Dissociation between musical and monetary reward responses in specific musical anhedonia

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Running Head: Specific musical anhedonia

Summary

Music has evolved along with mankind and its civilization and has always been present in all human cultures since prehistoric eras until today [1-2] although it is not associated with any apparent biological advantages (as are food, sex, etc) or utility values (as is monetary reward). Nevertheless, music is ranked among the highest sources of pleasure [3] and its important role in our society, culture and life has led to the assumption that ability of music to induce pleasure is universal. However, this assumption has never been empirically tested. In fact, music may not be pleasant or have reward value in some individuals. In the present report we identified a group of healthy individuals who reported low sensitivity to musical reward, and showed no autonomic responses to pleasurable music, despite normal musical perception capacities. However, such participants showed preserved behavioral and physiological responses to money, indicating that this low sensitivity to music was not due to a global hypofunction of the reward network. These results point to the existence of specific musical anhedonia and suggest that there may be individual differences in access to the reward system.

Highlights

- Healthy people with specific musical anhedonia are identified.
- These individuals do not find music pleasurable but enjoy other rewarding stimuli.
- They show no autonomic responses to pleasant music, but normal responses to monetary rewards.
- Specific domain anhedonia may reflect the existence of different access to the reward system.

Results

It is well established that some psychiatric disorders are associated with a loss in the capacity to experience pleasure from positive reinforcements such as food, drink, caress or music, a deficit known as anhedonia [4-5]. Healthy populations also exhibit a wide range of individual differences in their hedonic capacity (anhedonia trait) [6-7], which has been related to differences in the brain reward system [8-9]. Anhedonia has generally been treated as a uniform factor, that is, a reduction in the rewarding aspects of all or most known pleasant stimuli (whether physical or abstract) but to our knowledge no studies have examined whether dissociations in anhedonia for different types of stimuli exist. The identification of specific anhedonia to some stimuli but not others might support the existence of different access to the reward system.

In the present work we studied whether pleasure induced by music can be specifically dissociated from monetary reward. Concretely, we sought to identify whether there exist healthy individuals with specific musical anhedonia, that is, with normal perceptual function and hedonic response to other types of reinforcements but with no emotional response to music. Finding such people could be important in understanding the sources of rewarding experience associated with music. In addition, the existence of a specific anhedonia would also give rise to the question of common vs. specific reinforcer-dependent brain circuits associated to reward processing and how individuals evaluate different rewarding stimuli.

We selected three groups of ten people each with high (Hyper-Hedonic group, H-HDN), average (Hedonic group, HDN), or low sensitivity to musical reward (Anhedonic group, ANH), assessed using a previously developed psychometric instrument, the Barcelona Musical Reward Questionnaire (BMRQ) [10] which is known to be a reliable indicator of interindividual variability in music-induced reward. In addition, the three groups had comparable overall sensitivity to reward, anhedonia trait and music perception functions (Table 1).

Participants performed two different experiments: a music task in which they had to rate the degree of pleasure they were experiencing while listening to pleasant music [11] and a monetary incentive delay task (MID) [12] where participants had to respond quickly to a target in order to win or not to lose real money. The two tasks have been shown to engage reward-related neural circuits in each domain (both music and money) and lead to releases of the dopamine neurotransmitter [13-14]. In order to have objective physiological measures of emotional arousal, we recorded changes of skin conductance response (SCR) and heart rate (HR) which are reliable measures of autonomic nervous system expression of emotion (for further details see also the Supplemental Experimental Procedures available online). Additionally, one year later we performed a second follow-up session with 26 participants in order to study (a) the consistency of the behavioral effects reported on the first session and (b) whether those effects could be driven by differences among groups in familiarity or musical emotion recognition. Besides, participants were asked to evaluate the degree of pleasure they experience with different kind of rewards (food, sex, music, money, exercise and drugs) using a visual analog scale (VAS). One-way ANOVA, applied for each category, showed no differences among groups in the ratings (evaluation of pleasure) for sex, food, money, exercise and drugs (all *ps* > .2) but a significant effect on the music scale ($F(2,23) = 19.14$, $p < .001$). As it is shown in Fig 1A, the three groups clearly differed on this scale: ANH reported lower scores than HDN ($p = .004$) and HHDN ($p < .001$), while HHDN tend to report higher scores than HDN ($p = .07$). These results support the idea that there are no differences among groups in other reward stimuli different than music.

Music Task

<u>Behavioral</u>

In this task, the participants had to rate, in real-time while listening to pleasant music, the degree of pleasure they were experiencing by pressing one of four different buttons on a keyboard (1=neutral, 2=low pleasure, 3=high pleasure, 4=chill, adapted from [11]). The proportion of responses associated with chills and high pleasure ratings compared to low and neutral ratings was predicted only by the overall scale of the BMRQ when all the psychometric scores available were included in a stepwise regression analysis ($R^2 = .11$, $F(1,28) = 4.71$, $p = .04$). That is, the highest the BMRQ scores, the highest proportion of ratings associated with chills and high pleasurable ratings (Figure 1B). Similarly, the BMRQ scores significantly predicted the reported intensity of the chills ($R^2=0.30$, $F(1,22) = 10.66$, $p = .004$) and the average of liking rates ($R^2=0.29$, $F(1,28) = 10.32$, $p = .003$; Figures 1C,D). In both cases, participants with higher BMRQ scores tend to experience more intense chills and to report higher liking rates.

In the follow-up session, the BMRQ again predicted the proportion of responses associated with chills and high pleasurable rates ($R^2=0.22$, $F(1,24) = 6.75$, $p = .016$) and the average of linking rates ($R^2=0.18$, *F*(1,24) = 5.23, *p* = .031). In addition, the BMRQ scores of the first and the second session were highly correlated (*r*(26) = .94, *p* < .001). These results indicate that the behavioral effects found in the first session were replicated one year later and, therefore, were consistent across time. In addition, during the second session, participants also rated the degree of familiarity of each excerpt. The three groups reported similar mean familiarity rate on those excerpts selected for the SCR and HR analysis (*F*(2,25) = .45, *p* = .64). Similar results were obtained when participants rated the familiarity of 16 new musical pieces that were not previously used in the experiment but that were classified according to their familiarity [8 with low familiarity and 8 with high familiarity (see Supplemental Experimental Procedure)]. Participants correctly identified both highly familiar and low familiar pieces. This effect was similar in all three groups (familiarity x group: *F*(2,23) = .63, *p* = .54) and no overall effect of group was found either (*F*(2,26) = 1.05, *p* = .37) (see Supplemental Analysis for further details). Interestingly, in this subset of excerpts, the average liking rate also correlated, although marginally, with the BMRQ (*r*(26) = .35, *p* = .08). These findings discard the possibility of some sort of bias because of differences in familiarity among groups.

