Associations of aesthetic experiences with listeners' physiology in music segments of live concerts

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Abstract

A study of 690 participants attending classical public concerts was conducted with the goal of analyzing the associations between self-reported aesthetic experiences and physiological responses. The concerts staged chamber music by Ludwig van Beethoven, Brett Dean, and Johannes Brahms. Participants' physiological signals were recorded with wearable sensors during the concerts. After the concerts, music segments were individually presented to participants. The segments were excerpts selected from the concert just attended, partially on the grounds of each participant's salient physiological response. Eight segments were shown to each participant in a stimulated-recall procedure, and the participant's experiences of the music in the segment were obtained using the Aesthetic Emotions Scale. Mean segment levels of heart rate, heart rate variability, respiration rate and skin conductance response were found linked to varying aspects of segment experience. Experiences of beauty and high valence of aesthetic emotions were associated with sympathetic activation and attenuated parasympathetic activation. The associations were less clearly pronounced in segments drawn from the contemporary Dean piece, which generally gave rise to fewer sympathetic responses than the Brahms and Beethoven pieces. It was concluded that future research should complement the shown experience-physiology links by additional information on audio features of the music segments.

Keywords: aesthetic experience; chamber music; classical concerts; music segments; physiological responses

Introduction

The project Experimental Concert Research (ECR) recorded aesthetic experiences and physiological responses of concert visitors under naturalistic conditions in a series of eleven public classical concerts. The main research questions concerned the associations between participants' physiological data and self-reported aesthetic experiences – how was the presented music associated with listeners' physiological and subjective responses?

The concerts were organized in 2022 in two venues located in Berlin, Germany. The same musical program consisting of string quintet pieces of Ludwig van Beethoven, Brett Dean and Johannes Brahms were presented in varying concert formats. It was a specific concern of ECR to maintain a context of ecological validity, thus all concerts were open to the public, and study

participants were recruited from the population of people predominantly interested in the performing ensembles, the presented music and the concert venues. The physiological recordings were enabled by wearable devices, a 'data glove' and an elastic belt worn over the clothing.

All participants answered a survey before the concert and another survey immediately after the concert. In the post-concert survey a method of stimulated recall was applied: the complete concert was partitioned into 96 different musical segments, which were predefined beforehand by the investigators as meaningful phrases of the music. The duration of segments was approximately 40 seconds on average. During each concert, musicological 'loggers' prepared an electronic protocol of the exact time-stamps of the beginnings and ends of all segments. On the basis of this protocol, each participant was presented, after the concert, with audio-visual replays of eight segments. After each replay, the participants rated their appreciation and experience of this specific music segment using a list of 25 items. Three of the eight segments were pre-selected by ECR researchers ('index segments'), four segments were selected because of each individual participant's physiology detected during the concert, and one segment was drawn randomly from the sample of all (minus the seven already shown) segments. Thus, the selected music segments presented three index passages considered theoretically salient, four passages deemed noticeable because of the participant's physiological responses, and one randomly chosen passage.

Heart rate (HR), heart-rate variability (HRV), respiration rate (RR) and skin conductance response (SCR) of each participant were extracted from each segment. These physiological signals represent the activity of the autonomous nervous system (ANS) that continuously energizes or relaxes all organs of the body. The ANS also plays a dominant role in emotional responses. The ANS has two antagonistic branches, the sympathetic and the parasympathetic branch: sympathetic activation is associated generally with emotional arousal (e.g. with stress, fear or joy) and parasympathetic activation with relaxation (e.g. resting, sleepiness, recreation). It may be noted that the ANS does not differentiate between 'good' or 'bad' arousal, thus not between, for instance, joy and fear (Eerola & Vuoskoski, 2013). The cardiac measures HR and HRV and the rate of breathing RR are governed by both ANS branches but in different directions – activating sympathetic influences lead to higher HR and RR, but to decreased HRV. High HRV is a sign of parasympathetic activation. SCR is a signal that results from sympathetic

innervation only; increase of SCR reflects an increase of sympathetic activation (Birbaumer & Schmidt, 2010).

A growing number of studies has focused on physiological changes that music can induce in listeners (Wright, Bégel, & Palmer, 2022). The strong coupling between emotional responses to music and physiological processes is also present in aesthetic experiences of 'being moved' (Menninghaus et al., 2015), which are often linked to sympathetic physical phenomena such as chills ('goose bumps'), or to tears when listening to sad songs (Mori & Iwanaga, 2017). Musical attributes have been found associated with physiological responses: slow-tempo music was observed to correlate with decreased HR, RR and SCR and with increased HRV (Ooishi et al., 2017). In another study, tempo was found especially linked to HR (Van Dyck et al., 2017). Bullack et al. (2018) compared emotional and physiological responses to high- and low-valence music (happy and sad instrumental music excerpts). Participants showed increased SCR and RR during happy compared to sad excerpts, whereas HR did not vary with respect to valence. Krabs et al. (2015) conducted a study on ANS effects of pleasant joyful music, isochronous complex tones, unpleasant and dissonant music-like noise, and a silent control condition. The authors found increased SCR and HR and decreased HRV during music listening regardless of valence. The pleasant music however elicited a trend towards larger physiological responses than the emotionally neutral isochronous tones. Lynar et al. (2017) studied the physiological responses (HR, RR, SCR and HRV) to music in an attempt to find appropriate music for therapeutic purposes. They compared a prescribed classical and a jazz piece, an uplifting piece of the participant's own choice and a white-noise control stimulus. In self-report, the classical piece was assessed as most relaxing and the self-selected music as most joyful. The classical piece was linked to increased HRV consistent with parasympathetic dominance and relaxation, whereas the self-selected piece generated physiological arousal (increased SCR and HR).

