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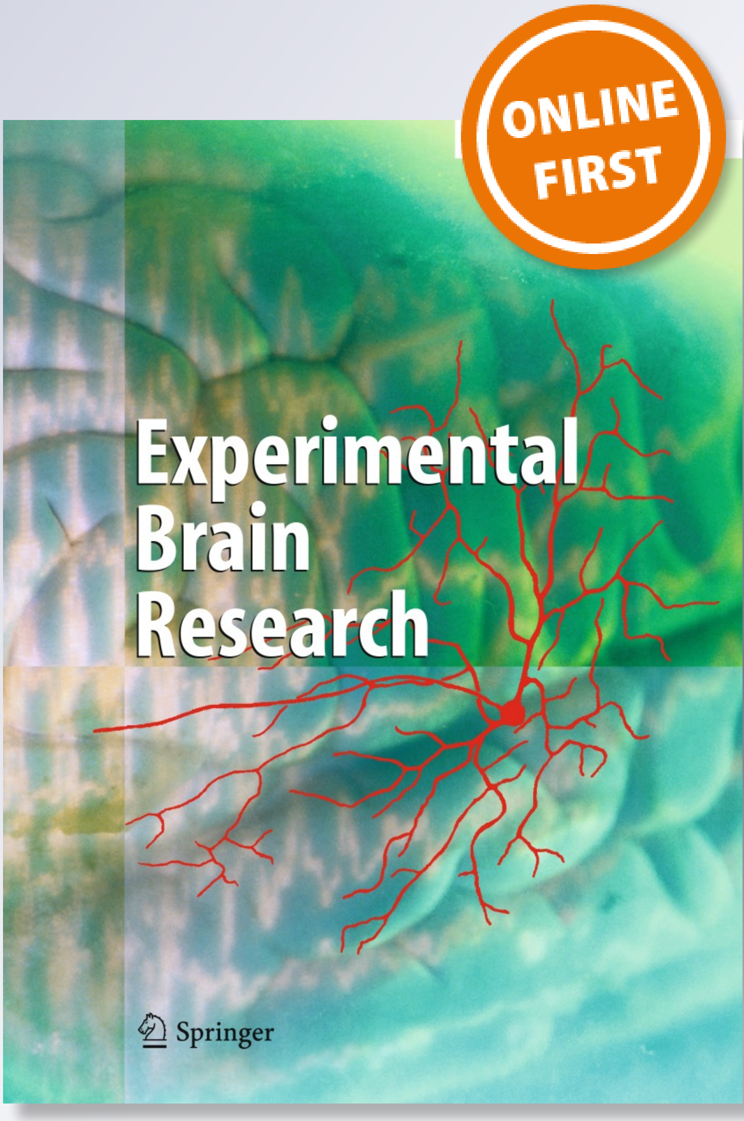

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RESEARCH ARTICLE

Music-related reward responses predict episodic memory performance

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Abstract Music represents a special type of reward involving the recruitment of the mesolimbic dopaminergic system. According to recent theories on episodic memory formation, as dopamine strengthens the synaptic potentiation produced by learning, stimuli triggering dopamine release could result in long-term memory improvements. Here, we behaviourally test whether music-related reward responses could modulate episodic memory performance. Thirty participants rated (in terms of arousal, familiarity, emotional valence, and reward) and encoded unfamiliar classical music excerpts. Twenty-four hours later, their episodic memory was tested (old/new recognition and remember/know paradigm). Results revealed an influence of music-related reward responses on memory: excerpts rated as more rewarding were significantly better recognized and remembered. Furthermore, inter-individual differences in the ability to experience musical reward, measured through the Barcelona Music Reward Questionnaire, positively predicted memory performance. Taken together, these findings shed new light on the relationship between music, reward and memory, showing for the first time that music-driven reward responses are directly implicated in higher cognitive functions and can account for individual differences in memory performance.

Keywords Episodic memory · Reward · Music · Musical hedonia

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Introduction

Present since the beginning of human evolution (Wallin et al. 2001) and since the early stages of human development (Perani et al. 2010), music represents a special type of reward (Blood and Zatorre 2001; Zatorre and Salimpoor 2013). The pleasure experienced in music is strictly related to the emotions induced, changed or enhanced by the music itself, and goes in parallel with changes in the autonomic nervous system and the recruitment of the mesolimbic dopaminergic reward system (Salimpoor et al. 2009, 2011; Zatorre and Salimpoor 2013). However, contrary to reward-activating stimuli such as sex or food, music has not a clear advantage at an evolutionary level. Beyond the fact that humans obtain pleasure from stimuli, which are conceptually meaningful, but with little direct evidence for survival (i.e., aesthetic rewards; Zatorre and Salimpoor 2013), several studies claimed that the emotions evoked by music may improve not only mood symptoms, but also cognitive functions (Mas-Herrero et al. 2013). According to the neo-Hebbian framework for episodic memory (Lisman et al. 2011), as dopamine can strengthen the late synaptic potentiation produced by learning thus boosting consolidation processes, stimuli triggering dopamine release could result in long-term memory improvements. An exciting hypothesis is, therefore, that music-related reward responses might play a role in establishing human episodic memories.