SCR and HR

Figure 2 shows SCR responses associated with the four different degrees of pleasure experienced by the three groups of participants while listening to musical pieces. Visually, H-HDN and HDN groups presented increases of SCR amplitude as the rate of pleasure increases. However, the ANH group only showed a small peak while reporting chills. Individual SCR curves revealed that this peak was due only to one of the anhedonic participants who presented a significant increase of the SCR while reporting chills (see S1 in Supplemental Information) and could be considered an outlier in this group. To test the relationship between the degree of pleasure experienced by participants and SCR amplitude on a trial-by-trial basis, we performed a regression analysis for each individual, using SCR amplitude as dependent variable and pleasure rating as independent measure. Kolmogorov-Smimov (K-S) test for normality indicated that the slopes obtained were normally distributed (*D* = .12, *p* = .2, Figure S2A) and that therefore, parametric analysis might be used in this data. One-way ANOVA yielded a significant main effect of group (*F*(2,27) = 7,22, *p* = .003; post-hoc analysis are available in the Supplemental Analysis) indicating that the relationship between the physiological responses and pleasure ratings differed across the three groups. The mean slopes for the HDN and H-HDN groups were positive and significantly different from zero (HDN: $t(9) = 5.43$, $p < .001$; H-HDN: $t(9) = 5.99$, $p < .001$). Higher ratings were associated with larger SCR amplitude in these two groups. However, the mean slope for the ANH group was not significantly different from 0, showing no relationship between the behavioral ratings and SCR ($t(9) = 0.88$, $p < .4$). Stepwise linear regression analysis was used to assess the relationship of the obtained slope with all the psychometric measures evaluated. The BMRQ was the only variable that significantly predicted each individual's slope ($R^2 = 0.32$, $F(1,28) = 13.37$, $p = .001$).

It appears that although some ANH participants reported chills and high pleasurable ratings behaviorally, they were not accompanied by a significant increase of the SCR amplitude (Figure 3A,C). We have to take into account that participants were told that four different buttons were available. Therefore, they could assume that the experimenter was expecting them to press all four during the session, and thus they may have altered their behavior to conform to the expectations. In that sense, the lack of physiological responses in the ANH group suggests that even those ANH individuals who reported chills may have been responding to a demand characteristic, rather than reporting a true physiological response, in contrast to HDN and HHDN participants.

We applied the same regression analysis with the HR data as dependent measure. K-S test indicated that the slopes were normally distributed ($D = .09$, $p = .2$, Figure S2B), again indicating that parametric analysis might be used. One-way ANOVA showed that the mean slope obtained differed across groups ($F(2,27) = 4{,}46$, $p = .021$; post-hoc analysis are available in the Supplemental Analysis), that is, the relationship between HR and pleasure ratings was different across the different groups. Similar to the SCR data, the mean slope of HDN ($t(9) = 5.24$, $p = .001$) and H-HDN ($t(9) = 3.3$, $p = .009$) was positive and significantly different than 0. In contrast, the mean slope for the ANH group was not significantly different from 0 ($t(9) =0.24$, $p = .80$, Figure 3B,D). Consistently with the SCR, these results suggest that there is a relationship between the autonomic responses and the behavioral ratting in the H-HDN and HDN groups, but not in the ANH group. In addition, the BMRQ was the only variable that significantly predicted each individual's slope ($R^2 = 0.16$, $F(1,28) = 5.34$, $p = .03$) (Figure 3B,D). Similar results were obtained performing the same SCR and HR analyses without including the self-selected excerpts (analysis are available in the Supplemental Analysis).

Monetary Task

Behavioral

In this task, the participants had to respond quickly to a target in order to win or not to lose real money. Magnitude and valence of the potential outcome was indicated by a cue at the beginning of the trial. The participants achieved an average hit rate of 61.8 % (SD = 7.9). No differences in performance were observed among groups ($F(1,27) = .09$, $p = .91$). Reaction time (RT) analysis showed that the participants tended to respond faster to the target in trials with higher magnitude ($F(1,27) = 3.85$, $p = .06$). There was no significant effect of valence ($F(1,27) = .56$, $p = .46$) or the interaction between both factors ($F(1,27) = .89$, $p = .35$). These effects were not affected by group in any case ($Fs < 1$), suggesting that the three groups were equally motivated to seek and avoid monetary rewards and punishment, respectively.

SCR and HR

Figure 4 shows SCR response to the four different monetary reward-cues. Similar to RT data, SCR amplitude was greater in trials with high magnitude outcomes (magnitude effect: $F(1,27) = 69.37$, $p < .001$). No differences were observed between reward and punishment (valence effect $F(1,27) = 0.23$, $p = .64$). Moreover, there were no significant interactive effects between group and conditions (Val x Group: $F(2,27) = 1.67$, $p = .20$; Mag x Group: $F(1,27) = .15$, $p = .60$) (Figure 4). These results parallel the results obtained with the RT and the fact that the three groups were matched according to the anhedonia trait and the sensitivity to reward and punishment. No significant effects were observed in the MID with the HR ($Fs < 1$).

Musical Emotion Recognition task

We also tested differences among groups in music emotion recognition during the follow-up session. To this end, participants performed a musical emotion recognition task [15] in which they had to rate the absence/presence of four emotion domains (happy, sad, scary, peaceful) on 56 excerpts, previously classified by a reference group of listeners according to the conventional emotion expressed: happy (14 excerpts), sad (14), scary (14) and peaceful (14). Overall, our participants recognized at above-chance levels the emotion expressed on the four different categories (p's $< .002$). One-way ANOVA indicated that there were no significant differences among groups in any of the four emotion dimensions (Happy: $F(2,23) = .86$, $p = .44$; Sad: $F(2,23) = 2.43$, $p = .11$; Scary: $F(2,23) = 2.24$, $p = .13$; Peaceful: $F(2,23) =$

.22, *p* = .81) (Figure 5). If anything, it was the HDN group that showed a non-significant tendency to have poorer emotion recognition. Thus the presence of musical anhedonia is not related to difficulty with emotion recognition.

Discussion

In the present study we explored the differences in physiological responses associated with two different types of reward (music and money) in three groups of participants classified according to their sensitivity to music reward (H-HDN, HDN and ANH). We found, for the first time to our knowledge, the existence of a group of healthy people for whom music is not rewarding (ANH). This was reflected not only in self-reported scores but also on their relative lack of physiological responses (SCR and HR) to music. However, increases of both SCR and HR as a function of increasing degree of reported pleasure to music were systematically observed in the other two groups. These differences could not be explained by a generalized abnormal functioning of the reward system: psychometrically, the three groups were matched according to their overall sensitivity to reward and anhedonia trait using reliable psychometric measures [6, 16-17]. Behaviorally, the three groups presented similar RT when trying to seek or avoid potential monetary rewards or punishments respectively; and physiologically, the three groups presented similar SCR and HR to monetary reward-predicting cues. Therefore, the present results suggest that monetary and musical reward can be dissociated. In addition, these differences could not be explained either by: (a) perceptual deficits in the recognition of melodies and wrong or out-of-tone notes (amusia) as the three groups were matched according to their scores in a widely used battery to assess amusia (MBEA) [18], or (b) deficits in familiarity, as ANH individuals recognized excerpts at the same level as the other groups, or (c) deficits in recognizing emotion in music as the three groups showed similar accuracy scores recognizing different emotional dimensions in music.