Almost all research on the associations between physiological measures and emotional assessments was conducted in the laboratory, with few exceptions (Merrill et al., 2023; Tschacher et al., 2023a). It was one of the principles of the Experimental Concert Research project to enable close-to-lab quality recordings in concert halls open to the public in order to optimize ecological validity.

In general, we expected that the self-reported aesthetic experiences would be linked to the physiology measured during the segments. The first expectation was specified by hypothesis H1

saying that aesthetic experiences are linked to heart rate, heart rate variability, respiration rate and skin conductance responses. Based on previous findings, we expected that high-valence experiences and emotions would be connected to sympathetic arousal, and low valence to either parasympathetic activation or reduced sympathetic activation. H2 addresses this link between experiences and physiology at the level of pieces. We expected that the experience-physiology linkage would differ between the three staged pieces the segments originated from. H3 extended the exploration of experience and physiology to the level of music movements; here we expected that musical characteristics of the movements would be represented in the associations. H4 addressed the associations between recognition of a music segment ("I remember this segment") and how the segment was experienced. It was hypothesized that segments with high-valence experiences would be remembered better.

A secondary goal of the study was to describe the physiological values measured during the segments. Exploratory study questions (Q) were if there were physiological differences between segments within the three pieces (Q1) and between the movements within pieces (Q2). Q1 and Q2 were motivated owing to the different musicological qualities of pieces and movements. Q3 concerned the differences between segments chosen by the three different criteria, 'index segments', 'minimum segments' and 'random segment'.

Method

Participants and setting

The research project “ECR – Experimental Concert Research” has the goal to investigate concert experience with a multidisciplinary approach that connects musicology, cultural management, physiology and psychology (Tröndle et al., 2022; Wald-Fuhrmann et al., 2021). A series of eleven concerts were organized in Berlin in April and May of 2022, the initial two concerts in the Pierre Boulez Saal and nine further concerts in the Radialsystem concert hall. The following pieces were played in all concerts: Ludwig van Beethoven, String Quintet op. 104 in c-minor (first movement); Brett Dean, Epitaphs; Johannes Brahms, String Quintet op. 111 in G-major, hence Viennese classical, contemporary and romantic Western art music. Only the first movement 'Allegro con brio' of the Beethoven piece was played, and it was always located at the beginning of concerts. The Brahms piece had four movements: 1. Allegro non troppo, ma con

brio; 2. Adagio; 3. Un poco allegretto; 4. Vivace ma non troppo presto. The five movements in Dean were titled 1. "Only I will know"–Gently flowing, with intimate intensity; 2. "Walk a little way with me"–Moderato scorrevole; 3. "Der Philosoph"–Slow and spacious, misterioso; 4. "György meets the 'Girl Photographer'"–Fresh, energetic; 5. "Between the spaces in the sky"–Hushed and fragile. Three concerts were played by the Yubal Ensemble, eight by the Ensemble Epitaph.

The concerts were announced by the program information channels of the respective venue, by mailing lists and by regional media. Potential audiences were also informed about the possibility to participate in the ECR study at a reduced fee for tickets. Persons interested in participating were invited to arrive one hour early at the venue, where they were informed about the study procedures and written information was handed out. All participants who signed the written informed consent were recruited until the capacity of 88 participants per concert was reached. About 75% of the concert audiences consisted of study participants. The present analyses are based on 690 participants with mean age 44y (SD=17.2y). 57.7% of participants were female, 41.8% male, 0.5% preferred not to say.

Self-report measures

Surveys were organized before and after each concert. The surveys were coded using LimeSurvey, an open-source software for conducting online surveys (LimeSurvey GmbH, Hamburg), which sends scales and questionnaires to portable terminals (here, Apple iPad tablets) that were handed out to each participant by the team of project assistants. The pre-concert survey consisted of demographic data acquisition and further questionnaires not used for the present analysis.

In the survey after the concert, participants were given music experience items based on the Aesthetic Emotions Scale (AESTHEMOS, Schindler et al., 2017). Items were used to assess the whole concert and the three presented pieces by Beethoven, Brahms and Dean. Finally, each participant was presented with eight musical segments recorded during the concert just attended, and asked to evaluate each segment using a stimulated-recall method. The eight segments were selected from a sample of 96 segments predefined by the ECR investigators. Durations of single segments were on average 38s (SD=8.4s, range 17s–53s). The segments were presented on the

tablet as short video excerpts of the ensemble who played the concert, and the participant listened to the respective music with headphones.

The self-report survey after each presentation of a segment consisted of 25 five-point Likert scales. First item was "I remember this segment" ("strongly disagree" to "strongly agree"), followed by three further items initiated by "How do you rate the following moment in the concert?". The items were "The music at this point", "How the music was played" and "How the music was staged", and evaluations were given on scales ranging from "very bad" to "very good". After these initial items, 21 AESTHEMOS items were presented in random sequence initiated by "This moment in the concert..." Statements were, for example, "...was beautiful" or "...annoyed me". Responses were given on five-point scales ranging from "does not apply" to "applies". All 25 items focusing on the music segments constitute the self-report database of the present analyses.