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The well-established effect of reward on cognitive functions, and more specifically learning and memory (Wittmann et al. 2005; Adcock et al. 2006; Shohamy and Adcock 2010; Wolosin et al. 2012; Gruber et al. 2014), has been attributed to the interaction of the reward network and the memory circuit (substantia nigra–ventrotegmental area–hippocampal loop; Goto and Grace 2005; Lisman et al. 2011). More specifically, the crucial role that the reward system plays in successful encoding seems to be mediated by dopamine midbrain phasic cell firing, which results in dopamine release in the hippocampus, thus enhancing memory formation (Schultz 2002). It has been shown that high-rewarding cues (e.g., giving the possibility of monetary gain) increased activation not only in the reward system, such as midbrain regions and the ventral striatum, but also in the hippocampus (Wittmann et al. 2005; Adcock et al. 2006). Indeed, the prospect of receiving reward has been shown to improve long-term episodic memory for novel stimuli in both incidental and intentional encoding paradigms (see Lisman et al. 2011 for a review). Furthermore, it has been recently suggested that dopaminergic stimulation may specifically improve consolidation (Chowdhury et al. 2012), resulting in enhanced recollection associated with better quality, high confidence, and more detailed (i.e., relational) memory responses (Tulving 1985; Yonelinas 2002; see also Wixted and Mickes 2010).

Music processing shares a strong link with higher cognitive functions, and a consistent part of research on music cognition has been specifically focusing on the memory for music itself, also investigated in clinical populations with strong memory deficits, such as Alzheimer's patients (Cuddy and Duffin 2005; Baird and Samson 2009). Musical memory, which can be modulated by variations in intrinsic musical features such as timbre or tempo (Halpern and Müllensiefen 2008), seems to be strongly mediated by the emotional component (i.e., emotional valence and arousal dimensions) (Platel et al. 2003; Eschrich et al. 2005, 2008; Halpern and Müllensiefen 2008; Jäncke 2008; Peretz et al. 2009; Vieillard and Gilet 2013; Alonso et al. 2015). For example, Eschrich et al. (2005) tested memory performance for Bach excerpts with a remember/know paradigm and found better memory for very arousing excerpts when compared to very pacifying music. In a further study (Eschrich et al. 2008), the authors employed an old/new recognition paradigm to test memory for emotional film music, and found that very positive excerpts were better recognized than less positive pieces. However, Altenmüller et al. (2014) failed in replicating the same arousal and emotional valence effects. Notably, these two experiments only employed positively valenced material and did not include negative emotional excerpts. This could at least in part explain the weak effect of emotional valence, as well as the distruption of the arousal effect (Eschrich et al. 2008). In line with this explanation, other studies showed that negative valence musical stimuli can be better recognized than positive ones (Aubé et al. 2013; Alonso et al. 2015). All in all, although the arousal dimension seems to strongly influence memory performance (Samson et al. 2009; Eschrich et al. 2005; Alonso et al. 2015), the effect of emotional valence is still controversial and it is difficult to disentangle which component may specifically drive the positive effect on memory.

As previously introduced, reward response to music is associated with both arousal and emotional modulations (Salimpoor et al. 2009). Nevertheless, musical reward is not only linked to these two components, but also to prediction and motivation mechanisms related to dopamine release, as well to the hedonic experience (see Zald and Zatorre 2011). Reward constitutes, therefore, a crucial factor to take into account when looking at music and memory processes. However, despite the fact that the effects of music on memory have been previously investigated, to the very best of our knowledge, no study up to now investigated the possible mediating role of experienced music reward on musical memory while controlling for arousal and emotional valence dimensions. The behavioural approach to the investigation of the reward response to music usually employs subjective ratings related to the "liking experience" (Berridge et al. 2009), such as reporting general pleasantness and "chills", as well as motivational tasks related to the "wanting" experience, such as the purchase of musical excerpts (Salimpoor et al. 2013; Mas-Herrero et al. 2014). Recently, the Barcelona Music Reward Questionnaire (BMRQ) was developed to pinpoint inter-individual differences in reward response to music (Mas-Herrero et al. 2013). Using this questionnaire, the general population could be divided into musical anhedonics, hedonics, and hyperhedonics. While musical hedonic and hyperhedonic subjects can experience medium-to-large music-related reward responses, musical anhedonics show no pleasure as well as differential brain activity and connectivity in response to music (Mas-Herrero et al. 2013; Martínez-Molina et al. 2016).

The main aim of the present study is, therefore, to investigate if differences in music-related reward responses may play a role in episodic memory performance. To this aim, we focused not only on individual ratings, both in terms of "liking" and "wanting" experience (Berridge et al. 2009), but also on inter-individual differences in music-related reward experience (i.e., BMRQ). Observing different memory performance according to music and the pleasure, it can generate would help to triangulate on what is causing the beneficial effect of music on memory and to improve the debate about the link between rewarding stimuli and cognitive functions. More specifically, following the hypothesis of Lisman's model (Lisman et al. 2011), we hypothesized that higher reward responses experienced while listening (encoding) music excerpts may be associated with better episodic memory performance for these pieces. To investigate this issue, and focusing on the episodic memory system (Tulving 1972), we evaluated memory for unfamiliar classical music excerpts according to reward responses using an Old/New paradigm. Furthermore, to test whether the music-related reward responses may specifically influence the recollective experience (see Chowdhury et al. 2012), we employed a remember/know/guess paradigm to distinguish between familiarity ("know" responses) and recollection ("remember" responses) processes.

