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Title: The broken link in specific musical anhedonia: ventral striatum activation and functional connectivity with auditory cortex

Short title: Neural correlates of specific musical anhedonia

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Abstract

Although music is ubiquitous in human societies, there are some people for whom music holds no reward value despite normal perceptual ability and preserved reward-related responses in other domains. The study of these individuals with music-specific anhedonia may be crucial to better understand the neural correlates underlying musical reward. Previous neuroimaging studies have shown that musically induced pleasure may arise from the interaction between auditory cortical networks and mesolimbic reward networks. If such interactions are critical for music-induced pleasure to emerge, then those who do not experience it should show alterations in the cortical-mesolimbic response. In the current study, we addressed this question using fMRI in three groups of fifteen participants, each with different sensitivity to music reward. We demonstrate that the music anhedonic participants showed selective reduction of activity for music in the nucleus accumbens (NAcc), but normal activation levels for a monetary gambling task. Furthermore, this group also exhibited decreased functional connectivity between the right auditory cortex and ventral striatum (including the NAcc). In contrast, individuals with greater than average response to music showed enhanced connectivity between these structures. Thus, our results suggest that specific musical anhedonia may be associated with a reduction in the interplay between the auditory cortex and the subcortical reward network, indicating a pivotal role of this interaction for the enjoyment of music.

Significance statement: This study provides direct evidence supporting the model of reward-auditory cortex interaction as underlying musical pleasure: people who do not experience that pleasure have selectively reduced responses in that system. People who are especially sensitive to musical reward conversely seem to show an enhanced interaction. Our paper offers new insights into the neurobiological basis of music-induced pleasure that could also provide the basis for thinking more broadly about other types of aesthetic rewards. Our results also provide an important step towards the understanding of how music may have acquired reward value through evolution.

"Without music, life would be a mistake". This quote by Friedrich Nietzsche in his book *"Twilight of the Idols"* highlights the importance of music for the life of most people. Indeed, although music is not a primary reward (such as food or sex), it is reckoned as one of the most important sources of pleasure in life. Furthermore, music has been present in every culture throughout history (1) and most of the current literature on music psychology has described it as a universal reward for human beings (2). Its ubiquity and antiquity prove the importance of music in our society (3).

Paradoxically, not everybody loves music: a small percentage of healthy individuals do not find music pleasurable, a phenomenon known as specific musical anhedonia (4). A detailed study on this population revealed that this phenomenon cannot be explained by perceptual problems (e.g. hearing impairment or specific impairment in perceptual capabilities, a condition known as amusia), nor by general anhedonia (lack of pleasure for all types of rewarding stimuli). When listening to music rated as pleasant by others, people with music-specific anhedonia showed a reduced emotional arousal as indexed by autonomic nervous system activity (in particular, skin conductance response and heart rate measurements) compared with people having standard or high sensitivity to music. Notably, they showed normal responses to other types of reward (e.g. money(4)). Therefore, individuals with music-specific anhedonia represent an ideal population in which to test models of music reward processing.

Previous studies have consistently reported that, in addition to sensory and cognitive areas involved in the processing of musical information, such as auditory and frontal cortices (5–8) music recruits regions of the mesolimbic reward circuitry (8–15), especially the nucleus accumbens (NAcc). Most importantly, a recent study (16) has shown that the reward value of a novel piece of music was predicted by the functional connectivity between the NAcc and auditory cortices, as well as regions involved in valuation such as amygdala, orbitofrontal and ventromedial prefrontal regions. According to this model, it would be the functional link between the auditory perceptual/cognitive mechanisms on the one hand and the evaluative/reward mechanisms on the other, which would be driving the experience of music reward. If this model is correct, then we would expect that reductions in the interactions within this network would lead to lack of experienced musical pleasure.

In the present study, we aim to unravel the brain mechanisms responsible for the specific impairment in music reward processing observed in people with specific musical anhedonia. To reach this goal, we selected 45 healthy subjects that differed in their sensitivity to music reward using a previously developed psychometric instrument, the Barcelona Musical Reward Questionnaire (BMRQ) (17), which is known to be a reliable indicator of inter-individual variability in music reward sensitivity. Three groups of subjects (musical anhedonia, average, or high sensitivity to musical reward) engaged in two separate experimental sessions. In the first session, skin conductance responses were recorded while participants listened to excerpts of previously rated pleasant, neutral and unpleasant music, in order to validate the group classification via an objective index of musical reward sensitivity. In the second session, subjects were scanned with fMRI while performing two different tasks: a music listening paradigm in which online pleasure ratings for 16 excerpts were given; and a monetary gambling task used as a control. We hypothesized that specific musical anhedonia would be associated with reduced activity in ventral striatum (especially the NAcc) in response to pleasant music, and also a downregulation in the interaction between auditory cortices and reward-related regions, as compared with people with high and average sensitivity to music. Moreover, we hypothesized that the activation of these areas would be similar in the three groups in response to monetary rewards and punishments, demonstrating the specificity of this phenomenon for music reward processing.

RESULTS

45 university students were divided in three groups of 15 subjects (8 females, 7 males each) according to their sensitivity to music reward as assessed using the Barcelona Music Reward Questionnaire (BMRQ): high sensitivity to music (Hyper-Hedonic Group, HHDN), average sensitivity to music (Hedonic group, HDN), and low sensitivity to music (Anhedonic group, ANH). Participants were matched in other measures such as age, general anhedonia, sensitivity to punishment and reward scale and amusia score (Table 1).

SCR data: emotional arousal

In the first session, participants engaged in a music-listening task, similar to that used by (4). They had to listen to 32 previously rated musical excerpts (10 pleasant, 10 neutral and 10 unpleasant and 2 pleasant ones selected by the participant). We carried out this procedure for music selection in order to overcome the limitation that musical anhedonic participants have difficulties providing self-selected pleasurable music. The fixed selection resulted from a pre-experiment test in which an independent sample of 65 students with similar demographic characteristics rated 82 musical excerpts. From these data, we selected the 10 excerpts with the highest liking rate score across subjects (pleasant excerpts), the 10 with the lowest (unpleasant excerpts) and other 10 with a mean liking rate just below the overall mean liking rate (neutral excerpts). While listening to music, participants were required to indicate online the degree of pleasure they were experiencing at any given time point (1 = unpleasant, 2 = neutral, 3 = low pleasure, 4 = high pleasure, 5 = chill) by pressing a corresponding key. After each excerpt, participants rated the degree of global pleasure (global liking rate), familiarity with the excerpt, emotional valence, arousal and number and intensity of any experienced chills. For each participant, the four excerpts rated as most pleasant and the four rated as least pleasurable were selected to be used in the fMRI experiment, along with a fixed selection of four pleasant and four unpleasant excerpts (for further details see *Material and Methods*).

Behaviorally, we confirmed significant differences on average in the global liking rates reported by the three groups on those 16 excerpts that were subsequently selected for the fMRI experiment ($F(2,42) = 12.44$, $P < 0.001$). Post hoc comparisons using the Tukey HSD test revealed that ANH participants rated the excerpts as less pleasurable than the HDN ($P = 0.044$) and HHDN ($P < 0.001$) groups. The excerpts were also reported as less emotionally arousing by the ANH group (group effect, $F(2,42) = 9.01$, $P < 0.001$; post hoc Tukey HSD, ANH versus HDN, $P = 0.071$; ANH versus HHDN, $P < 0.001$). In contrast, there were no differences among groups in the familiarity ($F(2,42) = 1.60$, $P = 0.213$), nor for mean valence rates ($F(2,42) = 0.34$, $P = 0.712$).

In order to study which variables affected pleasure ratings, the percentage of online responses associated with high pleasure (responses 4 and 5, corresponding to high pleasure rates and chills respectively) was entered as dependent variable in a stepwise regression with all the psychometric scores available (BMRQ, PAS, SPSRQ, and MBEA; see *Material and Methods* for details) included as independent variables. Percentage of high pleasurable rates was predicted only by the overall BMRQ score ($R^2 = 0.40$, $F(1, 43) = 29.59$, $P < 0.001$; Fig.1a). Similarly, stepwise regression showed that global liking rates and number and duration of chills were only predicted by BMRQ (global liking rate: $R^2 = 0.38$, $F(1,43) = 26.15$, $P < 0.001$; Fig.1b; duration of chills: $R^2 = 0.13$, $F(1, 43) = 6.31$, $P = 0.016$; intensity of the chills: $R^2 = 0.29$, $F(1,43) = 17.11$, $P < 0.001$; Fig. S1a,b).

Fig. 2 presents SCR responses associated with the different online ratings experienced by the three groups for the 16 excerpts used as stimuli in the scanning session. Consistent with previous findings, SCR curves show that the ANH group have in all conditions lower amplitude than those of the other two groups. Indeed, those ANH participants reporting chills did not show increase in the SCR (Fig.2a). To test the relationship between the degree of pleasure experienced and SCR amplitude on a trial-by-trial basis, we carried out a regression analysis for each individual, using SCR amplitude as dependent variable and pleasure rating as independent measure. If SCR amplitude scales with the degree of pleasure rated by the participants, then the slope of this relationship should be positive and significantly different from 0. This was the case for HDN ($t(14) = 2.28$, $P = 0.039$) and HHDN ($t(14) = 5.65$, $P < 0.001$), i.e higher online ratings were associated with larger SCR amplitude in these two groups (Fig. S1c), whereas ANH participants showed only a marginal relationship between the SCR and the behavioural rates of pleasure ($t(14) = 1.91$, $P = 0.077$). Similarly, the stepwise regression analysis between the individual's slope and all the psychometric measures evaluated showed that the BMRQ was the only variable that significantly predicted each individual's slope in the SCR analysis ($R^2 = 0.11$, $F\,(1,43) = 5.44$, $P = 0\ .024$).

fMRI data: behavioural correlates of sensitivity to music reward

In the fMRI session, participants had to perform two experiments: a monetary gambling task and a music listening task, in which they had to provide online rates of the degree of pleasure they were experiencing (Fig. 3).