Traditionally, anhedonia and sensitivity to reward have been usually treated as indivisible constructs related to the integrity of the reward system. However, the identification of people with specific musical anhedonia might indicate the existence of different impact of reinforcers in the reward system. That is, although some individuals might have a disturbance of the reward system and therefore, present a decrease of pleasure experience to all rewarding stimuli, other individuals might have affected only some specific pathways that access this system, yielding specific forms of anhedonias. Both music and other primary reinforcers (those with a biological bases, such sex or food) and secondary reinforcers (those associated with primary reinforcers, such as money) engage reward-related brain circuits [12, 19-24] and lead to release of the dopamine neurotransmitter in certain subcortical pathways [13-14]. However, given the complex and abstract nature of musical reward, emotions evoked by music might not be exclusively processed within the reward network, but might be influenced by other cortical areas such as those related to auditory perception [25] and integrative areas such as frontal cortices [20]. In fact, some case studies with patients showing a loss of the capacity for feeling emotions when listening to music after brain damage, have reported lesions not in reward-related structures, but in temporal, frontal or parietal regions [26-27, but see 28]. Consistent with this line of reasoning, Salimpoor and colleagues [24] showed that the reward value associated with a specific excerpt of music was predicted not only by activation in reward-related regions (ventral striatum, amygdala and ventromedial prefrontal cortex) but also by modulation of functional connectivity between ventral striatum and auditory cortices. These results suggest that musical reward depends not only on the engagement of the mesolimbic structures, but also on how this network interacts with other cortical regions related to music.

In parallel to these results, Sescousse et al. [21] performed a meta-analysis of 87 fMRI studies comparing responses to food, erotic and monetary rewards. The authors showed that although all three rewards engage a common brain network (orbitofrontal cortex, ventral striatum, amygdala, insula and thalamus), the location of the activity within these regions varied somewhat across rewards. In addition, each reward type activated type-specific regions depending on their properties. These recent findings suggest that assignment of reward value may not be associated only with a unique reward network, but rather may depend on the recruitment of specialized areas involved in the perceptual processing of each reward type. Therefore, we hypothesize that the music-anhedonic participants identified in the present study, although preserving sensitivity to other rewards, and intact music perception, might show an altered interaction between music processing related regions and the reward network. It could be argued that what we describe here is nothing new, because there will always be some people who prefer one type of rewarding stimulus over another (one person may like oysters, another hate them; one person may enjoy opera while another may find it boring). However, what our findings reveal is not a particular preference for one stimulus, or a class of stimuli, over another, but an inability to derive pleasure from an entire domain, music, which the vast majority of human populations do find pleasurable. Such domain-specific anhedonias may also exist in other forms. Studying this particular and rather encapsulated aspect of anhedonia described here may help shed light more generally on why the link between perception and pleasure can sometimes be broken.

Finally, an interesting result of the present study is that HHDN and HDN did not differ in their physiological responses to music. Therefore, although HHDN participants subjectively reported experiencing greater emotions with music, objective measures of emotions, like SCR and HR, did not reflect these differences. One plausible hypothesis is that although both groups experience similar emotional reactions to music, the same experience is more motivationally salient for the HHDN group. In that sense, a recent study [29] with patients who developed musicophilia (specific pathological craving for music [30,31]) showed that they presented differences in gray matter within the salience network, a system involved in reward anticipation and consummation. This could imply a double dissociation between ANH and HHDN: while ANH participants might have altered interactions between auditory cortices and limbic regions, thus reducing the reward/pleasure induced by music (reduced liking experience), HHDN participants might have an altered interaction among regions evaluating the motivational value of reward, specifically among sub-regions specialized in musical reward processing (increased wanting).

In conclusion, in the present study we described a group of healthy subjects with specific music anhedonia. We showed dissociations between monetary and musical reward, both psychometrically and physiologically, suggesting the existence of different access to the reward system. Further studies in these individuals might be important to understand the neural basis underlying emotion and music rewarding experiences, and reward processing more generally. They could also be useful in other related domains such as musical therapy and learning. In addition, the study of dissociated rewards across individual might shed some light on how the reward system interacts with sensory regions to assign reward value.

Experimental procedure

Participants

The BMRQ [10] was used to assess the distribution of sensitivity to musical reward in a population of 1029 university students (41% males, M = 21 years, SD = 3.7). In order to select the sample for the present study, participants were classified into 10th percentile groups by the overall score of the BMRQ: those with potential musical anhedonia (scoring lower than 10th percentile, BMRQ < 65, ANH group), participants with average musical reward scores (between 10th and 90th percentile, 65 < BMRQ < 87, HDN group), and high musical hedonics (higher than 90th percentile, BMRQ > 87, H-HDN group). Participants were then classified according to (i) global sensitivity to reward and punishment using the BIS/BAS scale [16] and the Sensitivity to Punishment and Sensitivity to Reward Questionnaire (SPSRQ) [17]; (ii) hedonism 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) [6] which evaluates difficulty in feeling physical and aesthetic pleasure in response to typical pleasant stimuli (food, sex, beautiful scenes, etc) and (iii) amusia score using the Montreal Battery of Evaluation of Amusia (MBEA) [18]. Then, three groups were selected, matched in these four measures (BIS/BAS, SPSRQ, PAS and MBEA) but differentiated in the BMRQ scores (Table 1).

Thirty students (10 for each group) from the original sample were selected based on those criteria, and participated in the first session (43% males; M = 22.8 years, SD = 4.9 years). Participants were also contacted for a second behavioral session one year later. Twenty-six out of thirty participants were recruited (8 ANH, 9 HDN and 9 HHDN). During this second session, participants were asked to evaluate the degree of pleasure they experienced with different kind of rewards (food, sex, music, money, exercise and drugs) using a visual analog scale (VAS). Participants were required to mark, on a 10 cm line, the corresponding amount of pleasure they experienced for each type of reward. The left hand end of the line indicated no experience of pleasure at all while the right hand end indicated that participant experienced a high level of pleasure. The VAS score was then determined by measuring the distance, in centimeters, from the left hand end of the line to the point that the participant marked. All participants signed an informed consent and received a monetary compensation which varied depending on the participants' performance in the monetary rewarding task. Procedures were approved by the local ethics committee and followed the Declaration of Helsinki.

Music Task

Participants listened to all musical pieces in a randomized order. While listening to music, the participants had to rate, in real-time, the degree of pleasure they were experiencing by pressing one of four different buttons on a keyboard (1=neutral, 2=low pleasure, 3=high pleasure, 4=chill, adapted from [11]). Chills are experienced at the climax of pleasurable responses [11] and previous studies have suggested that they are in fact a physical manifestation of the most rewarding experience to music listening [32]. The participants had to keep pressing the button as long as they were experiencing the corresponding degree of pleasure. Additionally, at the end of each excerpt, the participants were asked to rate the previous excerpt according to the overall degree of pleasure they felt (from 1 to 10) and to report the number and the intensity of chills they experienced (from 1 to 5). The last rating was only included in the first session; during the second session, they had to rate the degree of familiarity of each except (from 1 to 5). For each participant, the four pieces of music (including both fixed selection and self-selected excerpts; M = 1.4 self-selected excerpts, SD = 0.81) with the highest rating (in liking rate, number of chills and intensity) were selected to study differences among groups in emotional responses (neutral, low pleasure, high pleasure and chill rates) to highly pleasurable excerpts, both at behavioral and physiological levels (SCR and HR). In addition, baseline physiological data was obtained during five minutes of rest prior to the task.