Physiological measures

Before the concert, as soon as participants were seated in the concert hall, research assistants equipped each participant with sensors integrated in a glove to collect electrodermal activity, and with a respiration belt to measure breathing (Figure 1). Devices were produced by biosignalsplux (PLUX Wireless Biosignals, S.A.). Physiological data were acquired at 200 Hz sampling rate and were processed using the BioSPPy library (Carreiras et al., 2015) to extract higher-level signals from the raw data of the devices. Blood-volume pulse was captured by a photo-plethysmographic sensor placed over one fingertip. Heart-rate (HR) and heart-rate variability (HRV) were obtained from blood-volume pulse. HRV was computed by the RMSSD (root mean square of successive differences) procedure, which captures short-term variability. Respiration rate (RR) was derived from belt distension. Electrodermal activity was measured from electrodes of the glove attached to two fingers of the non-dominant hand, and pre-processed using Ledalab (Benedek & Kaernbach, 2010). In the present analysis, phasic skin-conductance response (SCR) was used.

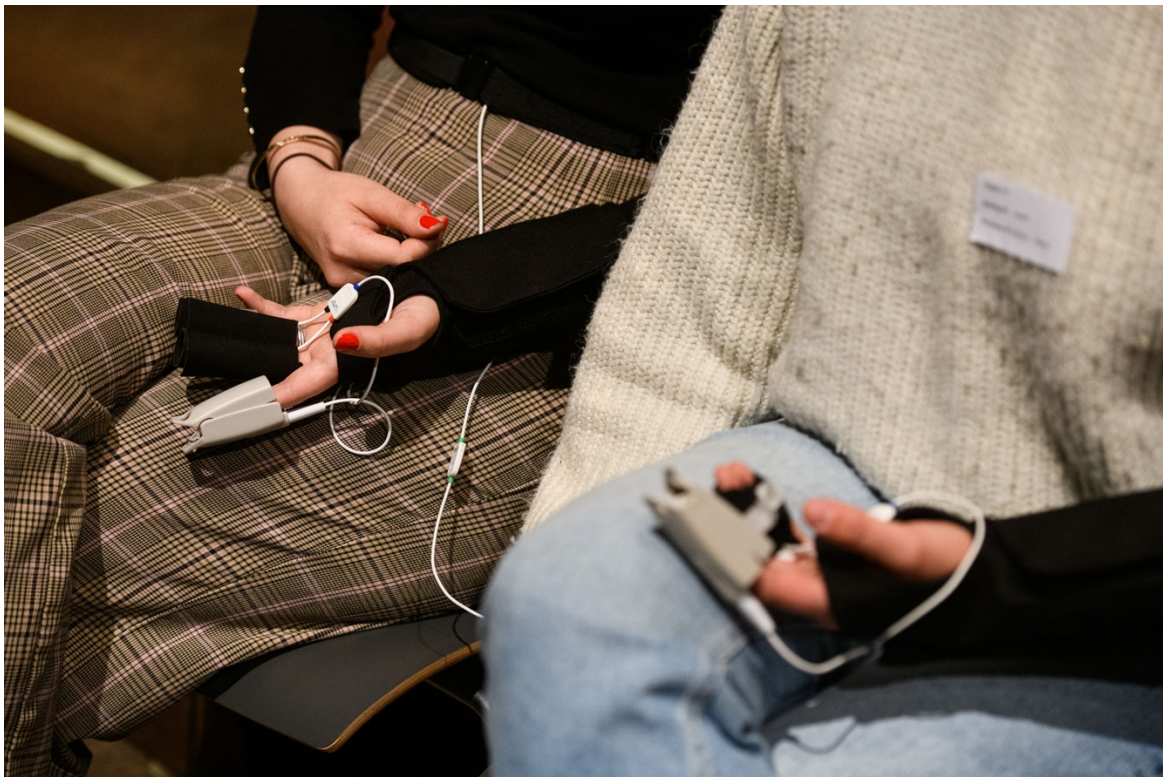

Figure 1. Sensors for physiological measurement. Photo: Phil Dera

For the present analyses, each participant's physiological values of all 96 segments, including the eight presented segments, were stored (mean, standard deviation, 10th and 90th percentiles, of HR, HRV, RR, SCR). This complete dataset consists of over 240'000 measurements (690 participants, 96 segments, 4 physiological measures, minus 9.2% missing data). The stimulated-recall dataset contains 20'400 measurements (690 participants, 8 segments per participant, 4 physiological measures, minus 7.6% missing data).

Organization and infrastructure of data acquisition

Out of the available 96 segments, the eight segments presented to a participant were selected by these criteria: Four locally salient segments were individually chosen based on the physiological responses of each participant monitored during the concert, namely on his or her minimum values of heart rate (HR), heart rate variability (HRV), skin conductance response (SCR) and respiration rate (RR) relative to this participant's mean values of the respective movement within a piece. We labelled these physiologically determined segments 'minimum segments'. Three 'index segments', one out of each of the three pieces, were presented to all

participants of a concert identically. Index segments were pre-selected by the investigators to represent musical passages of the concert deemed characteristic for each piece. In the three initial concerts of the Radialsystem, a different set of index segments was presented, which were however also located in the same movement of each piece. One 'random segment' was chosen randomly. All eight segments (five individually allocated, three identically allocated to all participants of the concert) were rated in self-report on 25 items.

This study design of presenting individually tailored segments generated a three-fold challenge. First, the exact timing of each of the 96 segments had to be documented while the respective concert was being performed. This was done by two loggers who entered the start time and end time of all segments directly into the central server (the 'dashboard'). Second, the physiologically salient segments had to be determined after the end of the performance, for each participant, for all 96 segments and four physiological signals, based on the loggers' time-stamps. Third, the video and audio of all segments had to be cut from the video and audio recording of the concert, again based on the logged time-stamps. The ensuing complex computations were to be performed in few minutes after the concert, before participants would arrive at the stimulated-recall section of the post-concert survey (Figure 2).