Methods

Participants

Thirty university students (20 females, mean age = 20.57, sd = 4.11), all no professional musicians (18 non-musicians and 12 amateurs), took part in the study in exchange of course credits (if from the University of Barcelona) or money (25 euros, if from other Universities). For each subject, a measure of exposure to classical music (i.e., "How often do you listen to classical music?) was obtained (1–5 scale, from 1: "never" to 5: "every time I listen to music, I listen to classical music"). All of them were tested with a modified versions of the BMRQ, which included 20 questions on musical reward (Mas-Herrero et al. 2013) and two additional items selected from the Montreal Battery of Evaluation of Amusia (MBEA, Peretz et al. 2003) for being particularly sensitive to amusia (item 21 "Can you recognize a very familiar melody -such as the national anthem- without the help of lyrics?" and item 22 "Can you perceive when someone sings out-of- tune?"). None of the participants reported amusia. 15 of them resulted musical hedonics (Barcelona Music Reward Questionnaire—BMRQ mean score = 76, sd = 3.85), 11 musical hyperhedonics (BMRQ mean score = 92.09, sd = 3.43), and 4 musical anhedonics (BMRQ mean score = 48.25, sd = 11.32). Musical anhedonics were additionally tested with the complete version of MBEA and Physical Anhedonia Scale (Chapman et al. 1976) and did not report amusia or general anhedonia.

Procedure

Written informed consent was obtained from all participants. The study fully obeyed to the Helsinki Declaration, Convention of the Council of Europe on Human Rights and Biomedicine, and all methods were carried out in accordance with local ethics committee (University of Barcelona).

Participants were exposed to three presentations of the auditory material. Musical stimuli consisted in unfamiliar instrumental classical excerpts selected through the Spotify application "Sort Your Music", which allows to control, among other features, for valence, energy, and popularity. The selected pieces were additionally tested on a sample of 23 participants (12 females, mean age = 33.3 sd = 14.3) and rated for familiarity (from 1 = completely unfamiliar to 5 = completely familiar; mean = 1.6, sd = 0.25), arousal (from 1 = very relaxing to 5 = very arousing; mean = 2.7, sd = 0.8), emotional valence (from 1 = very sad to 5 = very happy; mean = 2.8, sd = 0.7), and general pleasantness (from 1 = no pleasantness to 5 = very high pleasantness/ chills; mean = 3.1, sd = 0.4).

During the first exposure, subjects listened in the earphones to 24 excerpts, lasting 20 s each (Eschrich et al. 2008), normalized (− 10 dB) and faded (3 s in and 3 s out). Participants were told to listen to the excerpts attentively, because they will have been asked to remember them later. After each excerpt, they were asked to rate (1–5 points scales) the level of arousal, emotional valence, and familiarity, and the general pleasantness experienced when listening to the piece (i.e., "liking" measure, Berridge et al. 2009). Furthermore, to insert a reward-related motivational rating (i.e. "wanting" reward measure, Berridge et al. 2009), we additionally asked participants to indicate in which position of a top-ten classification they would like to place each excerpt (thus they could assign to each piece a number from 1 to 10, and it was not allowed to not assign a number). They were instructed that they were going to have two possibilities to rank each excerpt and that the excerpts ranked in the first three positions were more likely to be part of a final playlist resulting from the mean of all participants, while those in the last three positions had more probability to be excluded. Participants were also told that they were going to receive by e-mail the link for the final playlist on Spotify, where discover the excerpts, their authors, and listen to them entirely. Therefore, they were encouraged to create their own playlist. During the second exposure, participants were simply asked to listen again to the same excerpts. During the third exposure, they were asked to listen to them another time and to rate again general pleasantness and top ten. Only few minutes passed between one exposure and another. The total duration of the encoding phase lasted about 45 min.

24 h after, subjects were presented with 24 old and 24 new excerpts, lasting 10 s each. Selection of these 10 s (Halpern and Müllensiefen 2008) was made by excluding the first and last 3 s (i.e., the faded ones) of the excerpts and by selecting at least one musical phrase. For each one, participants had to indicate if they listened to it the day before (old/ new recognition). If yes, they had to commit to one of three additional options (recollection task): remember (R), know (K), or guess (G). R indicated that they could recollect something specific about the study episode; K indicated that the excerpt was confidently familiar, but they had no recollective experience; G responses were given when unsure whether

the excerpt was old (R/K paradigm, Yonelinas 2002). The total duration of this retrieval phase lasted about 20 min. The orders of the items and of the two groups of excerpts (i.e. old/new) were randomized across subjects. Auditory stimuli were presented using a headset, and the overall loudness of the excerpts was adjusted subjectively to ensure constant loudness throughout the experiment.

Analysis

First, a correlation analysis was conducted to explore the subjective ratings, and more specifically the relations between reward (i.e., pleasantness and top-ten) measures and the other ratings (arousal, emotional valence, familiarity, see supplementary material for further analysis). Given the high correlations between the two different ratings (i.e., first and third exposures) for both general pleasantness and top-ten ($r = 0.85$, $p < 0.001$ and $r = 0.66$, $p < 0.001$, respectively), the mean value of the two ratings was used for the analyses further reported.

D prime score and one-sample *t* test for corrected R responses (i.e., number of R responses for old items minus number R responses for new items) were used to check the general memory performance. Paired *t* test was also employed for testing the difference between recollection (corrected R) and familiarity (corrected K, i.e., number of K responses for old items minus number K responses for new items) responses. After testing for outliers, two subjects with particularly poor memory performance ($d' = 0.10$ and 0.12, both musical anhedonics) were excluded from the analyses below described.