Stimuli selection

Each participant was instructed to provide three excerpts (with duration from one to two minutes) of music that elicited intensely pleasant emotional responses. However, we expected that musical anhedonic participants, who by definition should have low emotional responses to music, would have difficulties to provide intensively pleasurable pieces of music (see Table S3 in Supplemental Materials). Indeed, one participant of the ANH group was unable to provide any piece of music and two participants only provided one. For that reason we created a pool of pleasurable music that had a great emotional impact in most of the studied population. To this end, we performed a survey of 228 university students (55% of males, M = 21 years, SD = 3.5) in which we asked them to indicate 3 instrumental and 3 lyrical songs with high emotional impact for them. Music excerpts were sorted according to the number of votes, that is, according to the number of participants that reported the same item. Then, we selected the ten instrumental and the ten lyrical songs that were more repeated among participants. Finally, those 20 excerpts were tested in a new sample of 45 participants who rated the degree of pleasure experienced with each excerpt (from 1, ‘I do not get emotional listening to this song’, to 10, ‘I get very emotional listening to this song’). Excerpts that showed an average liking rate above 7 were selected, getting a final selection of 13 pieces of music (see Table S1 in Supplemental Materials).

Monetary Incentive Delay (MID)

The MID task (adapted from [12]) consisted of 50 trials. At the beginning of a trial, participants saw one of five cue shapes during 2 seconds. Cue signaled whether participants were playing to win potential rewards (20 trials; denoted by circles) or to avoid losing potential losses (20 trials; denoted by squares). The magnitude of the possible outcomes was indicated using horizontal lines in the cue, and could be large (gain or loss 2€, three horizontal lines, 10 trials for each valence) or small (gain or loss 0.2€, one horizontal line, 10 trials for each valence). Six seconds after cue offset, participants had to respond, as fast as possible, with a button press to a white target square that appeared for a variable length of time (target, 160–260 ms). In win trials, if participants responded on time they obtained the corresponding amount of money. In contrast, in loss trials, if participants responded on time they avoided losing the corresponding amount of money. Six seconds after participants' response, a feedback notified whether they had won or lost money during that trial. Eight seconds later, another cue was presented. Additionally, a neutral condition (10 trials; denoted by a triangle) in which participants were not playing for money was also included. Task difficulty, based on reaction times collected during the practice session, was set such that each participant could succeed on 66% of his/her target responses. Trial types were randomly ordered within each session.

Musical Emotion Recognition (MER)

The MER (adapted from [15]) consisted on the presentation of 56 musical stimuli with an average duration of 12.4 s. From those excerpts, 14 expressed happiness; 14, sadness; 14, fear; and 14, peace. Order of presentation of the excerpts was randomized. After listening to each excerpt, participants had to judge to what extent they recognized each of the four emotions (happy, sad, scary and peaceful). For each emotion domain, participants rated the presence/absence of that emotion on a 10-point scale (from 1, absent, to 10, present).

Supplemental Information

Supplemental Information includes three figures, three tables, Supplemental Analyses, and Supplemental Experimental Procedures and can be found online.

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Table 1: Psychometric scores in anhedonia, sensitivity to reward and punishment, amusia and the BMRQ of the three groups. 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; BIS = Behavioral Inhibition System; BAS = Behavioral Activation System).*

	Anhedonics	**Hedonics**	**Hyper-Hedonics**	
N	10	10	10	*p-value*
Age	24.7 (5.2)	20.6 (1.8)	23.0 (5.8)	.16
BMRQ				
Emotion Evocation	11.6 (3.7)	16.7 (2.3)	18.9 (1.4)	<.001
Mood Regulation	12.4 (2.9)	16 (2.3)	18.3 (1.4)	<.001
Sensory-Motor	14.3 (2.3)	15.7 (2.5)	17.6 (2.0)	.01
Social Reward	11.2 (2.9)	12.4 (3.6)	17.3 (1.9)	<.001
Musical Seeking	8.8 (2.4)	10.7 (2.8)	16.8 (2.0)	<.001
Overall	58.3 (5.9)	72.4 (5.9)	89.8 (3.2)	<.001
Anhedonia				
PAS	14.3 (5.7)	13.6 (5.6)	11.4 (5.3)	.50
SPSR				
Sensitivity to punishment	10.7 (6.0)	10.7 (5.8)	11.5 (5.1)	.94
Sensitivity to reward	8.0 (3.9)	7.0 (4.2)	8.9 (3.6)	.57
BIS BAS				
BAS Drive	10.2 (2.3)	10.9 (2.1)	11.3 (1.8)	.45
Fun Seeking	12.1 (1.6)	10.6(2.4)	11.0 (2.5)	.56
Reward responsiveness	14.9 (2.2)	15.2 (2.3)	15.8 (2.9)	.64
BIS	21.2 (2.7)	20.5 (3.9)	20.9 (4.8)	.92
Amusia				
Montreal Battery of Amusia	83.3 (4.9)	85.7 (4.9)	86.4 (5.8)	.47

Figure captions

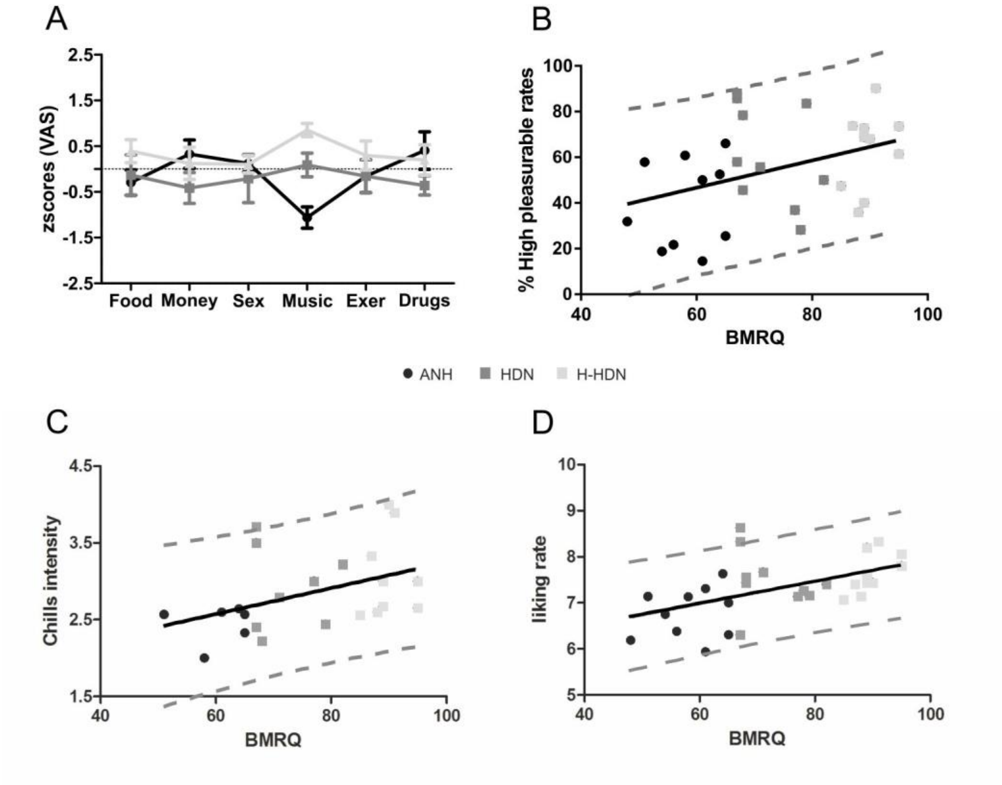

Figure 1. a) Average score for different reward types assessed by a visual analog scale. Note that the groups present similar scores in all domains except in the music scale (*Exer = Exercise*)**.** Scatter plot of b) the proportion of responses associated to chills and high pleasurable rates, c) the reported intensity and d) the average liking rate with overall scores of the BMRQ in the music task. Black circles represent ANH participants; dark gray squares, HDN; and light gray, H-HDN. The solid black line represents the slope of the linear fit and the dash gray line represents the 95% confidence interval.

