to alter dopamine levels (Ferreri et al., 2021, see also Ferreri & Rodriguez-Fornells, 2022). By altering reward responses to music listening and measuring their impact on memory, the findings demonstrated that the influence of music on memory can be mediated by dopamine and the brain-reward system. In congenital amusia, it has been previously shown that the emotional content of music influences cognitive processes required in a visual task. Specifically, when amusics judge the direction of an arrow, their performance is influenced to the same extent as controls by the emotional content of music presented in the background (Fernandez et al., 2021).

Typically, links between liking and memory are studied in the opposite direction, with a two-phase paradigm similar to the one used in the present study, but with liking judgments collected in the second phase. In the first phase, a set of stimuli is presented with a perceptual question, such as estimating the tempo in the case of music. In the second phase, participants provide liking or pleasantness ratings for old (previously exposed) as well as new excerpts. The resulting *mere exposure effect* refers to the fact that simple exposure to a neutral stimulus increases liking for it (Zajonc, 1968; for review see Montoya et al., 2017), an effect that has also been reported for music (Peretz et al., 1998b; Schellenberg et al., 2008; Szpunar et al., 2004). Such an increase in liking can arise only if participants remember the stimulus, at least implicitly. Zajonc (1968) proposes, moreover, that affective responses to a stimulus (e.g., liking) typically precede a cognitive response (e.g., recognition; Montoya et al., 2017; Moreland & Zajonc, 1977).

In the present study, liking music in the exposure phase may have improved encoding and memorization, as evidenced by better recognition in the test phase. Typically, tasks used to evaluate emotional processing are less demanding (relative to attention or working memory tasks) and more global compared to music-related cognitive tasks, which are more analytic (e.g., same/different judgments). Emotional processing (e.g., emotion-intensity judgments, liking judgments, chills) is often assessed with implicit tasks (e.g., no verbal label to be associated with the music) in contrast to assessments of cognitive processing that require identification, discrimination, or judgments of closure. Future research could evaluate cognitive processing and memory in particular, using more implicit judgments (e.g., confidence instead of yes/no recognition) that are as similar as possible to those that index emotion processing. More generally, implicit encoding, as used in the present study, or implicit assessment, as in studies of the mere-exposure effect, could be considered in the design of future investigations.

Another interesting result of the present study was that disliking had no effect on recognition scores. As in Stalinski and Schellenberg (2013), disliked and neutral excerpts were recognized similarly. One might question whether our music stimuli were varied enough to evoke strong disliking, yet listeners' use of the entire liking scale suggests otherwise (Fig. 1). In one fMRI study, disliked music was not associated with cognitive or affective activations in healthy adults, compared with liked music (Pereira et al., 2011). Rather, liked (but not disliked) music activated regions in the cingulate cortex and frontal lobe, including the motor cortex and Broca's area, regions that are also activated for beautiful visual stimuli (Kawabata & Zeki, 2004). Pleasant (or liked) stimuli would thus be linked to a pattern of memory advantages and cerebral activations that are not observed for unpleasant stimuli.

Conclusions

The present study revealed the potential benefit of liking on musical long-term memory in individuals with congenital amusia. These individuals, who perform poorly at discriminating tones (short-term memory) and remembering musical pieces (long-term memory), showed an enhancement of music recognition due to liking, which was indistinguishable from that observed for controls. Although their capacity to recognize a previously heard musical piece was poorer compared to controls, amusic individuals were nevertheless sensitive to the aesthetic and subjective dimension of the musical experience, which was then shown to support memory processes.

Our results from congenital-amusic participants corroborate the hypothesis that positive emotions have the power to influence memory, even when memory is deficient. Despite the vulnerability of the memory trace for music in amusia, which is highly sensitive to interference, memory load, or time (Gosselin et al., 2009, Williamson et al., 2010; Williamson and Stewart, 2010), the memory network appears to benefit from connections with other networks: Both liking (as shown here) and tonality (Albouy et al., 2013a; Lévêque et al., 2022) improve musical memory. These findings, even if limited by the relatively small sample size, contribute to a body of research that reveals distinctions and interrelations between emotional and cognitive processes. Music intrinsically generates emotions and requires structural processing. Further understanding of its effects on brain and behavior could inspire new perspectives for training and rehabilitation, taking advantage of emotions to ameliorate impaired cognitive processes.

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Data availability Readers seeking access to the data, materials or code should contact the corresponding author Yohana Lévêque, at the Lyon Neuroscience Research Center. Access will be granted to named individuals for research projects or meta-analyses.

Declarations

Ethics approval The study was approved by a regional ethics committee (CPP Sud-Est IV).

Consent to participate Informed consent was obtained from all individual participants included in the study.

Consent for publication All authors consent to the publication of the manuscript.

Conflicts of interest/Competing interests The authors have nothing to declare.

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