All data from the physiological recordings and the questionnaire tablets were controlled and synchronized by the central dashboard. Immediately after the end of the concert, the physiological data of all participants were processed using the previously developed segment-detection algorithm. The processing was started via the dashboard's web interface and took approximately ten minutes to complete for all participants of a concert. Due to the time pressure, the physiology recording and online segment-detection of physiological signals required decentralized processing as the appropriate hardware architecture. Therefore, the ECR project employed small single-board computers (SBCs) called Raspberry Pi (Raspberry Pi Foundation, UK). Altogether 88 SBCs were used in the project, one for each participant with physiology recordings.

Figure 2. Filling out self-report questionnaires after the concert. Photo: Wolfgang Tschacher

The logger page located in the dashboard allowed for the manual documentation of all 96 segments online during the concert. Thus, the exact Unix time-stamps of all segments were available, so that physiologically salient moments could be assigned to segments immediately after the end of the concert. This assignment was accomplished by the distributed SBCs in near real-time instead of allocating this task to the central server, which would have generated an informational bottle-neck. The software LimeSurvey was used to dynamically integrate the videos of all segments. The instruments and infrastructure of data acquisition were developed and validated in a series of previous concerts (Tschacher et al., 2023b). A detailed description of the ECR methodology and computational infrastructure is in preparation.

The physiological data of the complete dataset (690 participants, 96 segments, 4 physiological measures) allowed a post-hoc determination of 'maximum segments' in addition to the salient

'minimum segments' detected during the concert and presented to participants. These maximum segments did not however receive evaluations by the participants in the stimulated recall survey.

Statistical analyses

The investigation of segments had descriptive and hypothesis-driven goals. For description we analyzed the complete dataset of over 240'000 physiological measurements: we describe the values of specific music segments, explore differences between pieces the segments are located in. All statistical analyses were performed using the software JMP Pro 15.1 (SAS Institute Inc., 2019).

The primary goal of the present study was to test the hypothesized experience-physiology associations. The hypotheses concerned the prediction of the physiology measured during the segments by the self-reported aesthetic experiences of segments. We factorized these self-report items to yield orthogonal predictors for ensuing regression models and hence avoid multicollinearity of predictors. The test of most hypotheses employed hierarchical regression models with 'participant' as the random effect. H1 was tested by four models, one for each measure, which predicted the respective physiology levels of all segments by the factorized self-report items. H2 concerned differences between the three pieces played in the concerts. The hierarchical regression modeling for H2 was repeated for segments of each piece. This procedure was also used for movements of each piece (H3). Since only one movement of Beethoven was performed, H2 and H3 were identical for Beethoven. Finally, we expected that positive aesthetic experiences would be remembered better (H4) and thus the AESTHEMOS items would be linked to the item "I remember this segment".

The secondary goal of the study was to describe the physiological values measured during the segments. Where appropriate, this was based on the complete dataset of over 230'000 measurements independent of self-report data. Exploratory study questions (Q) were which physiological differences existed between segments within the three pieces (Q1) and the movements within the pieces (Q2). Finally, Q3 addressed the physiological differences between the music segments chosen on the basis of selection criteria.

Results

Factorization of self-report items

We factorized 24 items (all AESTHEMOS items and three initial items; the first item "I remember this segment" was omitted as it does not concern aesthetic experience). Maximum-likelihood factor analysis was performed on segment evaluations performed by 767 persons, which included participants of the project who were part of a control group without physiological recordings. Six factors were Varimax-rotated and explained 54.9% of the total variance of the items. The factors were F1-impressing (22.1% explained variance, highest loading items were "impressing", "liked the music", "fascinating"), F2-beautiful (8.7%; "beautiful", "amusing"), F3-warming (6.8%, "warming", "relaxing"), F4-surprising (6.4%, "surprising", "nervous", "annoying"), F5-melancholic (5.7%, "melancholic", "made me think") and F6-physical (5.1%, "stimulated physically", "physical response/goose bumps").

Links between self-reported experience and physiology

Hypothesis 1 (H1) on the general link between factors of self-reported aesthetic experiences was evaluated using a regression model for each physiological signal across all segments. It was found that the mean segment levels of heart rate (HR), heart rate variability (HRV), respiration rate (RR) and skin conductance response (SCR) were linked to varying aspects of segment experience (Table 1). HR was increased when segments were rated as beautiful. HRV was decreased when segments were rated as impressing and beautiful, but increased when assessed as warming-relaxing. RR showed positive links to impressing, beautiful and physically stimulating. SCR was positively predicted by warming-relaxing and physically stimulating, whereas it was negatively linked to surprising and melancholic experiences. Consistent with H1, high-valence experiences 'F1-impressing' and 'F2-beautiful' were associated with sympathetic HR- and RR-increases and HRV-decrease. F6-physical was connected to sympathetic arousal in RR and SCR as expected. The low valence of predictor 'F4-surprising' and 'F5-melancholic' was also in line with H1, as the negative prediction of SCR pointed to reduced sympathetic activation. H1 was not supported by the 'predictor F3-warming' with sympathetic links to SCR.