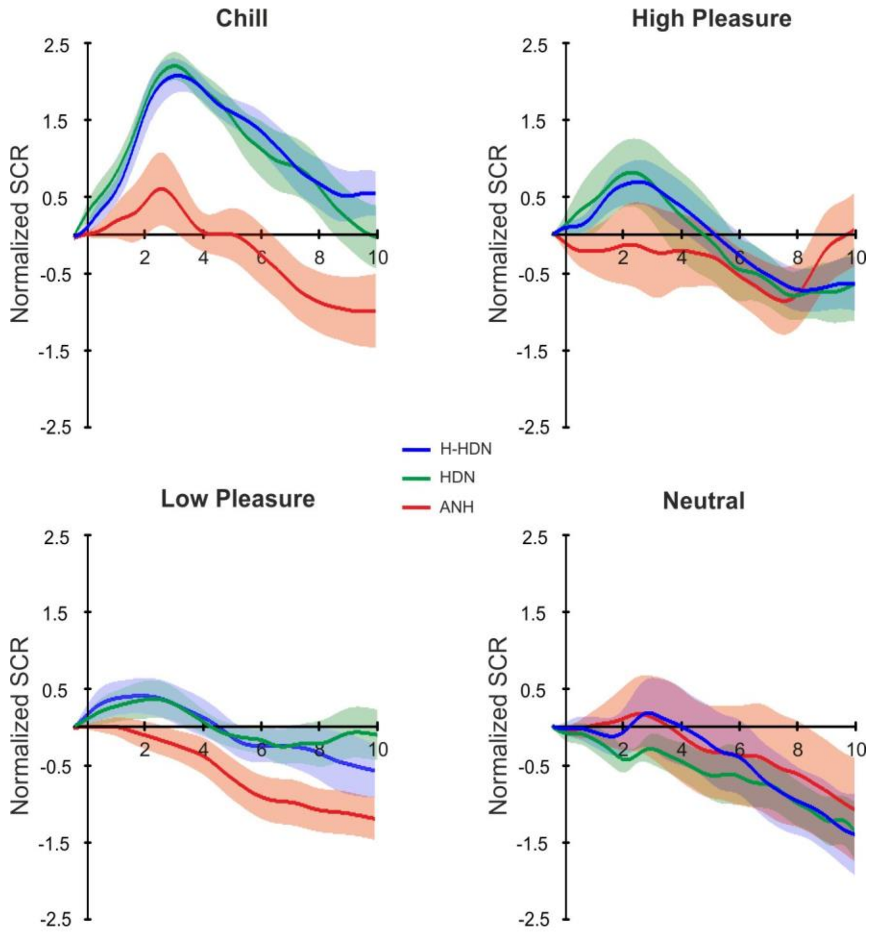

Figure 2. Normalized skin conductance response associated with the four different pleasure rates (chill, high pleasure, low pleasure and neutral) for the three groups in the music task. Note the increase of SCR in both H-HDN and HDN groups (but not in the ANH group) as a function of increasing pleasure rate. Solid lines indicate the averaged SCR with the corresponding standard error of the mean (SEM)

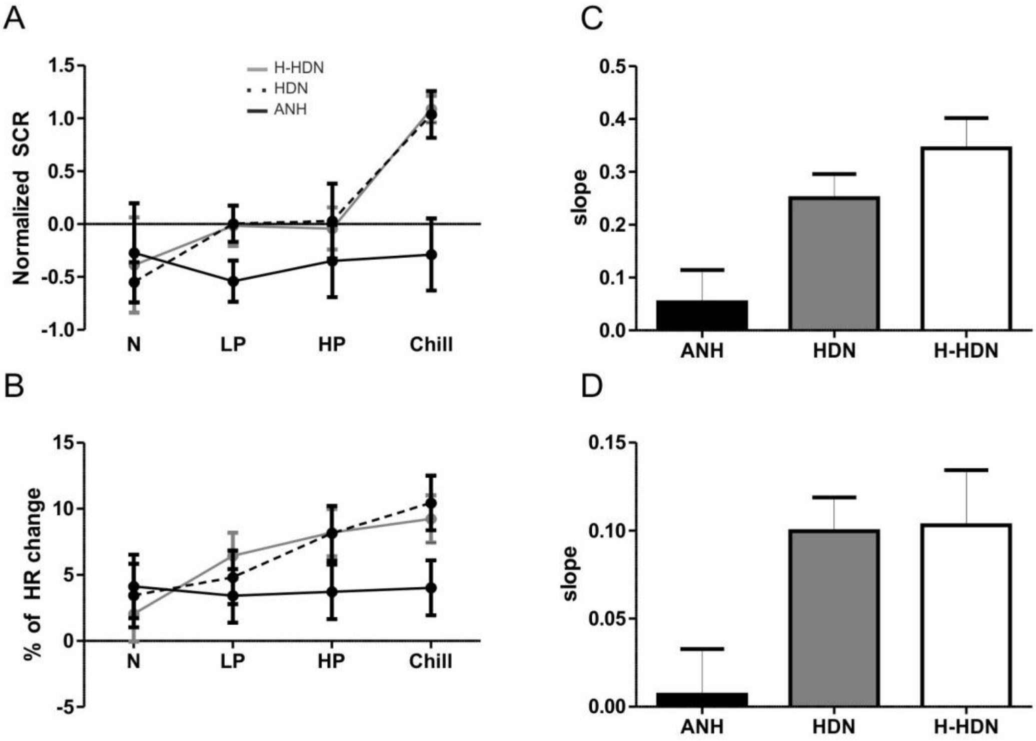

Figure 3. Average of a) the normalized SCR and b) the proportion of change of HR in comparison to baseline levels while participants report different levels of pleasure in the music listening task. The three groups are plotted separately: H-HDN and HDN groups (but not the ANH group) presented a clear increase in both measures while increasing pleasure rates**.** This is reflected on the mean slope for each group from the regression analysis performed with pleasure rating as independent variable and the c) normalized SCR and d) HR as dependent measures. The mean slope of the ANH group, in contrast to HDN and H-HDN, is close to 0 in both measures, suggesting no relationship between physiological responses and the reported degree of pleasure.