Behavioral effects paralleled those observed in the SCR session. Again, the frequency of online responses associated with high pleasure (high pleasure ratings and chills) for all excerpts during the scanning session was predicted only by the overall BMRQ score (R^2 = 0.36, $F(1, 43)$= 24.63, P < 0.001, Fig.1c). Similarly, the global online liking rate (calculated as the response value 1, 2, 3 or 4 multiplied by the duration of this response during each excerpt and averaged across excerpts) was only predicted by the BMRQ (R^2 = 0.23, $F(1,43)$ = 13.10, P < 0.001, Fig.1d). We found the same results in a stepwise regression considering as dependent variable the global online liking rate provided for pleasant (R^2 = 0.21, $F(1,43)$ = 11.67, P < 0.001) and unpleasant (R^2 = 0.12, $F(1,43)$ = 5.74, P = 0.021) excerpts separately.

fMRI results: reduced BOLD response in specific musical anhedonia

In order to examine the activation induced by music, we compared whole-brain fMRI activity when participants were listening to music against rest blocks. This contrast yielded significant BOLD signal change in the superior temporal gyrus (STG) of both hemispheres (right STG, x = 62, y = -25, z = 12; left STG, x = -47, y = -13, z = 0; P < 0.05, FWE corrected; Fig.4a and Table S1) as expected. However, there were no significant changes in the activation of the STG in the music versus rest condition when performing a one-way ANOVA across the three groups, indicating that sensory/perceptual processing is similar regardless of sensitivity to music reward. In addition, we included the online pleasure ratings as a parametric effect to test the activation of brain areas specifically related to the degree of pleasure experienced by the participants. This contrast yielded increased hemodynamic activity in the left NAcc (left NAcc, x=-13, y=12, z=-10; P < 0.05, small volume correction (SVC) for the NAcc defined in an unbiased manner using a neuroanatomical atlas (18, 19); Fig.4a), suggesting that activity in this region was directly related to the pleasure experienced by participants. Fig.4b shows the linear trend to increase of the beta value of the parametric regressor of pleasure rating split into the four online pleasure ratings for the peaks of the left and right VS when thresholding the parametric analysis at an uncorrected P < 0.005. Brain activity on monetary rewards and punishments was also determined by modulating reward magnitude and valence in the gambling task (see *Materials and Methods* for further information). When including these variables as parametric regressors, activation was found bilaterally in the VS (right VS, x = 9, y = 9, z = -10; left VS, x = -13, y = 9, z = -10; P < 0.05, FWE corrected; Fig.4a-b and Table S2). Conjunction analysis across music and gambling tasks confirmed that there was conjoint activation of the two types of rewards in the left NAcc (left NAcc, x = -13, y = 12, z = -10; P < 0.05, SVC; Fig.4a).

Crucial to our hypothesis for the existence of a dissociation between the activation induced by music and monetary gains in the ANH group was the interaction of group x task. Whole-brain analysis revealed a significant group x task interaction in the bilateral NAcc (right NAcc, x = 9, y = 12, z = -7; left NAcc, x = -7, y = 12, z = -7; P < 0.05, SVC; Fig.4c), showing that this region presented a differential activation for music and

monetary rewards across groups. Further analysis of contrast estimates at this region showed that striatal sensitivity to music-induced pleasure in ANH individuals was reduced in comparison to the other two groups, while the activation of monetary rewards was similar in all the groups (Fig.4c).
In order to decompose the effect of the group x task interaction, we conducted a region-of-interest (ROI) analysis in the NAcc using the same neuroanatomical mask than for our voxel-wise analysis with SVC. We computed the mean contrast estimates for the parametric effect of pleasure rating and monetary task within the left and right NAcc and then performed a repeated measures ANOVA with task and laterality as within factors. Only the main effect of group and the interaction of group x task were statistically significant (P = 0.01 and P = 0.03, respectively). Pairwise comparisons revealed that contrast estimates differed only when comparing the ANH group against the HHDN or HDN groups (ANH versus HDN, t(28)=2.65, P = 0.01; ANH versus HHDN, t(28)=2.44, P = 0.02; HHDN vs HDN, t(28)=-0.03, P = 0.98). In contrast, no significant differences were found across groups for the contrast estimates of monetary feedback (all $P > 0.2$).

Further, when comparing the ANH against the HHDN or HDN groups in the whole-brain analysis of the parametric modulation of pleasure rating, we found enhanced activity in the bilateral NAcc ($P < 0.05$, SVC). However, the comparison between the HHDN versus the HDN and all pairwise comparisons of the parametric analysis of monetary reward yielded no suprathreshold voxels within the NAcc (see SI Results).

PPI results: reduced connectivity in specific musical anhedonia

Critical to our hypothesis is to determine to what extent specific musical anhedonia may be explained by a reduced interaction between the cortical systems involved in perceptual and cognitive computations and the subcortical mechanisms for reward processing. To examine this, we performed a whole-brain "Psycho-Physiological Interaction" (PPI) analysis using the left and right STG (anterior and posterior, defined on the basis of a neuroanatomical atlas (18, 19)) as seed regions (Fig.5a). In order to examine differences across groups, we specified a linear contrast in a one-way ANOVA. This analysis revealed an increased functional connectivity between the right STG and the right NAcc during music listening (right NAcc, x = 12, y = 12, z = -7; $P <$ 0.05, SVC; Fig.5b). No significant connectivity was found between left STG and other brain regions.

In order to determine what differences were driven this effect, we conducted a ROI analysis focusing on the NAcc using the same neuroanatomical mask as that for fMRI activation (Fig.5c). In a one-way ANOVA we found a main effect of group (P = 0.05). Pairwise comparisons indicated a lower functional connectivity of the right STG and the NAcc in ANH participants compared to the HHDN group (HHDN versus ANH, P = 0.02; HDN versus ANH, P = 0.10; HHDN vs HDN, P = 0.39).

Further, we found a downregulated interaction between the right STG and right NAcc when comparing the ANH with either the HHDN or HDN group using a t-test in the whole-brain PPI with SVC for the NAcc but this was not the case for the comparison between the HHDN versus the HDN group (see SI results). In addition to the difference between the ANH group with HHDN and HDN participants, we also found an enhanced interaction between the right STG and VS in the comparison between HHDN and HDN when using SVC for the VS defined using NeuroSynth, a platform for large-scale automated meta-analysis of fMRI data (20) and reward as search term (see Fig.S5c and SI Results). Future research should confirm this three-way distinction in functional connectivity across groups.

Taken together, these findings are consistent with the idea that specific musical anhedonia is associated with a downregulation of functional connectivity between the auditory cortex and NAcc.

Discussion

In the present study we provided compelling evidence that activity in the Ventral Striatum (including the NAcc) and functional connectivity between this region and the right STG is crucial in giving value and experiencing pleasure from music. This finding was revealed by studying people with specific insensitivity to musical reward (specific musical anhedonia, ANH) along with people with standard (HDN) and high sensitivity to music (HHDN). Our main results suggest two brain mechanisms associated with specific musical anhedonia, a phenomenon which has broader theoretical implications for music reward processing. First, the NAcc activity of the ANH group was significantly reduced during music listening but not when participants were winning or losing money in a gambling task. Second, the functional connectivity between the right STG and ventral striatum (including the NAcc) is downregulated in ANH participants and upregulated in HHDN participants. In addition, activity in temporal-lobe auditory cortices was not changed in the ANH group, consistent with their intact auditory capacities. Taken together, these findings are in accordance with previous work (4) where ANH participants reported fewer chills and of lower SCR magnitude than people with average (HDN) or higher (HHDN) sensitivity to music, thus indicating a low emotional arousal in response to music that cannot be explained by perceptual problems or generalized anhedonia.

It is well-established that the ventral striatum, and especially the NAcc, plays a prominent role in music reward processing (9–11, 15, 16), as it does in processing of other, more biologically basic rewards (21, 22). Indeed, in a prior study it was shown that the degree of activity in the right NAcc was the best predictor of the bid amount participants were willing to spend to purchase previously unheard music (16). Moreover, the NAcc is consistently recruited as a function of increasing music-induced pleasure (23) and reaches its maximum activity during peak pleasure (chills) (11). In the current study, we observed a reduced activation in the NAcc in participants that subjectively reported music listening as not being a pleasurable experience. This finding is consistent with the aforementioned studies and with previous work showing that trait anhedonia is associated with a reduction in the activation of the NAcc (24).