	Mean segment physiology of...							
	HR		**HRV**		**RR**		**SCR**	
Predictors	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*
Intercept	72.7	160.2****	24.9	26.3****	15.8	226.9****	5.0	30.3****
F1-impressing			-1.10	-2.67**	0.15	3.71***		
F2-beautiful	0.25	2.66**	-0.94	-2.42*	0.42	11.4****		
F3-warming			1.18	2.86**			0.20	6.46****
F4-surprising							-0.11	-3.31***
F5-melancholic							-0.08	-2.28*
F6-physical					0.12	2.39*	0.11	2.88**
Random effect								
Participant (% variance)	84.6		55.5		38.9		88.8	
N	4434		4439		5168		4965	
r^2 (% variance)	86.6		61.0		46.5		90.3	

Table 1. Segment physiology and aesthetic assessment of segments. Results for hierarchical models of physiology (dependent variable) by aesthetic assessments. Only significant predictors are listed. *N*, number of observations. r^2, explained variance of model. * $p < .05$; ** $p < .01$; *** $p < .001$; **** $p < .0001$

An additional post-hoc analysis addressed the assumption of specific valence-physiology associations. Valence was defined on the basis of the differences of only two items, "pleased me" (representing high valence) and "annoyed me" (representing low valence), instead of all items represented in the factorial predictors of Table 1. Again, the self-reports and physiology data of all segments were included in this analysis. The results in Table 2 show that valence was related to higher sympathetic arousal (HR, RR, SCR) and lower parasympathetic activation (HRV) in concordance with hypothesis H1.

	Mean segment physiology of...							
	HR		**HRV**		**RR**		**SCR**	
Predictors	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*
Intercept	72.6	159.1****	25.6	26.1****	15.6	217.7****	4.94	30.1****
Valence	2.86	2.86**	-0.36	-2.00*	0.13	7.57****	0.03	2.45*
Random effect								
Participant (% variance)	84.6		54.7		38.4		88.6	
N	4437		4452		5215		4965	
r^2 (% variance)	86.6		60.2		45.2		90.1	

Table 2. Segment physiology and valence (computed as difference of items "pleased me" and "annoyed me"). Results for hierarchical models of segment physiology (dependent variable) predicted by valence. *N*, number of observations. r^2, explained variance of model. * $p < .05$; ** $p < .01$; **** $p < .0001$

H2 concerned the differences between pieces that may mediate the link between aesthetic experiences and physiology. In the complete dataset (cf. Table 6), considerable differences in physiology were found between pieces. We therefore modeled the experience-physiology associations separately in each piece. Table 3 provides models for the segments in the Beethoven piece, Table 4 in the Brahms and Dean pieces. Models without significant prediction by aesthetic experiences are not shown in the tables (Beethoven segments provided no significant prediction of SCR, Brahms none of HR and HRV, Dean none of HR and SCR). Most often, the 'F2-beautiful' predictor was found significant (in Beethoven and Brahms). The assessment of 'F4-surprising' was associated with RR in Brahms and Dean. Further predictors were 'F1-impressing' (in Brahms and Dean) and 'F5-melancholic' (in Beethoven).

The predictions for the Beethoven piece (which was actually movement 1 of Beethoven's work) was similar to the overall picture of Table 1 in that 'F2-beautiful' was associated with HR, HRV and RR towards sympathetic activation. 'F5-melancholic' was linked to parasympathetic activation of HRV.

	Mean segment physiology of...					
	HR (Beethoven)		**HRV(Beethoven)**		**RR (Beethoven)**	
Predictors	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*
Intercept	73.1	144.8****	25.2	20.3****	16.0	162.1****
F1-impressing						
F2-beautiful	0.37	1.98*	-1.72	-2.32*	0.47	6.97****
F3-warming						
F4-surprising						
F5-melancholic			2.40	2.50*		
F6-physical						
Random effect						
Participant (% variance)	90.1		67.5		54.3	
N	1254		1255		1455	
r^2 (% variance)	94.4		79.3		70.1	

Table 3. Segment physiology and aesthetic assessment of segments in the Beethoven piece. Results for hierarchical models of physiology (dependent variable) by aesthetic assessments. Only significant predictors are listed (SCR model received no significant prediction by assessments). *N*, number of observations. r^2, explained variance of model. * $p < .05$; **** $p < .0001$

In the Brahms piece (Table 4), the predictions of 'F2-beautiful' were as expected with respect to RR, but the negative prediction of SCR by 'F1-impressing' as well as 'F2-beautiful' was not. The direction of prediction 'F4-surprising' as arousing in both Dean and Brahms was reversed to the overall model of Table 1.

	Mean segment physiology of...							
	RR (Brahms)		**SCR (Brahms)**		**HRV (Dean)**		**RR (Dean)**	
Predictors	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*
Intercept	15.7	189.8****	5.03	28.5****	22.8	19.2****	15.8	142.3****
F1-impressing			-0.14	-2.47*	-1.39	-2.12*		
F2-beautiful	0.47	6.48****	-0.10	-2.05*				
F3-warming								
F4-surprising	0.17	2.09*					0.20	2.34*
F5-melancholic								
F6-physical								
Random effect								
Participant (% variance)	30.40		91.7		61.5		42.0	
N	2148		2069		1357		1565	
r^2 (% variance)	43.7		94.4		74.4		57.7	

Table 4. Segment physiology and aesthetic assessment of segments in the pieces by Brahms and Dean. Results for hierarchical models of physiology (dependent variable) by aesthetic assessments. Only significant predictors are listed, only models with significant predictors are shown. *N*, number of observations. r^2, explained variance of model. * $p < .05$; **** $p < .0001$

We again conducted post-hoc analyses to address the role of valence for segment physiology in pieces (Table 5). The results show that valence was again related to higher sympathetic arousal (HR, RR) in Beethoven and Brahms. No significant prediction of physiology by valence was found in the segments of the Dean piece.