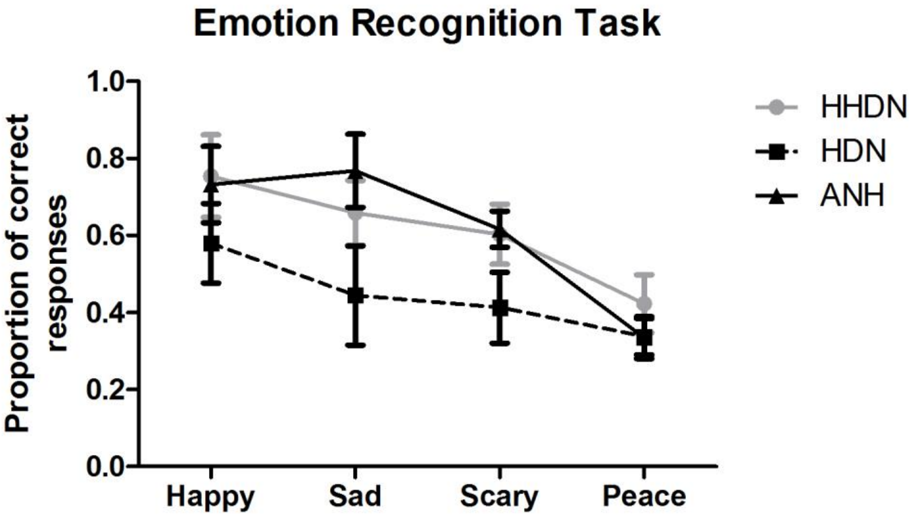

Figure 4. Normalized skin conductance response in the monetary task associated with anticipation of potential rewards and punishment according to the magnitude of the outcome for the three groups. Anticipation of high magnitude outcomes evoked higher SCR responses than low magnitude outcomes. However, no differences among groups were found.

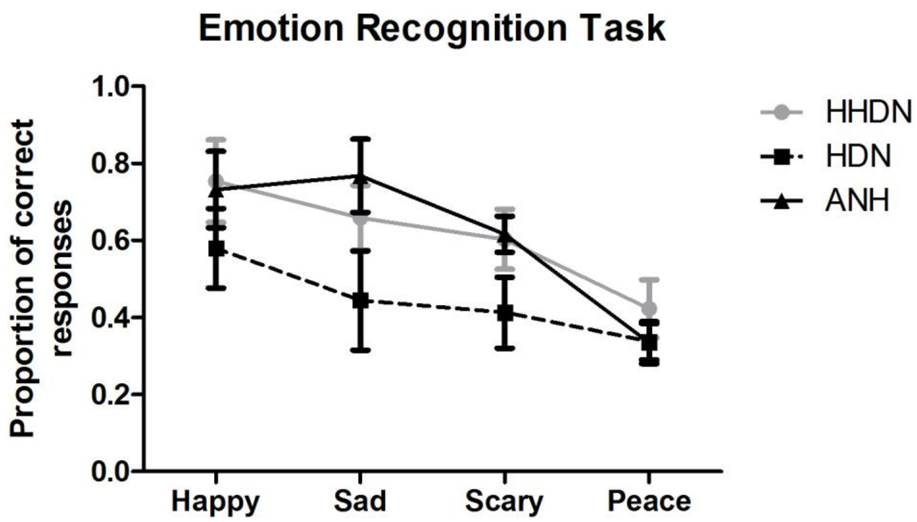

Figure 5. Accuracy scores in the identification of music emotion of the three groups depending on the type of emotion expressed by the music.

Supplemental Information

Supplemental Experimental procedures

Familiarity task

Participants listened to 16 musical pieces (1 minute of duration) selected according to their familiarity (eight with high and eight with low familiarity) in a randomized order (Table S2). At the end of each excerpt, the participants were asked to rate the previous excerpt according to the overall degree of pleasure they felt (from 1 to 10) and to report the degree of familiarity of each except (from 1 to 5). The purpose of this task was to study whether ANH participants could properly discriminate songs with different degrees of familiarity.

Skin Conductance Response (SCR) and Heart Rate (HR)

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 between the first and second phalanges. In addition, HR was also recorded using three adhesive electrodes placed on the upper left part of the chest.

The level of SCR was determined by measuring the mean SCR amplitude after stimulus or response onset with respect to baseline (-500 ms). In the music task, SCR amplitude was determined in the 0 s – 10 s windows 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 [1, 2]. In the Monetary Incentive Delay (MID) task, SCR amplitude was determined in the 0 s to14 s windows after cue onset. This time window corresponded to the anticipation of potential rewards and punishment.

Trials associated with specific conditions were averaged for each subject. In each task and for each participant, the resulting SCR amplitude value was normalized across conditions [3]. HR was analyzed by computing the proportion of change of beats per minute compared to the rest period (Music task) or the neutral condition (Monetary Incentive Delay, MID).

Statistical Analysis

Differences among conditions and groups in both SCR and HR during the MID task were determined by repeated-measures ANOVA (RM ANOVA). Two within-participants factors were used: valence (reward, punishment) and magnitude (high, low). Group (ANH, HDN, H-HDN) was included as between-participants factor. However, the same analysis was not possible to perform in the Music task because not all the participants experienced the four different degrees of pleasure (neutral, low pleasure, high pleasure and chill). For instance, most of the ANH participants did not report chills and some of the HDN and H-HDN participants did not report neutral rates. For that reason, the relationship between rates of pleasure and SCR amplitude and HR was assessed by two linear regression models for each subject using SCR amplitude or HR respectively as the dependent measures and rating as independent variable. The SCR amplitude and HR for each trial was determined separately for each subject. Using these values, two linear models could then be fitted for each subject:

SCR Amplitude =Rate*β+*intercept*+*noise*

HR=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. A significant difference from 0 would suggest a relationship between the degree of pleasure reported by the subject and the size of the SCR amplitude or the HR on individual trials. If these measures scale with the degree of pleasure reported by the participants then the slope of this relationship should be positive.

Finally, stepwise linear regression analysis was used to assess the relationship of each independent behavioral and physiological (SCR and HR) variable with the psychometric dependent variables (BMRQ, BIS/BAS, SPSRQ, PAS, Amusia). The entry criterion was $p < .05$ and the exit criterion was $p > .10$. Tests for multicollinearity indicated that a very low level of multicollinearity was present in the analysis (*VIFs* < 1.15).

Supplemental Results

Familiarity task

The scores obtained in the familiarity scale were included in repeated-measures ANOVA with familiarity as within-participant factor (Low and High) and Group (ANH, HDN and HHDN) as between participants factor. Results of the analysis showed a main effect of familiarity ($F(1,23) = 181.35$, $p < .001$): songs that were classified as highly familiar were correctly identified by the participants as highly familiar, and the same with the low familiar pieces. However, this effect was not modulated by group (familiarity x group: $F(2,23) = .63$, $p = .54$). The main effect of group was not significant either ($F(2,26) = 1.05$, $p = .37$). Interestingly, the average liking rate was again correlated, although marginally, with the BMRQ ($r(26) = .35$, $p = .08$).

Comparing slopes among groups

SCR. We performed a one-way ANOVA to test group differences in the slopes of the linear regression model between SCR and liking rates. As expected, the magnitude of the slope was significantly different across the three groups ($F(2,27) = 7,22$, $p = .003$). Tukey post-hoc comparisons of the three groups indicated that both the HDN (M = 0.25, SD = 0.15; p=.04) and H-HDN (M = 0.35, SD = 0.18; p=.003) groups presented a significantly higher slope than the ANH group (M = 0.05, SD = 0.19). No differences were found between H-HDN and HDN groups ($p = .45$).