Most importantly for purposes of testing our model, we found reduced functional connectivity between the right STG and VS (including the NAcc) in ANH participants compared to the other groups. This reduction fits in well with previous neuroimaging studies showing that music reward value increases with enhanced functional connectivity between the NAcc and a high-order temporo-frontal cortical network involved in perceptual analysis, emotional processing and valuation (16). Indeed, the unique ability of humans to appreciate aesthetic rewards such as music relies on higher-order perceptual/cognitive analysis and encompasses learning, experience, and cultural factors that would be expected to involve cortical systems (12, 25, 26). In line with this idea, our results also support the notion that to derive pleasure from music the cortical and subcortical systems must act in concert; in particular we found the interplay between the right STG and ventral striatum to be crucial. The auditory cortical regions involved in perceptual analysis of music and other sounds are found within the STG, and a right-sided predominance for tonal processing has long been noted (27).The role of the auditory cortex as a central hub of an affective-emotional network has also been highlighted by a previous study comparing music-evoked fear and joy (28). When listening to joyful music the auditory cortex showed enhanced functional connectivity with the cingulate and insular cortices, which are regions implicated in autonomic regulation and production of subjective feelings. Conversely, effective connectivity modulations between auditory cortex and the amygdala have been involved in the processing of aversive sounds (29). Taken together these findings implicate cortical-subcortical interactions in relating auditory features to affective value, a conclusion that fits well with our findings that reductions in these interactions are associated with lack of affective response to music.

An interesting analogy for the requirement of an intact coupling between the STG and the reward network for typical affective processing of auditory stimuli comes from studies of children with Autism Spectrum Disorder, whose inability to experience human voice as pleasurable may be explained by a reduced coupling between bilateral posterior superior temporal sulcus and distributed nodes of the reward system including the NAcc (30). These cortical-subcortical impoverished interactions could be crucial for the correct attainment of language learning milestones, probably because the reduced capacity in these children to experience auditory processing and language learning experiences as rewarding (31). On the other hand, enhancements to this system may be observed in musicians. Musical training is known to be associated with functional and anatomical enhancements of the superior temporal cortex (32–34), but also has been shown to modulate striato-cortical connectivity during music listening (35). Also relevant is that individual differences in structural connectivity in the tracts connecting the posterior STG with the anterior insula and medial prefrontal cortex have recently been associated with individual differences in music reward sensitivity (36). In future studies, it would be interesting to examine whether similar structural differences can be found in our sample in which we included individuals lacking reward responses to music specifically but with preserved capacities to experience pleasure from other reinforcers. The above-mentioned studies all point to individual differences in the links between cortical and subcortical systems as relevant for understanding differences in reward-related processing, a conclusion which is consonant with our claim that individuals with music-specific anhedonia lack the relevant functional relationship between auditory processing regions and reward-related structures.

Finally, our results support the idea that people might present distinct sensitivity to reward for different stimuli and, concretely, the existence of specific anhedonias and hyper-hedonias. Indeed, a recent meta-analysis showed that different types of rewarding stimuli (such as food, sex and money) specifically recruited brain areas associated with the sensory modality and/or associative areas involved in processing these stimuli (37). Moreover, previous lesion studies have reported single cases of patients with specific loss of pleasure for music after lesions, not only in reward-related areas, but also in temporal and parietal cortices (38–40). All these findings give support to the hypothesis that, to assign reward value the recruitment of cortical structures related to the perceptual, integrative and cognitive aspects of these complex reinforcing stimuli is essential. Therefore, our concept is that there would be different ways to access the core reward circuit, which would depend on the modality and nature of the reinforcer (41). Following this rationale, a reduced connectivity between these regions and the reward network, as is the case of reduced connectivity between NAcc and STG, would result in selective anhedonia for these reinforcers and conversely, an increased connectivity would yield increased hedonic experience as is the case for the HHDN group.

In conclusion, we showed that a reduced interaction between the auditory cortex and the mesolimbic reward network may point to the top-down mechanism that is impaired in people unable to derive pleasure from music but who show otherwise normal perceptual and reward processing. This finding may pave the way for the detailed study of the neural substrates underlying other domain-specific anhedonias and, from an evolutionary perspective, help us to understand how music acquired reward value.

Material and Methods

Participants. 45 university students participated in the experiment and were divided in three groups of 15 subjects (8 females, 7 males). Participants were selected using the Barcelona Music Reward Questionnaire (BMRQ), a psychometric instrument known to be a reliable indicator of interindividual variability in music-induced reward (17). In the first round of selection, the BMRQ was delivered to a population of 2600 university students from Barcelona (33.8% males, M =18.3, SD =6.9) in their classrooms or by email in reply to an advertisement. In the second round of selection, 111 right-handed individuals with no formal musical training were selected and asked to complete a second BMRQ in the laboratory to ensure consistency across measures. Participants were also assessed in their (i) global sensitivity to reward and punishment using the Sensitivity to Punishment and Sensitivity to Reward Questionnaire (SPSRQ) (42); (ii) hedonia trait using the Physical Anhedonia Scale (PAS, excluding those items referring to musical rewarding experiences to assess the hedonic impact of other activities or stimulus outside the music domain) (43); and (iii) amusia score using the Montreal Battery for Evaluation of Amusia (MBEA) (44). Upon completion of this round, we selected 45 participants who scored within the normal range in these scales and presented normal skin conductance response levels. We classified participants in three groups of 15 people according to their overall BMRQ scores: those scoring equal or lower than 65 were included in the anhedonic group (ANH), those with $65<\text{BMRQ}<87$ in the hedonic (HDN) and those scoring higher than 87 in the hyperhedonic (H-HDN) (adapted from (4)). The three groups were matched in these three measures (PAS, MBEA and SPSRQ) but differentiated in the BMRQ [overall scores averaged between the BMRQ overall score available from the first round of participant selection and that from the BMRQ completed in the laboratory during the SCR session (Table 1)]. There was a high reliability in the two BMRQ tests (correlation r (43) = 0.94, $P < 0.001$). All participants were healthy and free from any neurological or psychological disorders and gave written informed consent before participating in the study. All procedures were approved by the Ethics Committee of the Hospital Universitari de Bellvitge, Barcelona (PR181/13).

Stimuli selection. Participants were instructed to provide two pieces of instrumental music that elicited intensely pleasant emotional responses for them. Musical anhedonic individuals by definition experience low emotional responses to music and thus had difficulties providing such intensely pleasurable music. To guarantee that all participants were exposed to music that had a "global" emotional impact we created a musical list of 82 excerpts that was assessed by an independent group of students with similar demographics (N = 65). The first inclusion criterion was that the selected music could not include any lyrics in order to avoid language-related activations in the fMRI experiment. The second inclusion criterion was that music should have similar familiarity levels between groups. To this aim, and as most students are exposed to classical music since early years of education in the Spanish syllabus, we restricted the selection to the classical genre. We also included some excerpts that could be considered less pleasant or even unpleasant by the participants to have a continuous representation of all pleasure ratings and minimize the probability that those associated with higher degrees of pleasure would be over-represented. 40 potentially pleasant and 2 potentially unpleasant excerpts (approximately 50% of the musical stimuli) were selected from a sample of 200 chill-inducing music selection adapted from (45).The rest of the stimuli were selected by using the music recommendation program, Spotify radio (https://www.spotify.com). This program uses "collaborative filtering" to match new recommendations based on popular choices of other individuals who have similar music preferences. Specifically, we created a playlist with the 40 pleasant excerpts and started a radio from each playlist. Spotify recommendations of similar music were saved into a new playlist. The same procedure was followed to select new unpleasant music. Because there were only two unpleasant musical pieces in the initial playlist, we also added some music composed before the XVIth century or atonal compositions including those from the Second Viennese School. These compositions do not follow the rules of traditional Western music and therefore we would expect them to elicit a lower rewarding experience in our population. The new music stimuli included 30 potentially unpleasant and 10 potentially pleasant songs. These 82 excerpts (Table S3) were tested in a pre-experiment session with a sample of 65 university students who provided liking rates for each excerpt (from 1=unpleasant to 7=extremely pleasurable). Musical excerpts were then sorted according to the mean liking rate. The 10 excerpts that showed the highest mean liking rate were selected as pleasant and those 10 which showed the lowest mean liking rate were selected as unpleasant. Furthermore, those 10 with a mean liking rate just below the overall mean liking rate (4.5) were included in a neutral category. Hence the final fixed selection for the music stimuli in the SCR session included 30 musical excerpts (10 pleasant, 10 neutral and 10 unpleasant; Table S4). Musical excerpts were cut down to one-minute clips using the Audacity software (version 2.0.2) and normalized to maximum peak amplitude of -1.0 dB. The one-minute selection was made so as to ensure that at least one entire musical phrase was presented in the excerpt. All excerpts were saved in mp3 format at 296 bit rate. For the two self-selected excerpts, participants were asked to select the minute themselves to ensure that the most subjectively pleasurable minutes were used.

Music Task Design (SCR Experiment). Participants listened to all musical pieces in randomized order. Two blocks (15 one-minute excerpts, 5 of each type, and one self-selected) with a break in between were presented using Presentation software. While listening to music, the participants had to rate, in real-time, the degree of pleasure they were experiencing by pressing one of five different buttons on a keyboard (1=unpleasant, 2=neutral, 3=low pleasure, 4=high pleasure, 5=chill, adapted from (4, 45)) and they had to hold down the button as long as they were experiencing the respective degree of pleasure. At the end of each excerpt, the participants were asked to rate the overall degree of pleasure (from 1=disliking to 7=extremely pleasurable) and the familiarity with the excerpt (from 1=unfamiliar to 5=highly familiar) as well as the emotional valence (from 1=sad to 9=happy) and arousal (from 1=not at all arousing to 5=highly arousing) they felt in response to the musical excerpt. For these last two subjective rates, a self-assessment manikin was displayed for visual support (46). Finally, participants were asked to report the number and the intensity of chills they experienced (from 1 to 3). In addition to the experimenter's instructions, written instructions were provided on the screen at the beginning of the task.