To test the hypothesis that rewarding stimuli could lead to long-term memory improvements, we analysed the memory performance according to reward-related subjective ratings. To test memory performance for only unfamiliar stimuli, excerpts rated as familiar (i.e., 4 or 5) were excluded from all the analyses here reported. We first took, for each subject, the correctly recognized and the forgotten items (old/new recognition task). We then checked the general pleasantness ratings previously attributed to each of these excerpts (mean of the first and third exposures). With the aim to compare recollective to non-recollective aspects of recognition, we compared the differences between R/K/G responses (only for correctly recognized items) and forgotten items running a repeated-measures ANOVA with a four-level within-subjects factor (pleasantness ratings for forgotten items, R, K, and G responses), followed by post hoc pairwise Bonferroni comparisons. In the same way, we then tested the memory performance depending on top-ten ratings. The same procedure was further applied for the other subjective ratings (arousal, emotional valence, and familiarity) to control for their involvement in memory performance.

To better investigate the effect of motivational (i.e., top ten) reward ratings on memory, we additionally focused on the first and the last three positions of the ranking, i.e., the ones to select for pushing an excerpt in or out the final playlist, respectively. Following the same procedure described above, we compared the percentages of items in the first and last three positions of the top ten for remembered vs known, guessed, and forgotten ones (repeated-measures ANOVA).

Finally, a regression analysis was conducted to test the hypothesis that inter-individual differences in music-related reward experience, namely, differences in participants' musical hedonia, may modulate memory performance (i.e., *d* prime scores for recognition, number of corrected K responses for familiarity, and number of corrected R responses for recollection). To control for possible effects due to musical training and exposure to classical music, we performed a multiple regressions with BMRQ total scores, years of musical training, and musical exposure as predictors. To control for outliers values, we additionally performed a non-parametric Spearman correlation analysis between BMRQ scores and memory performances.

Results

Subjective ratings

Table 1 reports subjective ratings (correlations, means, and standard deviations) for arousal, emotional valence, familiarity, pleasantness, and top-ten scores given on the first day (encoding phase, see also Figs. 1 and 2 of supplementary material). Results confirmed a strong link between the two reward measures employed, showing that pleasantness and top ten were highly correlated ($r = -0.596$, $p = 0.001$): the higher the pleasantness, the higher the position in the rank (i.e., lower values in the top-ten ranking). Pleasantness also correlated with arousal (i.e., the higher the pleasantness, the higher the perceived arousal, $r = 0.481$, $p = 0.007$). Top-ten scores additionally correlated with familiarity (i.e., the higher the familiarity of an excerpt, the higher its position in the ranking, $r = -0.398$, $p = 0.045$).

Memory performance depending on reward subjective ratings

Memory performance resulted significantly above the chance level for both recognition [$t(27) = 41.716$, $p < 0.001$, one-sample *t* test; *d* prime mean = 1.29, sd = 0.39] and recollection ($t(27) = 10.652$, $p < 0.001$, one-sample *t* test). R responses resulted significantly higher than K responses [$t(27) = -4.161$, $p < 0.001$].

Although repeated-measures ANOVA comparing forgotten, remembered, known, and guessed responses showed no

Table 1 Correlations matrix, mean, and standard deviations (sd) values for arousal, emotional valence (Em. Val.), familiarity (Fam.), pleasantness ratings (Pl. first, second ratings, and their mean) and top-ten ratings (top first, second ratings, and their mean)

Ratings	Arousal	Em. Val.	Fam.	Pl. (1st)	Pl. (2nd)	Top (1st)	Top (2nd)	Mean Pl.	Mean top
Arousal[a]	1								
Em. Val.[a]	0.302	1							
Fam.[a]	0.234	0.367*	1						
Pl. (1st)[a]	0.512**	0.320	0.393*	1					
Pl. (2nd)[a]	0.410*	0.292	0.270	0.850**	1				
Top (1st)[b]	− 0.180	− 0.314	− 0.279	− 0.406*	− 0.440*	1			
Top (2nd)[b]	− 0.238	− 0.222	− 0.398*	− 0.513**	− 0.738**	0.663**	1		
Mean Pl.[a]	0.481**	0.320	0.346	0.967**	0.956**	− 0.439*	− 0.642**	1	
Mean top[b]	− 0.227	− 0.289	− 0.369*	− 0.502**	− 0.655**	0.900**	0.922**	− 0.596**	1
Mean	2.97	3.06	1.75	3.40	3.48	5.04	4.83	3.44	4.94
Sd	0.35	0.24	0.66	0.57	0.49	0.72	0.84	0.50	0.71

* and ** indicate correlations with $p < 0.05$ and $p < 0.01$ (two-tailed), respectively

Lower values in top-ten scores indicate higher positions in the ranking. Note that [a] = 1–5 scale and [b] = 1–10 scale

significant main effect ($F(3,54) = 2.578$, $p = 0.061$), pairwise comparisons revealed that pleasantness ratings for remembered excerpts were significantly higher than guessed ones (pleasantness ratings for R, $\mu = 3.54 \pm 0.54$; for G, $\mu = 3.05 \pm 0.81$, $p = 0.040$) (Fig. 1a).

Analysis on top-ten scores revealed main effect of recollection [$F(3,57) = 4.358$, $p > 0.008$, $\eta^2 = 0.19$], with remembered excerpts rated in significantly higher positions than forgotten (top-ten ratings for R, $\mu = 4.48 \pm 0.84$; for forgotten, $\mu = 5.48 \pm 1.06$; $p = 0.023$) and known ones (top-ten ratings for K, $\mu = 5.31 \pm 0.83$; $p = 0.007$) (Fig. 1b).