	Mean segment physiology of...					
	RR (Beethoven)		HR (Brahms)		RR (Brahms)	
Predictors	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*
Intercept	15.8	146.5****	72.4	156.2****	15.5	186.2****
Valence	0.22	6.85****	0.24	2.60**	0.09	2.74**
Random effect						
Participant (% variance)	54.2		81.9		29.3	
N	1455		1829		2148	
r^2 (% variance)	69.7		87.4		41.6	

Table 5. Segment physiology and valence (computed as difference of items "pleased me" and "annoyed me") computed separately in all pieces, no significance in Dean. Results for hierarchical models of segment physiology (dependent variable) predicted by valence. Only significant predictors are listed. *N*, number of observations. r^2, explained variance of model. ** $p < .01$; **** $p < .0001$

In all concerts, only the first movement (Allegro con brio) of Beethoven's work was played (see Table 3). The pieces of Brahms and Dean consisted of four and five movements, respectively, which vary markedly with respect to tempo and other musical attributes. Therefore, in assessing H3 we modeled the experience-physiology associations separately in each of these movements. The results of these models are given in Tables 6 (Brahms) and 7 (Dean) in abbreviated format: Only the *t*-values are listed, and models of dependent variables that were not significantly predicted by any of the six experience variables are omitted. The number of observations *N* varied considerably from movement to movement, largely owing to which segments were chosen as index segments, which were located in movement 1 of Brahms and movement 3 of Dean.

The assessment 'F2-beautiful' was positively associated with RR and/or HR in all four movements of Brahms (Table 6). There were two significant predictions by 'F4-surprising' and 'F5-melancholic', the latter was positively linked to HR in movement 2, but negatively to RR in movement 4. Post-hoc analyses of valence-physiology associations provided positive links for HR in Brahms movement 1 and positive links for RR in Brahms movements 2 and 3.

	Brahms							
	Mean segment physiology of...							
Physiological signal:	**HR**	**RR**	**HR**	**RR**	**RR**	**SCR**	**HRV**	**RR**
Movement:	**1**	**1**	**2**	**2**	**3**	**3**	**4**	**4**
Predictors	*t*	*t*	*t*	*t*	*t*	*t*	*t*	*t*
Intercept	149.8****	159.4****	76.8****	71.2****	84.5****	15.1****	10.1****	73.8****
F1-impressing						-2.01*		
F2-beautiful	2.16*	4.44****	2.66**	2.08*	3.90****			2.74**
F3-warming								
F4-surprising		2.57*					2.47*	
F5-melancholic			2.24*					-3.70***
F6-physical								
Random effect								
Participant (% variance)	81.4	31.5	91.9	35.0	43.3	95.5	66.9	6.6
N	1195	1398	244	286	257	249	171	207
r^2 (% variance)	89.8	47.7	98.4	57.9	68.7	99.3	88.2	21.3

Table 6. Segment physiology and aesthetic assessment of segments in movements of the Brahms piece. Results for hierarchical models of physiology (dependent variable) by aesthetic assessments. Only significant predictors are listed, only models containing significant predictors are shown. *N*, number of observations. r^2, explained variance of model. * $p < .05$; ** $p < .01$; *** $p < .001$; **** $p < .0001$

	Dean						
	Mean segment physiology of...						
Physiological signal:	**RR**	**RR**	**SCR**	**HRV**	**HR**	**RR**	**SCR**
Movement:	**1**	**2**	**2**	**3**	**4**	**5**	**5**
Predictors	*t*	*t*	*t*	*t*	*t*	*t*	*t*
Intercept	36.4****	53.1****	12.7****	15.5****	54.5****	64.8****	11.9****
F1-impressing	2.72**		-3.03**				
F2-beautiful				2.30*		2.77**	2.20*
F3-warming							-2.71**
F4-surprising		2.32*			2.15*		
F5-melancholic							
F6-physical							
Random effect							
Participant (% variance)	–	12.0	99.2	77.3	85.7	0.2	95.8
N	86	193	189	710	133	318	298
r^2 (% variance)	8.9	26.6	99.9	92.1	96.8	4.7	99.2

Table 7. Segment physiology and aesthetic assessment of segments per movement of the Dean piece. Results for hierarchical models of physiology (dependent variable) by aesthetic assessments. Only significant predictors are listed, only models containing significant predictors are shown. *N*, number of observations. r^2, explained variance of model. * $p < .05$; ** $p < .01$; *** $p < .001$; **** $p < .0001$

Table 7 provides the pattern of experience-physiology associations in the five movements of Dean. Of the five valence-physiology associations (not depicted in tables), two were significant: Valence was positively linked to SCR in the second and to HRV in the third movement.

Hypothesis H4 was tested using a hierarchical model with 'participant' as random effect and the six aesthetic experience variables as predictors of participants' recognition ("I remember this segment"). We found that three of the experiences were significantly associated with recognition: 'F1-impressing' ($t(5958)=39.5$, $p<.0001$), 'F2-beautiful' ($t(5963)=2.65$, $p<.01$) and 'F6-physical' ($t(5913)=13.3$, $p<.0001$), the initial two of which are aspects of high-valence experience. 'F3-warming', 'F4-surprising' and 'F5-melancholic' did not have significant predictive power regarding memory.