SCR Procedure. SCR was recorded during the task with two Ag-AgCl electrodes using a Brainvision Brainamp device. The electrodes were attached to the forefinger and the middle finger of the left hand and placed on the first phalange. The level of SCR was determined by measuring the mean SCR amplitude after stimulus or response onset with respect to baseline (-1000 ms). SCR amplitude was determined in the 0 s –10 s window after participants pressed a button to indicate a change in pleasure levels. Previous studies have shown that SCR during this time window is modulated according to the degree of pleasure experienced (47, 48).

SCR Statistical Analysis. As highlighted in a previous study by our group (4), most of the ANH participants did not report chills and some of the HDN and HHDN participants did not report neutral rates. In accordance with the analysis reported in that study, the relationship between pleasure ratings and SCR amplitude was assessed by a linear regression model for each subject using SCR amplitude as the dependent measure and rating as independent variable. The SCR amplitude for each trial was determined separately for each subject. Using these values, a linear model could then be fitted for each subject:

SCR Amplitude =Rate * β + intercept + noise

We then determined whether the mean value of the slope (β) was different from 0 for each group using a one-sample t-test.

Lastly, stepwise linear regression analysis was used to assess the relationship of each dependent behavioral variable and the individual's slopes with the psychometric independent variables (BMRQ, SPSRQ, PAS, MBEA). The entry criterion was $P < 0.05$ and the exit criterion was $P > 0.10$. Tests for multicollinearity indicated that a very low level of multicollinearity was present in the analysis (VIFs < 1.09 and tolerances > 0.9).

Music Task Design (fMRI Experiment). A total of 16 one-minute excerpts were presented in two runs encompassing 8 excerpts each. Half of the excerpts were fixed for all participants (Table S4), while the other half was selected for each individual based on the liking rates provided in the SCR experiment. The fixed excerpts consisted of the 4 excerpts (from the 30 stimuli used in the SCR experiment) which obtained the highest mean liking rate in the pre-experiment screening (pleasant music) and the 4 excerpts with the lowest rating (unpleasant music). In addition, for each individual, those 4 excerpts with the highest liking rate, number, intensity and duration of chills in the SCR experiment were included as pleasant music and those 4 with the lowest liking rate, number, intensity and duration of chills were selected as unpleasant music (for a detailed description of the excerpts selected for each group, see table S5). One day prior to the functional MRI study, participants were presented with the musical stimuli from the SCR experiment to ensure that all participants were similarly familiar with the stimulus material. In the scanning session, individuals listened to one-minute musical excerpts while rating the degree of pleasure they were experiencing to the music in real-time (1 = unpleasant, 2 = low pleasure, 3 = high pleasure) using three separate buttons on an MR-compatible four-button input device. They were required to hold down the appropriate button as long as they were experiencing the respective degree of pleasure, and press a fourth button when they were experiencing a chill. Individuals were always holding down one button to ensure that neural activity involved in button pressing and anticipation of button presses were equally distributed. Four one-minute excerpts of pleasant music and four one-minute excerpts of unpleasant music were played in pseudo-randomized order such that no more than two excerpts of the same type were presented consecutively. Between excerpts, a 30 s rest period was included to reduce carry-over effects. To allow for equilibration, each run started with a fixation cross lasting for 15 s. All participants were given instructions before entering the scanner in order to familiarize them with the music task.

Gambling Task Design (fMRI session). Stimuli were presented using Presentation software. Each trial of this task started with the presentation of two numbers ([25 5] or [5 25]) for two seconds (49). Participants were instructed to bet on one of the two numbers by pressing the spatially corresponding button with their right hand. The left-hand button-pad was not used in this task. After this, one of the numbers turned red and the other green. If the number selected by the participant turned green, the participant gained the corresponding amount of money in Euro cents. The number turning red indicated a loss. In order to take into account unexpected gains or losses, two more conditions were created (boost gain and boost loss). In these trials, instead of winning or losing 5 or 25 cents, participants gained or lost 125 cents. 30 gain trials, 30 loss trials, 15 boost gain and 15 boost loss trials were presented in each of the two runs of the task. Additionally, 25 trials of a three second-long fixation cross were presented per run. The inter-trial time varied between zero and two seconds. After each run, the amount of money gained or lost was presented, in the middle of the screen to the participant. As in the music task, each run started with a fixation cross lasting for 10 s to allow for equilibration. All participants completed a training block before entering the scanner in order to familiarize them with the gambling task. Unknown to the participants, the characteristics of the trial and its result (gain or loss) were decided by the computer program before the start of the experiment. Participants started the gambling task with 10 Euros and were instructed to earn as much money as possible. The amount of money won by a participant was paid to him/her at the end of the scanning session. The gambling task was counterbalanced for order with the music task across participants.

fMRI Acquisition. MRI data was collected on a 3T scanner (GE Discovery MR750w) using an eight-channel phased-array coil (GE Healthcare, Little Chalfont, UK). The session started with the acquisition of high-resolution whole-brain structural images (BRAVO; TR=11.668 ms, TE=4.79 ms, TI=450 ms, flip angle=12º, slice thickness=1 mm, matrix size=512×512) in order to allow precise coregistration with functional data. After this, whole-brain volumes of EPI images sensitive to blood-oxygenation level-dependent contrast (Gradient Echo EPI; TR=2500 ms, TE=30 ms, flip angle=90º, slice thickness=3.1 mm, 43 axial slices angled +30º to the plane intersecting the ACPC, matrix size=64×64, fat saturation band placed in the frontal sinus) were acquired for the two runs of the 288 sequential images of the music task. The same protocol was applied to acquire the two runs of the 216 sequential images of the gambling task.

Preprocessing and statistical analysis. Data were preprocessed using Statistical Parametric Mapping software (SPM8, Wellcome Trust Centre for Neuroimaging, University College, London, UK, www.fil.ion.ucl.ac.uk/spm/). Functional runs were first slice timing corrected (interleaved order bottom-up, sinc interpolation, reference slice 43), realigned and a mean image of all EPIs was created. The T1 image was coregistered to the mean EPI image and segmented into grey matter (GM) by means of the default segmentation options in SPM8 (Unified Segmentation algorithm, (50)). After an initial 12-parameter affine transformation of the GM tissue probability map to the GM MNI template included in SPM8 (4th Degree B-Spline Interpolation), the resulting normalization parameters were applied to the whole functional set (voxel size 3.1mm). Finally, functional EPI volumes were smoothed with an 8mm FWHM kernel. For the music and gambling tasks, the statistical analysis was performed according to the general linear model as implemented in SPM8. "Pleasant" and "unpleasant" conditions were modeled time locked to 5 s after the onset of each excerpt. The "rest" condition was modeled in a separate regressor with 30 s duration. Music-related "responses" were modeled as events time locked to the moment in which participant pressed the button to provide the pleasure rating. Consecutive responses of the same pleasure rate were excluded from this regressor. In addition, those chills occurring two events before the current chill were excluded if the difference in latency was less than 5 s. For the "responses" condition a first-order parametric regressor modeled the pleasure rate (1,2,3,4). Separate regressors to model the first 5 s of each excerpt and the excluded responses were also specified in the design matrix. For the gambling task, trial onsets were modeled time locked to the moment in which the cue ([25 5] or [5 25]) appeared on screen. For the "feedback" condition a first-order parametric regressor modeled the reward magnitude and valence including 6 levels to represent gain and losses for both standard and boost trials (-125,-25,-5, 125, 25 and 25). To model the moment at which participants pressed the button, a "response" condition was included along with a first-order parametric regressor modulating whether participants used the left or right button.

For both tasks, remaining motion effects were minimized by including 24 confounding factors from head movement. All regressors were subsequently convolved with the canonical hemodynamic response function. After model estimation, the contrast for the parametric modulator in the music task (responses modulated by pleasure rate) was calculated for each subject and introduced into a second level RFX analysis by using a one sample t-test in order to calculate group effects. The same was done in the gambling task by calculating the contrast for the parametric modulator of feedback. In the music task, we confirmed activation in auditory areas using the contrast music versus rest. To analyze the effect of group on each task we used a flexible factorial design including the interaction of group x task and specified a linear contrast with increasing levels of sensitivity to music. Results are reported at a FWE-corrected $P < 0.05$ with 100 voxels of cluster extent or at a FWE-corrected $P < 0.05$ using SVC for a mask of the bilateral NAcc based on a neuroanatomical atlas (18, 19) (in this case, whole-brain analysis was thresholded at an uncorrected $P < 0.005$).

Since we predicted specific musical anhedonic participants would show reduced activation especially in the nucleus accumbens (NAcc), we performed a ROI analysis with a NAcc ROI based on the aforementioned neuroanatomical atlas (18, 19) and compute the mean contrast estimate for the parametric modulator of pleasure ratings in the music task and monetary feedback in the gambling task.

Functional connectivity (fcMRI) and statistical analysis. For the functional connectivity analysis, a ROI was defined around the single subject peak value of the right and left superior temporal gyrus (STG) for the contrast of the parametric modulator of pleasure rating. The STG ROI was extracted from a probabilistic neuroanatomical adult atlas developed by Hammers *et al.* (18, 19). The adult atlas was downloaded from the author's website (http://brain-development.org/brain-atlases/) and the anterior and posterior parts of the STG were merged to generate the ROI, one for the left and other for the right hemisphere, taking the peak from the parametric analysis of the music task. Individual time-courses from this ROI were extracted for the music versus rest contrast. Next an extended model was built including the three conditions previously defined for the music task (rest, pleasant and unpleasant music) plus the extracted right STG time-course and the derived *psychophysiological interaction* (PPI) within the standard PPI approach as regressors (51). The computed first level PPI results were taken to a second level RFX analysis by using a one-way ANOVA and a linear contrast was specified. Results are reported at a FWE-corrected $P < 0.05$ using SVC for a mask of the bilateral NAcc based on a neuroanatomical atlas (18, 19) (in this case, whole-brain analysis was thresholded at an uncorrected $P < 0.005$).