Furthermore, a main effect was shown when focusing on the first three positions of the top-ten ratings, [$F(3,57) = 4.764$, $p = 0.005$, $\eta^2 = 0.20$], where R responses resulted higher then forgotten, K or G responses (percentage of items in the first three positions for R, $\mu = 28.78 \pm 20.05$; K, $\mu = 12.22 \pm 14.28$; G, $\mu = 8.78 \pm 23.76$; forgotten, $\mu = 10.77 \pm 11.99$), although Bonferroni post hoc comparisons did not reach statistical significance (R vs forgotten $p = 0.052$, R vs K $p = 0.082$, R vs G $p = 0.064$) (Fig. 2a). No significant differences were observed for percentages of the excerpts ranked in the last three positions (all $p > 0.05$, Fig. 2b).

Taken together, these results showed that the musical excerpts that received higher reward ratings were better remembered the day after the exposures.

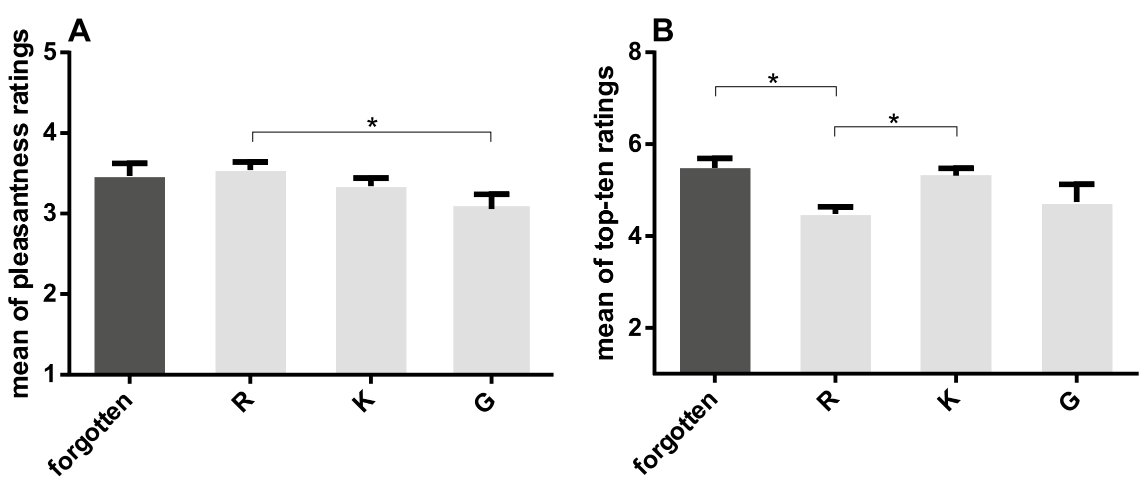

Fig. 1 Means and SEM of pleasantness (**a**) and top-ten (**b**) ratings for general memory performance and familiarity-recollection processes (forgotten items, R, K, and G responses for correctly recognized items). Note that lower values in top-ten ratings mean higher positions, and, therefore, better scores. * and ** indicate significant values resulted from Bonferroni-corrected post hoc pairwise comparisons ($0.01 < p < 0.05$ and $p < 0.01$, respectively)

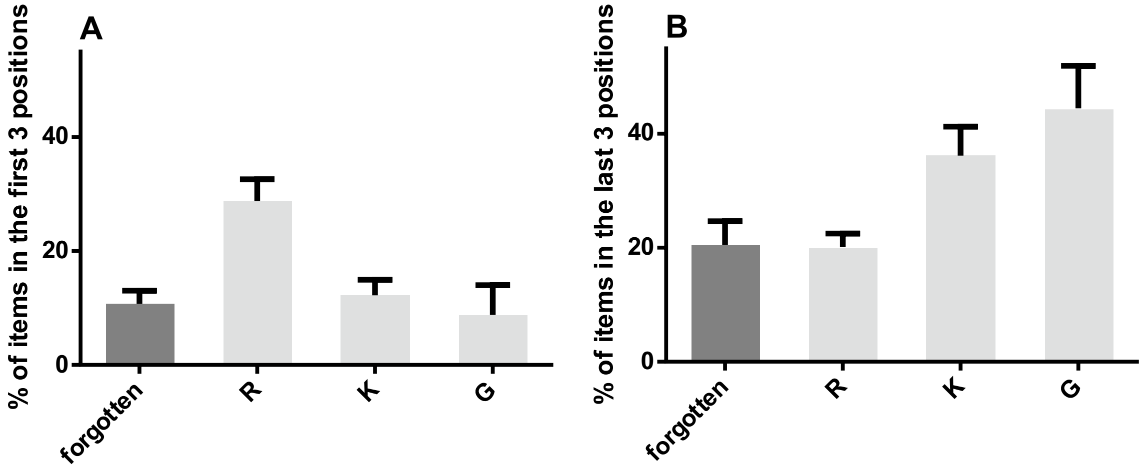

Fig. 2 Percentages and SEM of items in the top-ten ratings (**a** first 3 positions; **b** last 3 positions) for general memory performance and familiarity-recollection processes (forgotten items, R, K, and G responses for correctly recognized items)

Memory performance depending on music reward susceptibility

The multiple regressions with BMRQ total scores, musical exposure, and musical training as predictors (see Table 2) did not explain significant amount of the variance of general recognition [i.e., d', $F(3,24) = 2.932$, $p = 0.054$] and familiarity [i.e., corrected K responses, $F(3,24) = 0.551$, $p = 0.652$]. Importantly, regression analysis revealed that these predictors explained significant amount of the variance of recollection [$F(3,24) = 3.263$, $p = 0.039$]. However, musical expertise and musical exposure did not significantly predict recollection performance (all $p > 0.05$). Interestingly, only BMRQ scores significantly predicted the number of corrected R responses [$t(27) = 2.182$, $p = 0.039$], highlighting that the higher the musical hedonia, the better the episodic memory performance (Fig. 3).