Descriptive analyses of the dataset

The complete dataset consists of the physiological recordings of all 690 participants in each of the 96 pre-defined segments, thus up to 66'240 measurements of each of the four signals HR, HRV, RR, and SCR. Outliers of HR exceeding values of 100 beats per minute were deleted, the same with HRV exceeding 105 (RMSSD). Research question Q1 addressed physiological differences between the pieces by Beethoven, Brahms and Dean. We computed four hierarchical regression models with segment physiology (HR, HRV, RR, SCR) as dependent variables and Piece as the categorial predictor (Table 8; *t*-tests are provided for the Brahms and the Dean pieces, always in contrast to the Beethoven piece as the reference step). The random effects were 'Participant' and 'Participant X Piece'; models with these two random effects showed better model fit according to Akaike's Information Criterion (AIC) than modeling with the 'Participant' effect only. The models indicate that participants had significantly different physiological levels during segments depending on the piece the respective segments were located in. Dean segments had the lowest levels of HR, RR and SCR of all three pieces, consistent with low sympathetic activation. The segments in the Beethoven piece showed the lowest HRV levels, and SCR was highest in the Brahms piece (both pointing to high sympathetic activation).

	Mean segment physiology of...							
	HR		**HRV**		**RR**		**SCR**	
Predictors	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*
Intercept	72.7	173.6****	22.0	30.9****	16.2	240.3****	4.88	30.1****
Brahms	-0.17	-2.52*	1.28	8.19****	0.10	-4.43****	0.14	4.51****
Dean	-0.33	-4.91****	0.45	2.88**	-0.17	-7.92****	-0.13	-4.17****
(reference step: Beethoven)								
Random effect								
Participant (% variance)	88.1		66.2		49.5		87.6	
Participant X Piece	3.0		3.9		6.9		4.5	
N	53994		53661		65862		63279	
r^2 (% variance)	90.3		57.6		57.3		92.6	

Table 8. Segment physiology predicted by pieces Beethoven, Brahms and Dean (Beethoven is reference step of the categorical variable 'Piece'). Hierarchical regression models with random effects 'Participant' and 'Participant X Piece'. *N*, number of observations. r^2, explained variance of model. * $p < .05$; **** $p < .0001$

Table 9 describes the differences of segment physiology by movement related to study question Q2. We computed four hierarchical regression models with segment physiology (HR, HRV, RR, SCR) as dependent variables and 'Movement' as the categorial predictor. The results show considerable divergence between movements.

When the predictor 'Valence' was added to the models (not shown in Table 9), significant predictions were preserved, and valence was positively predictive of HR and RR, and negatively of HRV, hence likely related to sympathetic activation as already shown in Table 2. A further post-hoc analysis was based on the mean musical tempo of movements, calculated as number of bars contained in a movement per minute. Movements Brahms-4 had the highest and Dean-3 the lowest tempo. The tempo variable was significantly correlated to the mean SCR levels of all ten movements: $r(10)=0.82$, $p<.01$.

	Mean segment physiology of...							
	HR		**HRV**		**RR**		**SCR**	
Predictors	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*
Intercept	71.9	174.8****	21.73	22.5****	15.6	203.5****	4.90	29.7****
Brahms-1							0.15	3.03**
Brahms-2	-0.59	-2.18*	3.40	3.80***	-0.40	-3.24**		
Brahms-3					-0.26	-1.98*		
Brahms-4	-0.95	-3.03**					0.26	2.52*
Dean-1					0.60	2.82**		
Dean-2			-3.64	-3.49***			-0.40	-3.72***
Dean-3					0.41	5.22****	-0.33	-5.78****
Dean-4	0.70	1.99*						
Dean-5					-0.86	-7.30****	-0.22	-2.56*
Beethoven (reference)								
Random effect								
Participant (% variance)	85.0		53.6		39.4		88.9	
N	4335		4302		5215		5007	
r^2 (% variance)	86.3		54.1		47.2		90.4	

Table 9. Segment physiology by movement. Results for hierarchical models of segment physiology (dependent variable) by movement (Beethoven-1 is reference). Only significant predictors are listed. *N*, number of observations. r^2, explained variance of model. * $p < .05$; ** $p < .01$; *** $p < .001$; **** $p < .0001$

Table 10 describes the differences of physiology in the segments chosen by the different criteria for segment-selection following research question Q3. We again computed four hierarchical regression models with segment physiology (HR, HRV, RR, SCR) as dependent variables and 'Criterium' as the categorial predictor. The results show that the detection of minimum segments HR, HRV and RR corresponded with segment values of HR, HRV and RR lower than in the reference criterium 'random segment'. This however was not true for SCR – SCR *minimum* segments showed significantly *higher* levels of SCR than random segments. Overall, 22 out of 28 predictions were significant and in the expected direction, which suggests that the selection of salient segments was realized in 82% of cases. It was also found that most index segments were commonly higher in sympathetic activation (HR, RR, HRV), again with the exception of SCR.

	Mean segment physiology of...							
	HR		HRV		RR		SCR	
Predictors	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*	*estimate*	*t*
Intercept	72.2	176.7****	21.78	34.2****	15.8	226.4****	4.96	30.4****
HR-minimum	-3.30	-22.0****	4.88	8.51****	0.16	2.81**	0.15	2.71**
HRV-minimum	0.45	2.62**	-4.10	-3.52****	0.49	7.51****	-0.14	-2.27*
RR-minimum	1.00	6.53****	3.63	6.83****	-3.23	-55.5****	0.27	4.95****
SCR-minimum					0.57	9.30****	0.23	4.35****
Index1	0.77	5.08****	-2.44	-4.70****	0.64	11.0****		
Index2					0.25	4.19****	-0.37	-6.87****
Index3	0.49	3.15**	-1.29	-2.44*	0.72	12.0****		
Random (reference)								
Random effect								
Participant (% variance)	86.7		55.3		53.2		88.8	
N	4335		4302		5215		5007	
r^2 (% variance)	87.9		55.8		67.8		90.3	