In the ROI analysis we used the same neuroanatomical NAcc mask than that for SVC and applied this to the contrast estimated for the PPI regressor.

Acknowledgments

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Figures and tables

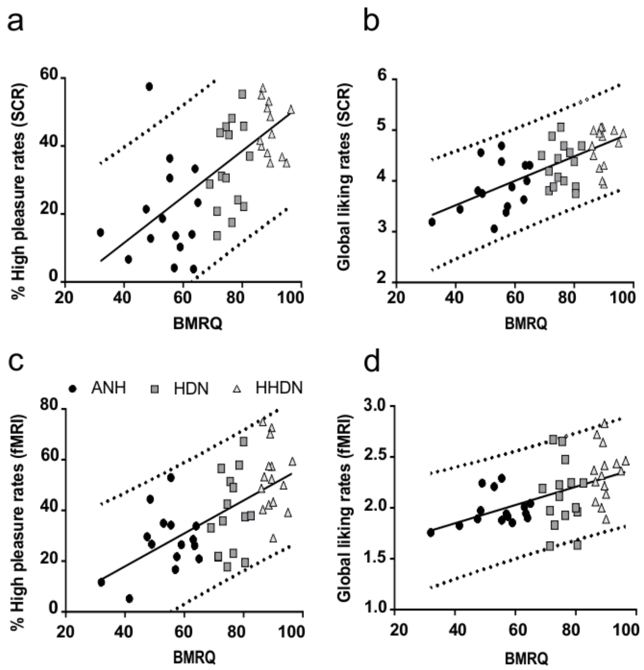

Figure 1. Behavioral differences to music reward. Scatter plot of the proportion of responses associated to chills and high pleasurable ratings with overall scores of the BMRQ in the music task during the SCR **(a)** and fMRI **(c)** session. Scatter plot of the global liking rates for all excerpts listened in the music task with overall scores of the BMRQ during the SCR **(b)** and fMRI **(d)** session (for further details see *Material and Methods*). In both scatter plots, black circles represent ANH participants; dark gray squares, HDN; and bright gray triangles, HHDN.The solid black line represents the slope of the linear fit, and the dotted gray line represents the 95% confidence interval.

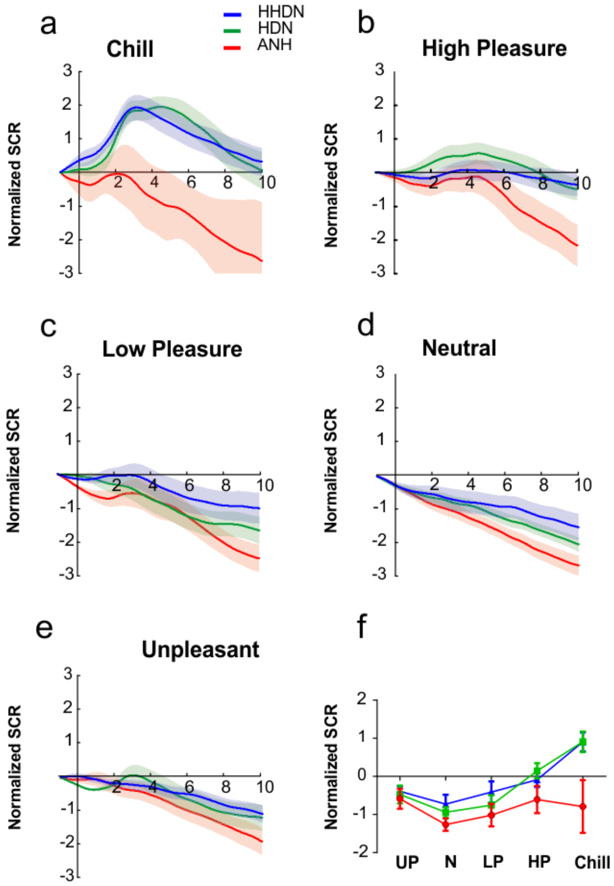

Figure 2. SCR to Different Degrees of Musical Pleasure. **(a-e)** Normalized SCR associated with five pleasure ratings (chill, high pleasure, low pleasure, neutral, unpleasant) for the three groups in the music task. Note the lower amplitude of SCR in ANH as compared to the other two groups. Solid lines indicate the averaged SCR with the corresponding SEM (shadow). The three groups are plotted separately: ANH, red line; HDN, green line; HHDN, blue line; time unit, seconds. **(f)** Average of the normalized SCR in comparison to baseline levels while participants report different levels of pleasure in the music listening task (UP: unpleasant, N: neutral, LP: low pleasure, HP: high pleasure, Chill). Both HDN and HHDN showed a clear increase in SCR while increasing pleasure rates. Same color code for groups applies.

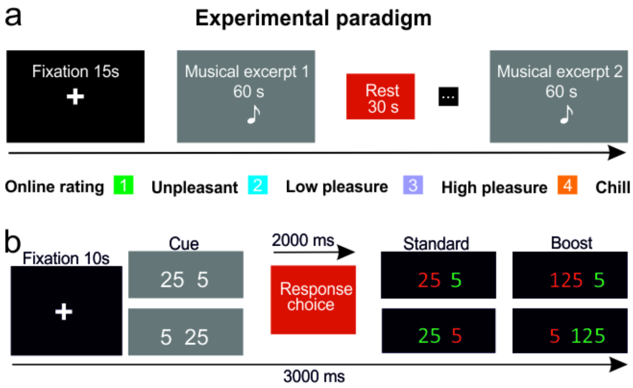

Figure 3. fMRI Experimental paradigm. **(a)** Music task. Each of the two runs started with a fixation cross lasting 15 s. Blood oxygenated level-dependent (BOLD) activity was collected while participants listened to 60 s excerpts of pleasant and unpleasant music (half matched to their own preferences and half fixed for all participants) with a rest period of 30 s between excerpts. While listening, participants had to rate their degree of pleasure from 1 (unpleasant) to 4 (chill). **(b)** Gambling task. Each of the two runs started with a fixation cross lasting 10 s. Trials started with the presentation of two numbers ([25 5] or [5 25]) for 2 s. Participants selected one of the two numbers, which then turned red (indicating a loss) or green (indicating a gain).