HR. Results of the one-way ANOVA showed that the mean slope differed across groups ($F(2,27) = 4,46$, $p = .021$). Tukey post-hoc analysis indicated that ANH group (M = 0.01, SD = 0.08) differed from HDN (p =

.04) and H-HDN (p = .04). However, no differences (p = .96) were observed between H-HDN (M = 0.1, SD = 0.09) and HDN (M = 0.1, SD = 0.06).

SCR and HR analysis without self-selected excerpts

We repeated the SCR and HR analysis but taking only into account the excerpts from the fixed selection. Visual inspection of the SCR (Fig S3) indicated a clear increase of the SCR in HDN and HHDN participants while increasing the degree of pleasure. In contrast, no increase was observed in the ANH group. To test for this effect, and following similar procedure than the original analysis, we performed a regression analysis for each individual, using SCR amplitude as dependent variable and pleasure rating as independent measure. The mean slope for the HDN and H-HDN groups was positive and significantly different from zero (HDN: $t(9) = 4.6$, $p = .001$; H-HDN: $t(9) = 5.67$, $p < .001$). Higher ratings were associated with larger SCR amplitude in these two groups. However, the mean slope for the ANH groups was not significantly different from 0 ($t(9) = 1.02$, $p = .34$). Similar results were obtained with the HR (H-HDN: $t(9) = 2.40$, $p = .04$; HDN: $t(9) = 3.1$, $p = .012$; ANH: $t(9) = 1.23$, $p = .25$).

Supplemental tables

Table S1

Title	*Artist*	*Excerpt*
Barcelona	Montserrat Caballé & Freddie Mercury	1:30 - 2:30
Nessun Dorma	Giacomo Puccini	1:42 - 2:56
Carmina Burana	Carl Orff	2:15 - 3:15
The Sound of Silence	Simon & Garfunkel	2:53 - 3:53
Canon in D	Johann Pachelbel	2:38 - 3:38
El Cant dels Ocells	Pau Casals	1:00 - 2:34
Für Elise	Ludwig van Beethoven	1:29 - 2:38
Now We Are Free	Hans Zimmer & Lisa Gerrard	1:22 - 2:29
Swan Lake	Pyotr Ilyich Tchaikovsky	0:49 - 2:20
River Flows in You	Yiruma	2:24 - 4:17
Schindler's List	John Williams	1:31 - 3:10
The Four Seasons (Spring-I Allegro)	Antonio Vivaldi	1:18 - 2:52
The Four Seasons (Summer-III Presto)	Antonio Vivaldi	0:18 - 1:31

Table S1: Excerpts selected for the present study

Table S2

Low Familiarity		**High Familiarity**	
Title	***Artist***	***Title***	***Artist***
Adagio for Strings	Barber	**Moonlight Sonata**	Beethoven
String quartet no1 mov2	Brahms	**Symphonie No9 - Il Molto Vivace**	Beethoven
Nocturne in G minor, Op 37, No 1	Chopin	**New World Symphony No9, 4 Allegro Con Fluoco**	Dvorak
Mazurka in A minor Op 17	Chopin	**Requiem Lacrimosa**	Mozart
Cello Concerto in E minor, Op 85; I Adagio; Moderato	Elgar	**Dance of the Suger Plum Fairy**	Tchaikovsky
String quartet in F, mov2	Ravel	**Swan Lake Suite Scéne**	Tchaikovsky
Gaspard de la Nuit no1 Ondine (Lent)	Ravel	**Winter mov1 Allegro**	Vivaldi
Firebird Suite Finale	Stravinsky	**Clair de Lune**	Debussy

Table S2: Musical excerpts used to test familiarity effects among groups. Eight songs were classified as low familiar (left) and eight, as high familiar.

Table S3

Title	*Artist*
Irish Traditional Music	Joe McKenna
Moonlight Sonata	Beethoven
Intro (Irish Pub)	Mägo de Oz
Take me out	Franz Ferdinand
Porcelain	Moby
La Flama	Obrint Pas
El amor Despues Del Amor	Fito Paez
Bitter Sweet Symphony	The Verve
Superman	Sinfonica de Chile
Concierto de Aranjuez	Joaquin Rodrigo
Fantasía Para un Gentil Hombre	Joaquin Rodrigo
Under the Waves	Pendulum
The Promise	Michael Nyman
La Valse d'Amelie	Yann Tiersen
Lux Aeterna	Clint Mansell
The Vulture	Pendulum
Skyrim	Lindsey Stirling & Peter Hollens
El cant dels Ocells	Pau Casals
Pirates of the Caribbean	Royal Philharmonic Orchestra
Tarantella Siciliana	popular
My Empty Bottle	Korsakoff
Concierto de Aranjuez	Joaquin Rodrigo
Last of the Mohicans	Trevor Jones
Schindler's list	John Williams
Lux Aeterna	Clint Mansell
Pirates of the Caribbean	Royal Philharmonic Orchestra
La Vita è Bella	Nicola Piovani
Avicii	Levels

Lux Aeterna	Clint Mansell
Claro de luna	Debussy
Popof	Toxic Love
Washed Out	Eyes Be Closed
Sing, Sing, Sing	Benny Goodman & Louis Prima
The Heart Asks Pleasure First	Michael Nyman
Time	Hans Zimmer
Pirates of the Caribbean	Royal Philharmonic Orchestra
Chariots of Fire	Vangelis
Bach Cello Suite No.1 in G	Mischa Maisky
Asturias	Isaac Albeniz
Circle of Life	Elton John
Four Seasons (Spring)	Vivaldi
Now We Are Free (Instrumental)	Hans Zimmer
Numb (Piano version)	Linkin Park
Caresse Sur l'Océan	Bruno Coulais
Undisclosed Blackhole (Instrumental)	MUSE
My Way	Andre Rieu
Schindler's list	John Williams
Roll Tide	Hans Zimmer
The Nutcracker	Tchaikovsky
El Tango de Roxanne	Mariano Mores
Comfortably Numb	Pink Floyd
Firth of Fifth	Genesis
Elephant Gun	Beirut
La Valse d'Amelie	Yann Tiersen
Old Pine	Ben Howard
Amazing Grace (Instrumental)	Gilbert Chase
Lux Aeterna	Clint Mansell
Con Te Partiro	Andrea Bocelli
Tennessee	Hans Zimmer

Für Elise	Beethoven
Truth	Balmorhea
Last of the Mohicans	Trevor Jones
El Mercenario	Ennio Morricone
Just Feel Better	Carlos Santana ft. Steven Tyler
Where Have You Been	Rihanna
Lux Aeterna	Clint Mansell
Liquid Tension Experiment	Acid Rain
Haste to the Wedding	The Corrs
Records d'infant	Albert Oliveres
End Title (You Are Karen)	John Barry
El Amor Brujo (Danza del Fuego)	Manuel de Falla
Ode to Joy	Beethoven
Entre Dos Aguas	Paco de Lucía
Varga-Varga	Chico Trujillo
Europa	Santana
Child in Time	Deep Purple
Nineteen	Karma to Burn
Godspeed	Earthless
Shine on Your Crazy Diamond	Pink Floyd
Entre Dos Aguas	Paco de Lucía

Table S3. Excerpts chosen by the participants (self-selected excerpts) in the study. Red background indicates those pieces selected by ANH participants; blue, by the HDN group; and green, those selected by H-HDN participants.