In line with these findings, results from Spearman correlation analysis showed no significant correlation between BMRQ scores and *d* prime (Spearman's rho = 0.178, $p = 0.364$), nor between BMRQ scores and K responses (Spearman's rho = − 0.081, $p = 0.681$), but a significant correlation between musical hedonia and the number of corrected R responses (Spearman's rho = 0.477, $p = 0.010$). Importantly, this effect was confirmed also when removing the anhedonic subjects from the analysis (Spearman's rho = 0.508, $p = 0.008$).

Control for emotional valence, arousal, and familiarity ratings

Considering the previously mentioned correlations of reward-related subjective ratings with arousal and familiarity, as well as the influence of emotions on musical memory (Eschrich et al. 2005, 2008; Alonso et al. 2015), we tested whether the arousal level of an excerpt, its emotional valence, and its familiarity also played a crucial role for memory performance. We, therefore, applied, for the other subjective ratings given on the first day, the same analyses employed for the reward ratings. No effect on memory

Table 2 Unstandardized (B and standard error of B) and standardized (beta) regression coefficients for recognition (i.e., *d* prime scores), familiarity (i.e., number of corrected K responses), and recollection (i.e., number of corrected R responses) performance

Variable	Recognition			Familiarity			Recollection		
	B	SEB	β	B	SEB	β	B	SEB	β
Constant	0.394	0.423		2.88	4.28		− 2.95	3.96	
Yrs. Train.	− 0.80	0.162	− 0.103	− 2.01	1.64	− 0.290	− 1.68	1.52	− 0.228
Mus. Exp.	0.130	0.062	0.420	0.342	0.625	0.124	1.03	0.579	0.350
Mus. Hed.	0.008	0.006	0.268	0.002	0.056	0.010	0.113	0.052	0.421

For recognition: $F(3, 24) = 2.932$, $p = 0.054$, $R^2 = 0.268$, R^2 Adj = 0.177, enter method. For familiarity: $F(3, 24) = 0.551$, $p = 0.652$, $R^2 = 0.064$, R^2 Adj = − 0.52, enter method. For recollection: $F(3, 24 = 3.263)$, $p = 0.039$, $R^2 = 0.290$, R^2 Adj = 0.201, enter method

Yrs. Train years of training, *Mus. Exp.* musical exposure ratings, *Mus. Hed.* musical hedonia, namely, BMRQ scores

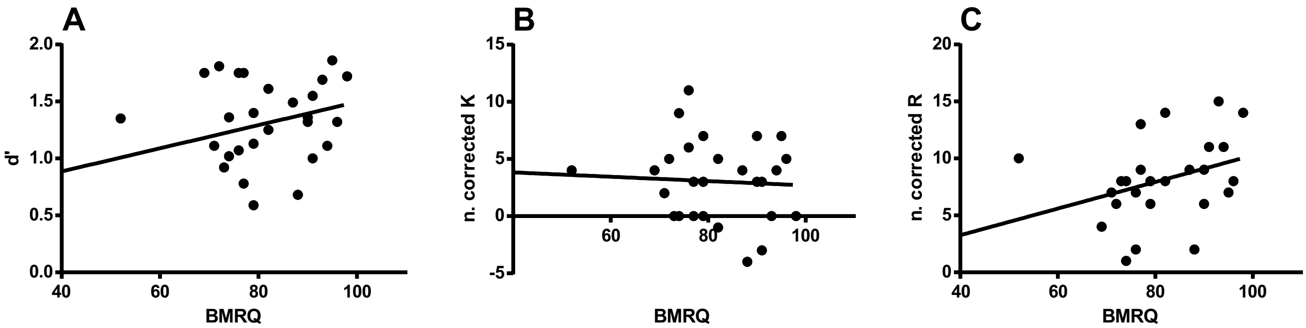

Fig. 3 Scatterplots showing the correlations between BMRQ scores and familiarity (i.e., *d* prime values, **a**, not significant), familiarity (i.e., number of corrected K responses, **b**, not significant), and recollection (i.e., number of corrected R responses, **c**, significant) performance

performance was found according to emotional valence ratings nor according to arousal ratings (all $p > 0.05$ resulted from repeated-measures ANOVA).

As shown in Table 1, although most of the excerpts were overall unfamiliar to the subjects (mean = 1.75, sd = 0.66), familiarity ratings positively correlated with emotional valence and reward ratings, thus being a potential confounding factor. However, by eliminating the excerpts rated as more familiar (i.e., 4 and 5 ratings) from the analyses, the correlations between familiarity and other subjective ratings disappeared (all $p > 0.05$), and no effect of familiarity on memory performance was found (all $p > 0.05$ resulted from repeated-measures ANOVA).

Discussion

The main aim of the present study was to investigate whether music-related reward responses could modulate episodic memory performance. Based on the model proposed by Lisman et al. (2011), we expected to observe an influence of experienced reward on the encoding of musical excerpts. Overall, our findings revealed that both intra- and inter-subjective measures of reward can strongly influence the memory for music. A crucial finding is indeed that musical excerpts rated as more rewarding were also better remembered (Figs. 1 and 2).