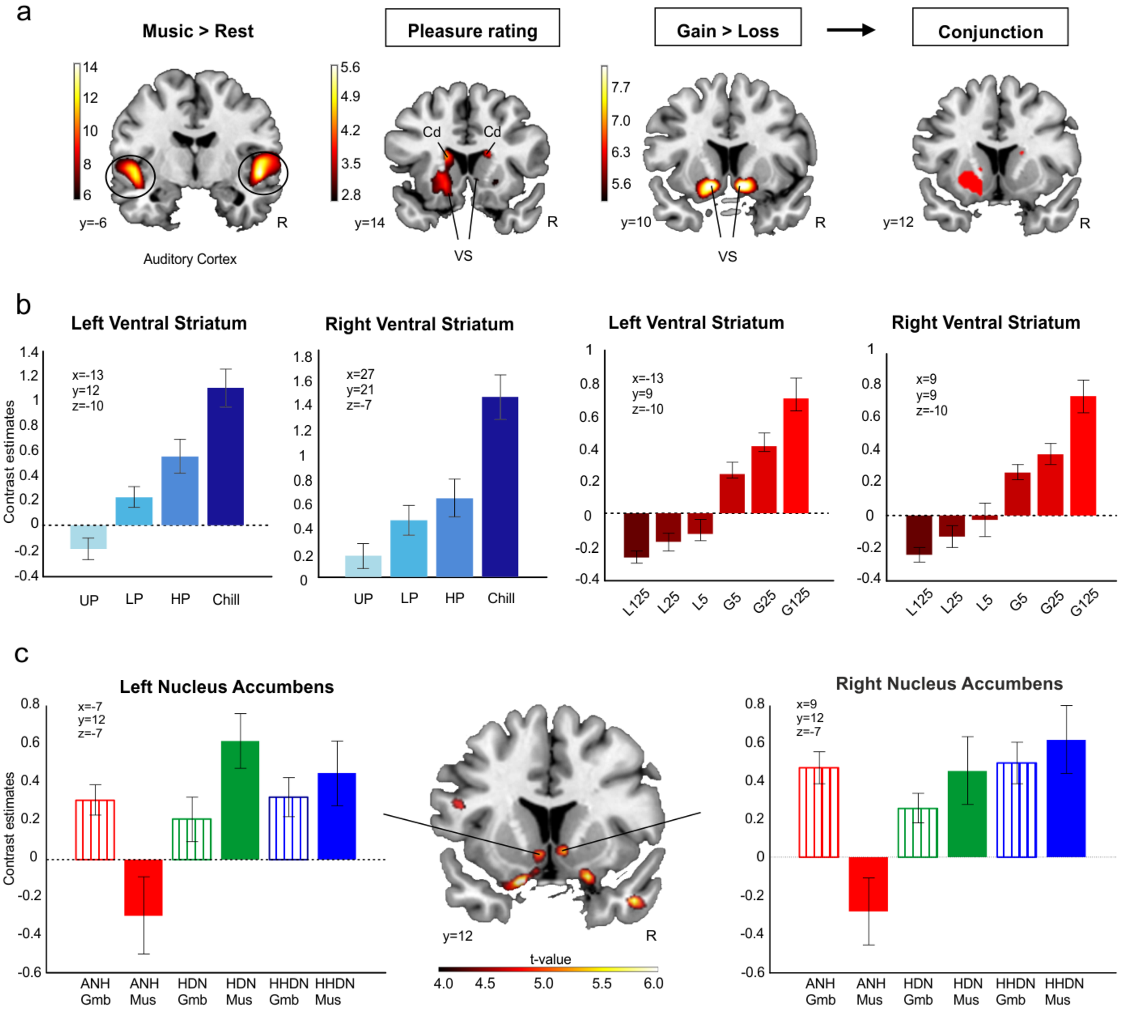

Figure 4. Brain activation differences in specific musical anhedonia. **(a)** In red-yellow (from left to right), enhanced group-level fMRI signal for the music versus rest contrast (FWE corrected, $P < 0.05$); the parametric effect of musical pleasure rating ($P < 0.005$ unc.) and the parametric effect of monetary feedback in the gambling task (FWE corrected, $P < 0.05$). The map on the right illustrates the conjunction analysis between both tasks ($P < 0.005$ unc.). **(b)** Bar graph represent contrast estimates (proportional to percent signal change; 90% confidence intervals are included; blue: parametric effect of pleasure rating, red: parametric effect of monetary feedback) for the peaks of the right and left VS in the whole-brain analysis. Note the linear increase in contrast estimates as the pleasure and monetary reward increase. UP: unpleasant, LP: low pleasure, HP: high pleasure, Chill, L125: loss 125 (euro cents), L25: loss 25, L5: loss 5, G125: gain 125, G25: gain 25, G5: gain 5. **(c)** Results for the interaction group x contrast ($P < 0.005$ unc.). Bar graph represent contrast estimates with SEM of the nucleus accumbens' peak in the group x task contrast. Gmb: gambling task; Mus: music task. Neurological convention is used, with Montreal Neurological Institute (MNI) coordinates at the bottom left of each slice. VS, ventral striatum; Cd, caudate.

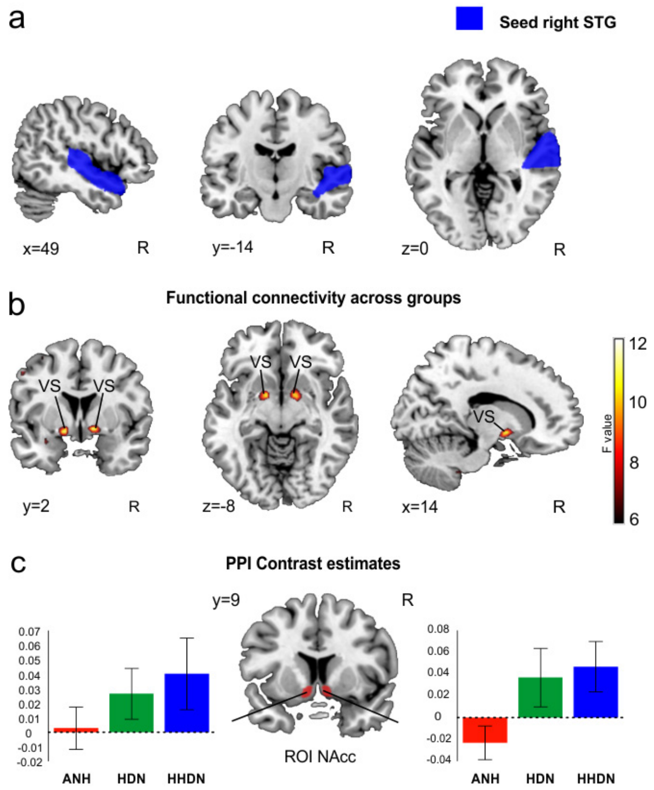

Figure 5. Functional connectivity between the right STG and VS. **(a)** The right STG seed used in the PPI analysis is depicted in blue. **(b)** Higher coupling (red-yellow) of the right STG with the bilateral VS in the context of music versus rest condition for one-way ANOVA of PPI regressor; $P < 0.005$ unc. **(c)** Bar graphs indicate contrast estimates with SEM of functional connectivity within the NAcc ROI: ANH, bright gray; HDN; dark gray, HHDN, black. Neurological convention is used, with Montreal Neurological Institute (MNI) coordinates. STG, superior temporal gyrus; VS, ventral striatum.

Table 1. Psychometric scores in BMRQ, Anhedonia, SPSR and Amusia of the Three Groups. ANH: anhedonic group; HDN: hedonic group; HHDN: hyperhedonic group.

	ANH	**HDN**	**HHDN**	***P* value**
n	15	15	15	
Age	21.9 (3.2)	20.8 (3.4)	21.3 (5.0)	0.760
BMRQ				
Overall	54.1 (9.2)	75.8 (4.0)	89.4 (3.3)	<0.001
Musical seeking	8.0 (2.2)	13.1 (1.5)	16.0 (1.9)	<0.001
Emotion evocation	10.9 (2.9)	15.8 (2.2)	18.0 (1.4)	<0.001
Mood regulation	13.0 (3.1)	16.3 (2.0)	19.2 (1.0)	<0.001
Sensory-motor	11.7 (3.9)	16.3 (2.4)	18.4 (1.4)	<0.001
Social reward	10.5 (2.2)	14.3 (1.9)	17.0 (1.5)	<0.001
Anhedonia				
PAS	11.9 (4.3)	10.2 (3.9)	10.9 (3.9)	0.531
SPSR				
Sensitivity to punishment	10.5 (4.0)	8.2 (5.2)	9.9 (5.7)	0.439
Sensitivity to reward	9.9 (4.4)	9.7 (4.3)	9.5 (3.3)	0.974
Amusia				
MBEA	85.7 (7.7)	87.6 (7.2)	87.4 (6.8)	0.730

SDs are reported between parentheses. *P* value indicates the significance of the group effect in a one-way ANOVA. PAS, Physical Anhedonia Scale; SPSR, Sensitivity to Punishment and Sensitivity to Reward Questionnaire; MBEA, Montreal Battery of Evaluation of Amusia.

Supporting Information

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Results

Decomposition of the interaction group x task of the fMRI data: pairwise comparisons. We found a significant group x task interaction in the bilateral NAcc (right NAcc, x = 9, y = 12, z = -7; left NAcc, x = -7, y = 12, z = -7; $P < 0.05$, small volume correction (SVC) for the NAcc defined in an unbiased manner using a neuroanatomical atlas [1,2]. The decomposition of this interaction focused on the NAcc revealed that the effects were driven by the ANH group in the music task: the NAcc was only engaged when comparing the parametric regressor of pleasure rating between the HHDN versus the ANH groups (right NAcc x = 9, y = 9, z = -4; left NAcc, x = -4, y = 9, z = -7; $P < 0.05$, SVC) and between the HDN versus the ANH group (right NAcc x = 6, y = 12, z = -7; left NAcc, x = -7, y = 12, z = -7; $P < 0.05$, SVC). No suprathreshold voxels were found between the HHDN versus the HDN in the music task and all pairwise comparisons of the parametric analysis of monetary reward.

Changes in whole-brain PPI using SVC for the NAcc based on a neuroanatomical mask (see Material and Methods): pairwise comparisons. In addition to the group effect. the comparison between the HHDN and the ANH groups indicated enhanced coupling between the right STG and the right NAcc in the HHDN compared to the ANH (right NAcc, x=9, y=6, z=-7; $P < 0.05$, SVC). In addition, we found higher coupling in the right NAcc in the HDN versus ANH contrast (right NAcc, x = 12, y = 12, z = -7; $P < 0.05$, SVC). When comparing the HHDN versus HDN, no suprathreshold voxels were found within the NAcc.

Changes in whole-brain PPI using SVC for the VS defined using Neurosynth (see Material and Methods): pairwise comparisons. We found enhanced coupling between the right STG and the VS bilaterally in the HHDN compared to the ANH (right VS, x=12, y=3, z=-7; left VS, x=-13, y=3, z=-10, $P < 0.05$, SVC). In addition, we found higher coupling in the right VS in the HDN versus ANH contrast (right VS, x = 12, y = 12, z = -7; $P < 0.005$ unc., ($P = 0.1$, SVC)). When comparing the HHDN versus HDN, we also found differences in the VS bilaterally (right VS, x = 13, y = 3, z = -7; left VS, x = -13, y = 3, z = -10; $P < 0.05$, SVC).

Figures and tables

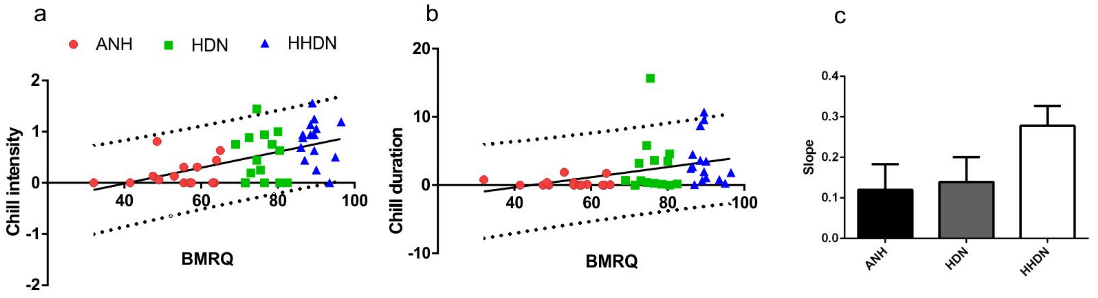

Figure S1. SCR experiment: behavioral correlates of sensitivity to music reward and physiological response to music reward

Scatter plot of (a) the reported chill intensity and (b) chill duration with overall score of BMRQ in the music task. Red circles represent ANH participants, green squares, HDN and blue triangles, HHDN. The solid black line represents the slope of the linear fit, and the dotted gray line represents the 95% confidence interval. (c) Mean slope for each group from the regression analysis performed with pleasure rating as independent variable and the normalized SCR measure. Note the general increase in the mean slope when the groups are ordered as a function of increasing sensitivity to music (from ANH to HHDN group). Error bars indicate the SEM.