Table 10. Segment physiology and selection criteria (physiological minimum; Index segment; Random segment) of segments. Results for hierarchical models of segment physiology (dependent variable) by selection criterium. Only significant predictors are listed. *N*, number of observations. r^2, explained variance of model. * $p < .05$; ** $p < .01$; *** $p < .001$; **** $p < .0001$

Discussion

Concerning the primary hypothesis of the study, multiple associations between factors of aesthetic experience and physiological measures were detected in our large sample of almost 700 participants who provided between 4400 and 5300 single ratings. The majority of these associations were in accordance with expectations: Music segments experienced more beautiful were accompanied by higher sympathetic activations of heart rate (HR), respiration rate (RR) and lowered heart-rate variability (HRV). This was also true of the experience of being impressed and physically stimulated by the respective music excerpts. Melancholic and surprising (including annoying) aesthetic emotions were linked with decreased skin-conductance responses (SCR). The experience of warming-relaxing was predicted by higher HRV, but unexpectedly by increased SCR. When, in a post-hoc analysis, self-reported valence was used as the predictor of the four physiological signals, all models were significant and consistent with the hypothesis of valence linked with sympathetic arousal and attenuated parasympathetic activation.

Hypothesis 2 addressed the experience-physiology associations separately in the pieces of Beethoven, Brahms and Dean. Whereas in the Beethoven piece participants responded to 'beautiful'-assessments with sympathetic activation, and with parasympathetic melancholy as in the overall associations, the responses to the Brahms and especially Dean pieces were partly inconsistent. In line with this observation, piecewise valence-physiology associations were significant only in RR and HR and in the Beethoven and Brahms pieces, here again supporting the hypothesized link between valence and sympathetic activation. No clear relationship between valence and physiology was found in the Dean piece.

Going into more detail, the single movements of the Brahms and Dean pieces were also analyzed (Hypothesis 3). Experiencing the music segments in Brahms as beautiful was again linked to higher sympathetic activation, whereas the melancholic and surprising impressions varied with the movements. A pattern of still higher complexity was found in the contemporary music of Brett Dean, where even beauty was linked with parasympathetic activation of HRV in movement 3, but sympathetic activation of RR and SCR in movement 5.

This divergence of some findings likely goes back in part to the overall differences of how the participants physiologically responded to the presented music. Descriptive analyses of the complete physiology dataset included more than 230,000 single measures. This dataset showed that sympathetic responses to the Dean piece were significantly smaller than to the Brahms and Beethoven pieces almost throughout. This likely means that in general the contemporary music was met with less arousal in a majority of participants.

Hypothesis 4 was supported in showing that high-valence experiences 'beautiful' and 'impressing' were more expressed in participants remembering the segments in the post-concert survey better. This was also true of segments assessed as physically arousing. Low-valence segments rated as melancholic, warming-relaxing or surprising-annoying were not remembered well.

In conclusion, we found a wealth of associations between physiology and self-rated experiences; aesthetic experience was found embodied in physiology (Tschacher & Tröndle, 2011). With few exceptions, experiences and emotions with high valence were connected to higher sympathetic arousal. The links between valence and physiological activation were validated in post-hoc analyses supplementing the comprehensive analyses using factorized scores.

This study has a number of strengths that are rarely present in music-psychological research to date. The first is the considerable statistical power that was made possible by the large sample size at level 2 (690 participants) and level 1 (8 segment evaluations per participant) of this hierarchical dataset. Thus, thousands of observations with self-reports in each of four physiological measures became available for the analyses. Furthermore, a complete dataset of the four physiological signals measured in all 96 segments, altogether more than 230,000 physiological records, were retrieved and await analyses in future research. Secondly, the data were recorded in naturalistic environments of public concerts, which generated a context of high ecological validity. Thirdly, the music segments that received ratings were presented by a sophisticated stimulated-recall procedure. This procedure allowed presenting to each participant as stimuli the exact video and audio recording of the segment that this participant had viewed and heard just before in the concert, a further point emphasizing the validity of the dataset.

At the same time, we also became aware of limitations of the present study. Repeated computations were performed in the same dataset of self-report and physiology measures to assess overall, piece-wise and movement-wise associations, so that one may consider imposing Bonferroni-type alpha corrections. This would have eliminated a few of the significances at the five-percent level, among them some of the 'cumbersome' unexpected findings. We still decided against this restrictive option because there is likely real heterogeneity in the concert data, so that it would not be constructive to weed out unwelcome results by alpha adjustments. This heterogeneity may have been produced by several issues, the first of which is the factorial structure of the self-reports. The experiences and appreciations of the three pieces were divergent, with the contemporary music less estimated and considered more challenging than the conventional Viennese-classical and romantic music by Beethoven and Brahms. The Dean self-reports may have a different factor structure than the other music. This evoked a trade-off between independent factorization of self-reports per each piece versus combined factorization of all pieces, generating shared predictors and models that are easily comparable. Here we decided for the latter option. The second issue is that the present results may have been influenced by potential confounding variables. Ensuing analyses will therefore determine the audio features of all music segments to explore in which way features such as tempo, sound energy or spectral composition may have affected both the participants' rated experiences as well as their physiological responses to the segments. The reported post-hoc analysis has already

shown that specifically SCR was correlated to the mean tempo at the level of movements. Audio features at the segment level are likely good candidates to moderate or mediate the experiential and physiological responses towards these segments; this needs to be studied in more detail in upcoming research.

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