We employed old/new recognition task together with R/K paradigm to investigate not only general memory performance, but also the recollective experience (Yonelinas 2002) associated with reward musical experience. The first important finding of this paper is that general memory performance, and more specifically recollection, benefits from high reward subjective ratings related to music listening, thus suggesting a strong impact of reward experience on the stimulation of the episodic memory system (Tulving 1972, 2002). Indeed, our results showed that the higher reward ratings, the easier a musical excerpt, was later recognized and remembered. Although we pre-selected musical excerpts rated as mostly unfamiliar, we observed a large between-subjects variability in familiarity ratings. Familiarity and reward measures have been shown to be strictly related (Van Den Bosch et al. 2013): the more we listen to a musical excerpt and get familiar with it, the more we tend to like it. Therefore, when looking at reward-related memory modulations, participants' familiarity with the experimental stimuli might have been a critical confounder. For this reason, we removed excerpts rated as most familiar from the analyses, and included subjective ratings about exposure to classical music as a potential predictor of memory performance. Nevertheless, our findings highlighted a clear effect of reward on memory, especially on R responses. This suggests that the recollection, more than the familiarity process, is specifically driven by reward experience.

As claimed by Berridge et al. (2009), brain reward mechanisms are driven by neurochemical mechanisms promoting the incentive motivation ("wanting" states) and the hedonic value ("liking" states). Gruber et al. (2014) previously showed that intrinsic motivation, such as high states of curiosity, can promote memory for relevant and incident information by enhancing midbrain and hippocampus activity. Ripollés et al. (2016) also showed that intrinsic elicitation of reward-related signals could increase the probability of retaining new information via the modulation of the midbrain–hippocampal dopaminergic loop. Our results show that both "liking" and "wanting" aspects of musical excerpt can improve its long-term memorization. However, our findings highlight that top-ten rating can modulate memory performance more strongly than pleasantness ratings. This may be due to a methodological reason. Indeed, while a 1–5 scale was employed for measuring pleasantness, a 1–10 scale was used for reward-motivational (i.e., top ten) ratings. A closer look at individual data (see supplementary material Fig. 2) shows that mean top-ten values do not cover the entire range of possible ratings, and this could explain a lack of main effect during the analysis of the last three position of the top-ten ratings. However, due to its higher amount of rating possibilities, it is possible that 1–10 scale is more sensitive to catch reward modulations than the 1–5 scale employed for pleasantness ratings. Nevertheless, a more theoretical explanation may also be possible. Indeed, we employed top-ten ratings as a measure of the "wanting" aspect of musical reward, previously associated with increased activity in nucleus accumbens and dopamine release (Salimpoor et al. 2011, 2013). As midbrain in dopamine signalling can strengthen synaptic potentiation involved in memory formation (Lisman et al. 2011), our findings suggest that motivational processes, more than hedonic ones, may specifically enhance memory formation via dopaminergic release. Accordingly, music could act as a unique intrinsic reward which, via dopamine release, and probably through the participation of other neurotransmitters (e.g., norepinephrine, see Panksepp and Bernatzky 2002), might boost memory formation (see also Ripollés et al. 2016). This would be in line with the previous literature showing that simple exposure to music can benefit short- and long-term memory for verbal or visual material in healthy young and older adults (Balch et al. 1992; Thompson et al. 2005; Ferreri et al. 2013, 2014, 2015; Kang and Williamson 2014; Proverbio et al. 2015; see also Jäncke and Sandmann 2010 for contrasting findings) and in clinical populations (Thompson et al. 2005; Särkämö et al. 2008; Judde and Rickard 2010; Simmons-Stern et al. 2010; Rickard et al. 2012). Further studies are needed to specifically test whether modulations in reward responses to music can modify the incidental encoding of other non-musical information presented during the encoding phase, and, therefore, promoting the idea of music as powerful intrinsic motivator. This idea might be in agreement with the "penumbra hypothesis" (see Lisman et al. 2011; Miendlarzewska et al. 2016). According to this hypothesis, the hippocampal-dependent memory enhanced effect due to dopamine release might also help to encode better any type of material presented during a specific time window. This could be possible even for events that might be irrelevant to the current task, therefore, favouring also their further consolidation (Rickard 2004; Gruber et al. 2014).

It is also worth to discuss the influence of the other subjective ratings, where we observe no effects of emotional valence on memory performance. Eschrich et al. (2008) previously described the effect of musical emotional valence on subsequent recognition. However, this study was limited to the use of positive music (i.e., ratings going from less to more positive valence). This may explain why, using musical excerpts rated from very sad to very happy, we did not find any effect of positive emotional music on memory. Nonetheless, it was recently showed (Alonso et al. 2015) that delayed recognition benefits for negatively valence music pieces, thus increasing the debate on the effects of musical emotional valence.

Contrary to the effect of emotional valence, the effect of arousal on memory is well stated in the literature (see, e.g., Samson et al. 2009; Eschrich et al. 2005; Alonso et al. 2015). However, we found no effect of arousal for recognized or remembered excerpts over forgotten or known or guessed ones. Nevertheless, it is important to mention that this study was not specifically designed to optimize the investigation of emotional parameters, but rather to study the reward component while controlling for emotional valence and arousal. Therefore, the interpretation of these findings must be done bearing in mind certain limitations. For example, for emotional valence, we employed "sad" and "happy" labels. Here, both valence and arousal interact, as "sad" is usually described as negative and low-arousing, and "happy" as positive and high arousing. In addition, describing an excerpt as "very relaxing" can be related to a positive valence connotation (see Mitterschiffthaler et al. 2007). Furthermore, although we selected the excerpts to be balanced in terms of subjective ratings between "old" and "new" groups of items, we did not organize them orthogonally in terms of arousal and emotional valence (see Table 1 and Fig. 1 in supplementary material). Finally, as previously discussed for pleasantness ratings, having employed 1–5 scales for all subjective ratings except for top-ten ones may have in some cases affected the results by making the analysis less sensitive to emotional responses with a smaller range (see Fig. 2 in supplementary material).