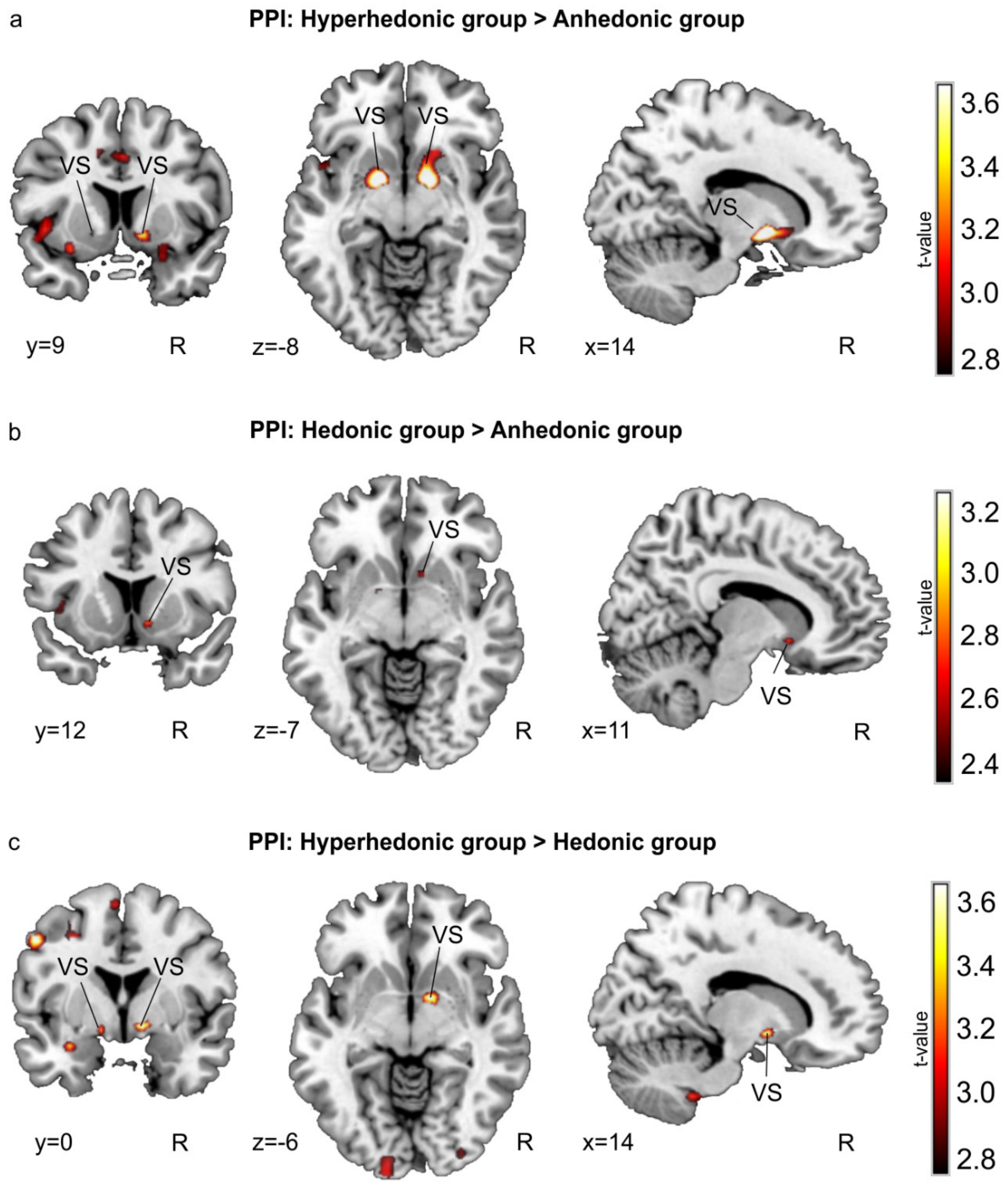

Figure S2. Functional connectivity results

(a) Higher coupling between the right superior temporal gyrus (seed region, see Fig. 5a in the main text) and the VS in the context of music versus rest in the hyperhedonic compared to the anhedonic group (P <.005 unc). (b) Higher coupling between the right superior temporal gyrus and the VS in the context of music versus rest in the hedonic compared to the anhedonic group. A lower statistical level (P < 0.01 unc.) is used for visual display. (c) Higher coupling between the right superior temporal gyrus and the VS in the context of music versus rest in the hyperhedonic compared to the hedonic group (P <.005 unc). (Neurological convention is used, with Montreal Neurological Institute (MNI) coordinates at the bottom left of each slice. VS: ventral striatum.

Table S1. Whole brain effects of music listening on fMRI signal: music versus rest contrast thresholded at a FWE-corrected $P < 0.05$ threshold with 100 voxels of cluster extent. MNI coordinates are used. Cluster size denotes number of voxels. For better location of the different regions, several peak voxels for each cluster are reported.

Anatomical area	Cluster size	Coordinates			t-value
Superior Temporal Gyrus Right	1449	62	-25	12	19.76
Right Heschl's Gyrus		52	-10	6	14.57
Superior Temporal Gyrus Left	1907	-47	-13	0	14.48
Left lobule VI of cerebellar hemisphere	829	-28	-66	-22	11.95
Right Inferior Frontal Gyrus, pars opercularis	258	49	18	27	8.67

Table S2. Whole brain effects of monetary gains on fMRI signal: parametric effect of feedback contrast thresholded at a FWE-corrected $P < 0.05$ with 100 voxels of cluster extent. MNI coordinates are used. Cluster size denotes number of voxels. For better location of the different regions, several peak voxels for each cluster are reported.

Anatomical area	Cluster size	Coordinates			t-value
Right Ventral Striatum	827	9	9	-10	9.06
Right Frontal Superior Orbital Gyrus		21	31	-19	5.58
Right Pallidum		21	3	-4	5.53
Left Ventral Striatum	1391	-13	9	-10	9.02
Left Frontal Middle Orbital Gyrus		-25	34	-19	6.29
Left Insula		-35	0	9	6.23
Left Inferior Parietal Lobe	1121	-50	-25	46	5.77
Right Midcingulate Area		3	-10	49	5.75
Left Midcingulate Area		0	-4	43	5.54
Left Superior Frontal Gyrus (BA 8)	201	-16	24	46	5.13
Left Middle Frontal Gyrus		-35	18	40	3.80
Right Middle Occipital Gyrus	824	34	-97	0	5.11
Right Calcarine Sulcus		12	-97	6	4.63
Right lobule VIII of cerebellar hemisphere	729	18	-62	-50	5.03
Left lobule VIII of cerebellar hemisphere		-22	-50	-50	4.95
Right Precuneus	443	6	-50	65	4.96
Left Precuneus		-7	-50	65	4.88
Right Postcentral Gyrus	128	46	-28	49	4.94
Right Supramarginal Gyrus		43	-31	40	4.80
Left lobule IV,V of cerebellar hemisphere	110	-16	-41	-28	4.09

Table S3. First selection of 82 potentially pleasant and unpleasant excerpts. Type: PPM, potentially pleasant music; PUM, potentially unpleasant music. Source: (1) Adopted from Salimpor *et al.* (2009); (2) Spotify radio recommendations (see main text for further details). Mean LR: mean liking rate.

Artist	Title	Type	Source	Mean LR
Vivaldi	The four seasons "Spring" Mov.1	PPM	1	6.30
Beethoven	Für Elise	PPM	2	6.26
Pachelbel	Canon In D	PPM	1	6.11
Vivaldi	The four seasons "Winter" Mov.1	PPM	1	6.06
Tchaikovsky	Dance Of The Sugar Plum Fairy	PPM	1	5.90
Tchaikovsky	Swan lake Op.20 Scene finale	PPM	1	5.86
Beethoven	Symphony No.9, Op.125, Mov.2	PPM	1	5.77
Dvorak	New World Symphony No.9, Mov.4	PPM	1	5.77
Beethoven	Moonlight Sonata	PPM	2	5.43
Holst	The Planets -Jupiter, the Bringer Of Jollity	PPM	1	5.40
Dvorak	New World Symphony No.9, Mov.2	PPM	1	5.31
Vivaldi	Concerto ripieno in C major, Mov.3	PUM	2	5.26
Debussy	Clair de lune	PPM	1	5.20
Vivaldi	The Four Seasons "Summer" Mov.3	PPM	1	5.17
Beethoven	Violin Sonata No. 5 “Spring" Mov.1	PPM	1	5.14
Rachmaninoff	Piano Concerto in C Minor No.2, Mov.2	PPM	1	5.09
Rimski-Korsakov	Sherezade "The Kalender Prince"	PPM	1	5.07
Dvorak	Symphony No. 8, Mov. 4	PPM	1	5.00
Beethoven	Piano Sonata No.8 in C Minor, Mov.3	PPM	1	5.00
Haendel	Organ Concerto Op.7, No.5 in G minor	PUM	2	4.97
Elgar	Cello Concerto in E minor, Op.85, Mov.1	PPM	1	4.97
Chopin	Prelude Op.28, No. 4 in E Minor	PPM	1	4.94
Corelli	Concerto Grosso In G Minor Op.6, No.8 Christmas	PUM	2	4.94
Bach	Cantata Bwv 208	PUM	2	4.90
Ravel	String quartet in F major Mov.2	PPM	1	4.87
Beethoven	Symphony No.5, Op.67, Mov.2	PPM	1	4.87
Mozart	Symphony No.29 in A major Mov.2	PUM	2	4.83
Holst	First Suite in E Flat major Op.28, No.1	PPM	1	4.83
Beethoven	Symphony No.7 in A major, Op.92, Mov.2	PUM	2	4.80
Haendel	II Concerto Grosso Op.6, No.4 In A minor	PUM	2	4.80
Kreisler	Praeludium and Allegro	PPM	1	4.77
Bach	Sonata No.4 in C minor Bwv 1017 Mov.1	PPM	2	4.77
Haendel	Organ Concerto Op.7,No.4 in D minor	PUM	2	4.77
Haydn	Symphony No.38 in C major Mov.3	PUM	2	4.77
Beethoven	Symphony No.2 in D major Op.36, Mov.1	PPM	2	4.74
Tchaikovsky	Violin Concerto in D major Op.35, Mov.1	PPM	1	4.74
Tchaikovsky	Symphony No.4, Mov.1	PPM	1	4.71
Haendel	Organ Concerto Op.4, No.2 In B Flat major	PUM	2	4.70
Stravinsky	Firebird Suite, Finale	PPM	1	4.70