Supplemental figures

Figure S1

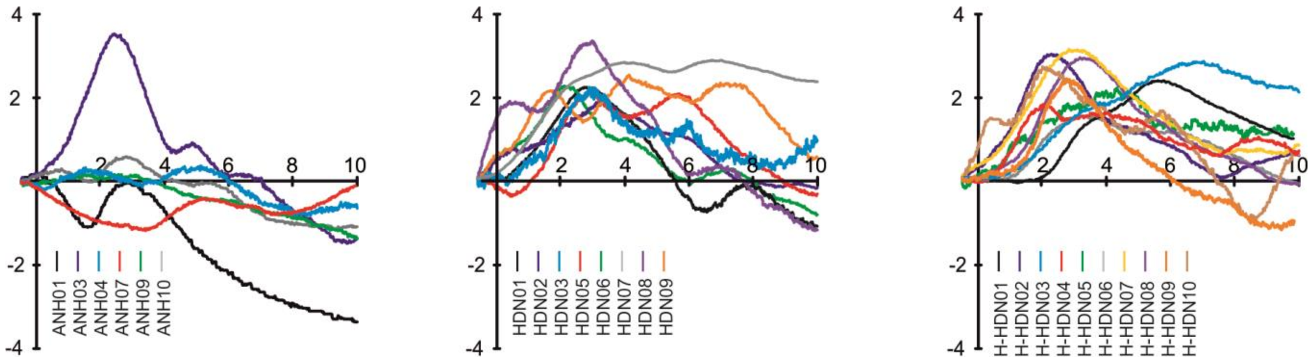

Figure S1. Individual normalized SCR associated to chill for each group. Only one individual of the ANH showed a significant increase of SCR. However all participants from both the HDN and H-HDN groups showed significant SCR increases associated to chills.

Figure S2

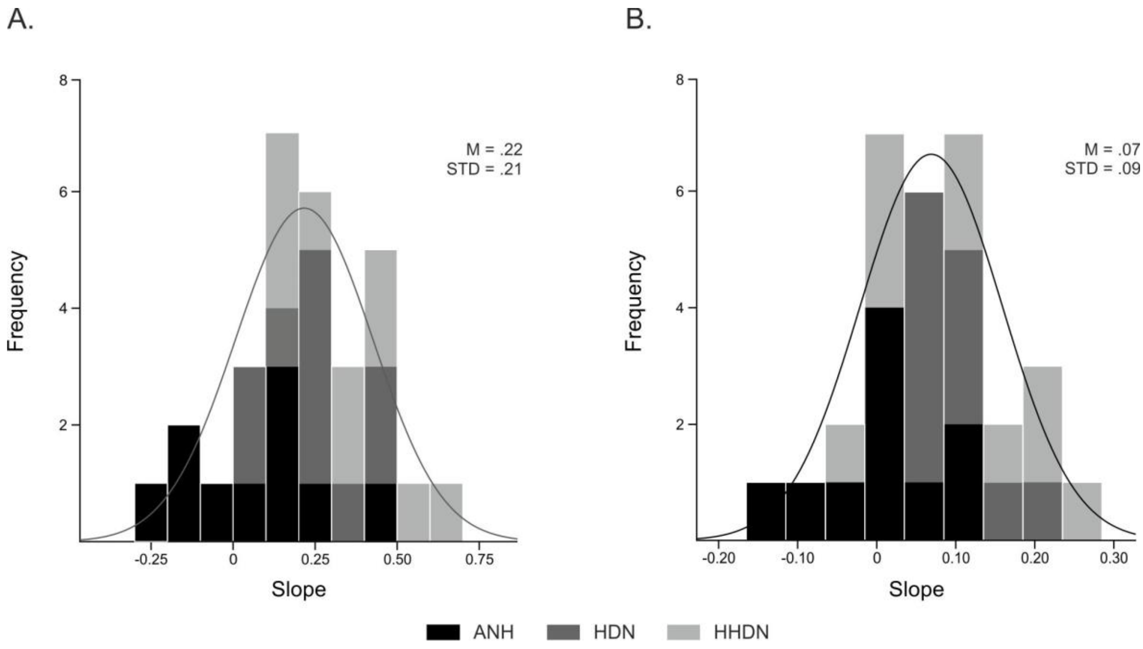

Figure S2. Distribution of the slopes obtained in the regression analysis with A) SCR and B) HR data. Note that slopes followed a normal distribution in both cases. Color bars differentiate participants from the ANH, the HDN and the HHDN group.

Figure S3

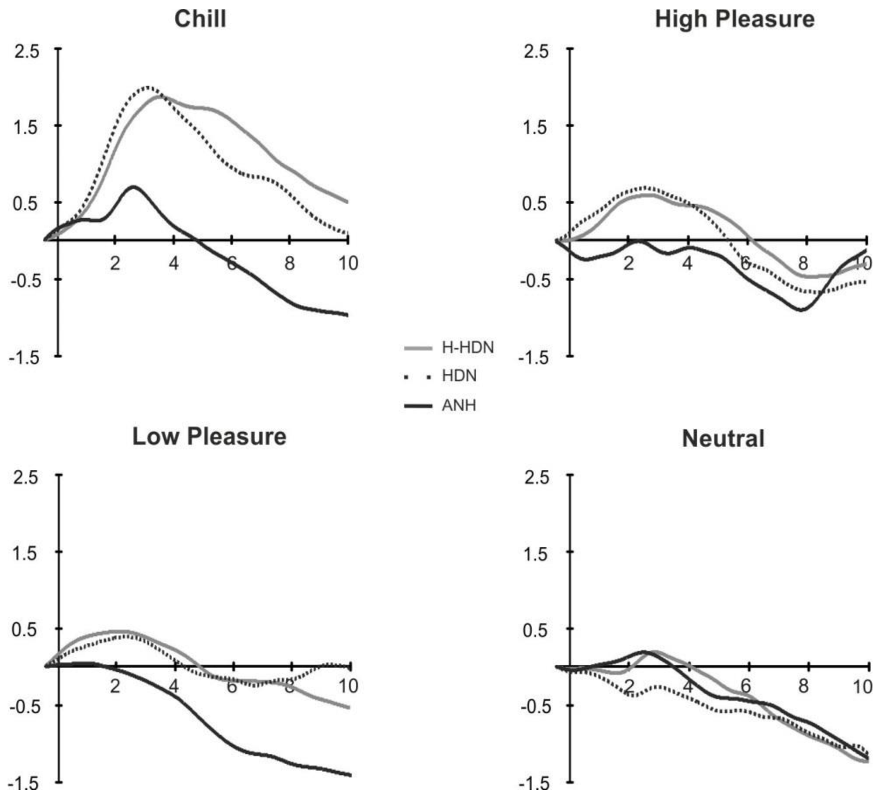

Figure S3. Normalized skin conductance response associated with the four different pleasure rates (chill, high pleasure, low pleasure and neutral) for the three groups in the music task without including self-selected excerpts. Note the increase of SCR in both H-HDN and HDN groups (but not in the ANH group) as a function of increasing pleasure rate.

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