The connection between reward, emotions, and arousal is still matter of debate and further studies are needed to clarify to which extent the emotional and arousal modulations are involved in music-driven reward experience. For example, it may be that not the level of arousal or the direction of the emotional valence, but rather, their expected and perceived intensity (Rickard 2004) modulates the reward and memory responses. Remarkably, the absence of a clear effect of emotional valence suggests that musical episodic memory may not be merely enhanced by a particular valence of a piece, but rather by subjects' ability to experience a real pleasure or motivation related to it. Accordingly, it has been shown that very unhappy music can also be considered as very rewarding (see Zald and Zatorre 2011). This is also in line with studies revealing that direct influences of reward on memory cannot be explained by arousal processes per se (Corbetta and Shulman 2002; Gruber et al. 2014), and supported by the fact that the hypothesized dopaminergic modulations implicated in learning and memory formation via the SN-VTA-hippocampal loop (Lisman et al. 2011) do not correspond to neuronal networks usually involved in attentional processes and emotional valence judgments (Corbetta and Shulman 2002; Koelsch 2014). However, it is worth to discuss that arousal and reward share a strong relationship (see Salimpoor et al. 2009), also confirmed by the correlation that we found between arousal and pleasantness subjective ratings (see also Ritossa and Rickard 2004). Although we found no effect of arousal on memory, our results show that strong correlation exists between arousal and reward ratings (see Table 1). It may, therefore, be possible that the positive effect of music-related reward on memory is at least in part driven by the arousal component. However, a clear difference between recollection and familiarity has been observed for reward ratings only, with R responses rated as more rewarding than K responses and forgotten items. Music-driven reward experience is not simple ascribable to arousal modulation (Zald and Zatorre 2011). For example, Scherer (2004) claimed that music can produce strong aesthetic emotions also in absence of physiological arousal. Therefore, it may be that recollection, namely the “qualitative” aspects of memory performance (i.e., the one related to subject’s ability to become consciously aware of his own past experience, Gardiner 1988), might be more sensitive to the reward-aesthetic experience than the mere ability to recognize familiar stimuli (i.e., “quantitative” aspects) (see Yonelinas 2002).

The fact that reward subjective ratings can modulate memory performance is consistent with the second main finding of the present study, namely, that inter-subjective differences in reward responses to music, measured via the BMRQ, also strongly influence episodic memory performance. Crucially, musical expertise and musical exposure were not significant predictors, suggesting that musical memory for unfamiliar stimuli does not rely on musical knowledge provided by amateur training and familiarity with the musical genre. More specifically, our results revealed that the higher the level of musical hedonia, the better the subsequent episodic memory performance. As for subjective ratings, this was specifically related to recollection scores, thus suggesting that musical anhedonia, in the absence of any deficit related to music processing, may specifically impair the reward-related encoding and/or the consolidation of musical episodes crucial for the recollective experience. The fact that reward responses can specifically stimulate episodic memory performance has been previously suggested by several studies using the dopamine precursor levodopa (Knecht et al. 2004; Chowdhury et al. 2012, Apitz and Bunzeck 2013; Shellshear et al. 2015). For example, Chowdhury et al. (2012) showed that levodopa enhanced memory consolidation and led to a dose-dependent long-term persistent episodic memory improvement (i.e., increase of R responses) for images in older adults. Recently, it has been found that increase in dopamine release can improve the learning of new words when a semantic information is provided, thus suggesting that dopamine can enhance the semantic salience of a stimulus (Shellshear et al. 2015). Considering that dopamine transmission is crucially involved in music-related reward response (Salimpoor et al. 2011, 2013), as well as the previously discussed effect of “wanting” aspect of reward on memory, it is possible that modulations in musical episodic memory depend on subjective variations in dopaminergic release underpinning the reward experience and enhancing the consolidation of the encoded information.

Studies investigating music and memory are characterized by a huge variability, which calls for a deeper understanding of the involved mechanisms responsible for inter-individual differences. This is important not only from a theoretical perspective, but also from a rehabilitative one: understanding how music can boost learning and memory performance is critical in developing specific paradigms targeting the training of deficits in several patient populations (see Ferreri and Verga 2016). To the very best of our knowledge, this is the first study investigating and showing the effect of subjective reward responses to music on memory. Further research, for example, focusing on dopaminergic modulations during music listening in both musical hedonic and anhedonic subjects, is required to better understand this issue. However, in our opinion, these findings shed new light on the relationship between music, reward, and memory. More specifically, we show for the first time that music-driven reward responses are directly implicated in higher cognitive functions and can account for inter-individual differences in memory performance.

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Author contributions LF and ARF conceived and designed the study. LF carried out the data acquisition and analysis. LF drafted the manuscript. LF and ARF edited the manuscript.

Compliance with ethical standards

Conflict of interest All authors declare that they have no competing financial interests, personal or otherwise, in relation with this work.

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