Haydn	Symphony No.38 in C major Mov.3	PUM	2	4.67
Chopin	Mazurka in A minor, Op.17, No.4	PPM	1	4.67
Fauré	Violin Sonata in A Major Mov. 1	PPM	1	4.66
Beethoven	Symphony No.4 in B Flat major, Op.60, Mov.2	PUM	2	4.63
Holst	The Planets - Venus, The Bringer of Peace	PPM	1	4.57
Mahler	Symphony No.2 "Résurrection", Mov.1	PPM	1	4.57
Mozart	Requiem Lacrimosa	PPM	1	4.57
Mozart	Symphony No.25 in G minor Mov.2	PUM	2	4.57
Gibbons	Fantasies a6	PUM	2	4.53
Mahler	Symphony No.1 "Titan", Mov.4	PPM	1	4.33
Bach	Chorals For Organ, Bwv 714 -740	PPM	2	4.33
Brahms	String quartet No.1, Mov.2	PPM	1	4.30
Chopin	Nocturne in G minor, Op.37, No.1	PPM	1	4.30
Saint-Saëns	Symphony No.3, Mov.1	PPM	1	4.29
Schubert	Minuet and Finale for wind octet in F D 72, I Menuetto Two Trios	PUM	2	4.26
Walton	Violin Concerto Mov.1	PPM	1	4.23
Bach	Highlights for trumpet and organ Bwv972 Mov.2	PPM	2	4.23
Rameau	Suite La triomphante Mov.2	PPM	2	4.20
Rameau	Pieces De Clavecin Suite In D Minor Major X	PPM	2	4.07
Pärt	Tabula rasa IV (Clip1)	PUM	2	4.07
Pärt	Tabula rasa IV (Clip3)	PUM	2	4.06
Barber	Adagio for Strings	PPM	1	4.00
Tchaikovsky	Symphony No. 5 - Mov. 1	PPM	1	3.97
Pärt	Tabula rasa I (Clip1)	PUM	2	3.97
Haendel	Organ Concerto No.13 "Cuckoo and Nightingale":1. Larghetto	PUM	2	3.94
Vivaldi	Concerto in C Major for Sopranino Recorder and Strings	PPM	2	3.91
Von Bingen	Salve Regina (Harp)	PUM	2	3.89
Ravel	Oiseaux Tristes	PPM	1	3.89
Schönberg	String Quartet No.1 in D minor Op.7,Mov.3	PUM	2	3.87
Bach	Choral Der Gott	PPM	2	3.86
Desprez	Ile fantazies de Joskin	PUM	2	3.83
Rachmaninoff	Morceaux de Fantaisie Op.3, No.2 Prelude in C Sharp minor	PPM	1	3.83
Shostakovich	Symphony No.4, Mov.3	PPM	1	3.69
Desprez	The Battle	PUM	2	3.66
Liszt	Danse Macabre	PUM	1	3.53
Pärt	Tabula rasa I (Clip3)	PUM	2	3.53
Gibbons	Fantazia of four parts	PUM	2	3.37
Schönberg	String Quartet No.1 in D minor Op.7,Mov.3	PUM	2	3.23
Schönberg	String Quartet Op.30,No.3, Mov.2	PUM	2	2.89
Berg	String Quartet Op.31, Mov.1	PUM	2	2.71

Webern	Symphony Op.21, Mov.1	PUM	2	2.53
Penderecki	Threnody For The Victims Of Hiroshima	PUM	1	2.27
Webern	Variations for piano, Op .7, Mov.3	PUM	2	2.11

Table S4. Music selection for the experimental paradigm in the SCR session and fixed music selection for the fMRI experiment. Type: PM, pleasant music; NM, neutral music; UM, unpleasant music.

SCR Experiment		
Artist	Title	Type
Vivaldi	The four seasons "Spring" Mov.1	PM
Beethoven	Für Elise	PM
Pachelbel	Canon In D	PM
Vivaldi	The four seasons "Winter" Mov.1	PM
Tchaikovsky	Dance Of The Sugar Plum Fairy	PM
Tchaikovsky	Swan lake Op.20 Scene finale	PM
Beethoven	Symphony No.9, Op.125, Mov.2	PM
Dvorak	New World Symphony No.9, Mov.4	PM
Beethoven	Moonlight Sonata	PM
Holst	The Planets -Jupiter, the Bringer Of Jollity	PM
Mahler	Symphony No.1 "Titan", Mov.4	NM
Bach	Chorals For Organ, Bwv 714 -740	NM
Brahms	String quartet No.1, Mov.2	NM
Chopin	Nocturne in G minor, Op.37, No.1	NM
Saint-Saëns	Symphony No.3, Mov.1	NM
Schubert	Minuet and Finale for wind octet in F D 72, I Menuetto Two Trios	NM
Walton	Violin Concerto Mov.1	NM
Bach	Highlights for trumpet and organ Bwv972 Mov.2	NM
Rameau	Suite La triomphante Mov.2	NM
Rameau	Pieces De Clavecin Suite In D Minor Major X	NM
Desprez	The Battle	UM
Liszt	Danse Macabre	UM
Pärt	Tabula rasa I (Clip3)	UM
Gibbons	Fantazia of four parts	UM
Schönberg	String Quartet No.1 in D minor Op.7,Mov.3	UM
Schönberg	String Quartet Op.30,No.3, Mov.2	UM
Berg	String Quartet Op.31, Mov.1	UM
Webern	Symphony Op.21, Mov.1	UM
Penderecki	Threnody For The Victims Of Hiroshima	UM
Webern	Variations for piano, Op .7, Mov.3	UM
fMRI Experiment		
Artist	**Title**	**Type**
Vivaldi	The four seasons "Spring" Mov.1	PM
Beethoven	Für Elise	PM
Pachelbel	Canon In D	PM

Vivaldi	The four seasons "Winter" Mov.1	PM
Berg	String Quartet Op.31, Mov.1	UM
Webern	Symphony Op.21, Mov.1	UM
Penderecki	Threnody For The Victims Of Hiroshima	UM
Webern	Variations for piano, Op .7, Mov.3	UM

Table S5. Distribution of excerpts for the music task in the fMRI experiment based on individual selection. ANH, anhedonic group; HDN, hedonic group, HHDN, hyperhedonic group, P, pleasant music; U, unpleasant music.

Artist	Title	ANH		HDN		HHDN	
		P	U	P	U	P	U
Tchaikovsky	Dance Of The Sugar Plum Fairy	8		8		6	
Beethoven	Symphony No.9, Op.125, Mov.2	9		8		6	
Beethoven	Moonlight Sonata	7	1	9	2	4	1
Mahler	Symphony No.1 "Titan", Mov.4	1	4	1	2	2	4
Brahms	String quartet No.1, Mov.2	3	1		1	2	
Saint-Saëns	Symphony No.3, Mov.1	3	1	3	1	2	2
Walton	Violin Concerto Mov.1	2	2	2	2	3	3
Rameau	Suite La triomphante Mov.2	3	1	3	1		
Desprez	The Battle	2	4	1	5		9
Pärt	Tabula rasa I	1	8	1	3	1	7
Schönberg	String Quartet No.1 in D minor, Op.7, Mov.3	1	2		4	2	2
Tchaikovsky	Swan lake Op.20 Scene finale	4		10		9	
Dvorak	Symphony No.9, Mov.4	5		7		7	1
Holst	The Planets -Jupiter, the Bringer Of Jollity	3	1	2	1	1	4
Bach	Chorals For Organ, Bwv 714 -740	1	1		2	2	4
Chopin	Nocturne in G minor, Op.37, No.1	2	1	2	1	1	2
Bach	Highlights for trumpet and organ Bwv972 Mov.2	2	2	1	5	2	2
Rameau	Pieces De Clavecin Suite In D Minor-major Mov. 10	1	3	1	5	5	3
Liszt	Danse Macabre	1	6		5	2	3
Gibbons	Fantazia of four parts	1	10	1	5	2	6
Schubert	Minuet and Finale for wind octet in F Major D.72 Mov.1		2		3	1	1
Schönberg	String Quartet No.3, Op 30, Mov.2		10		12		6