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The Embodied Mind in Music Listening

Abstract: *A study of participants attending public concerts that staged classical and contemporary chamber music had the goal to analyse the associations between self-reported experiences and physiological responses, hence addressing a core question of embodied cognition. A sample of 690 participants was recruited, whose physiological signals were recorded with wearable sensors during concerts. After the concerts, music segments were individually presented to participants. The segments were excerpts selected from the concert just attended. 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 rating scales. Cardiac, respiratory, and skin-conductance responses were found linked with varying aspects of*

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segment experience. Experiences of beauty and high valence of aesthetic emotions were associated with sympathetic activation and attenuated parasympathetic activation. We discuss the implications of empirical mind–body–music findings within the philosophy of mind and assess their compatibility with materialist, dualist, and emergentist conceptions of the mind–body debate and the science of consciousness.

Keywords: 4E cognition; aesthetic experience; classical concerts; music segments; physiological responses.

1. Introduction

The project titled '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 programme 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 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. The various physiological signals represent the activity of the autonomous nervous system (ANS) that continuously energizes or relaxes all organs of the body and 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 activation of the body and emotional and cognitive arousal, whereas parasympathetic activation is associated with relaxation.

1.1. Physiology and music

A growing number of studies has focused on physiological changes that music can induce in listeners (Wright, Bégel and Palmer, 2022).

The strong coupling between emotional responses to music and physiological processes is evident in aesthetic experiences of 'being moved' (Menninghaus *et al.*, 2015; Zickfeld *et al.*, 2020), which are often linked to sympathetic physical phenomena such as chills ('goose bumps'), or tears when listening to sad songs (Mori and Iwanaga, 2017). Musical attributes have been found associated with physiological responses: slow tempo music was observed to correlate with decreased heart rate (HR), respiration rate (RR), and skin-conductance response (SCR) and with increased heart rate variability (HRV) (Ooishi *et al.*, 2017). In another study, tempo was found especially linked to HR (van Dyck *et al.*, 2017). Bullack *et al.* (2018) studied emotional and physiological responses to valence (happy and sad instrumental music excerpts). Participants showed increased SCR and RR during happy compared to sad excerpts, whereas HR did not vary with 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).

1.2. Embodiment of the mind in music listening

The findings just cited point to numerous psychophysiological links coming into effect during music listening. This is consistent with the approach of 4E cognition (Figure 1) or, in short, embodiment (Newen, De Bruin and Gallagher, 2018), which views the mind, thus experiences and cognition, as *E*mbodied (grounded in the body), *E*mbedded (nested in an environmental frame, such as music), *E*xtended (using external resources as tools), and *E*nactive (based on continuous sensorimotor loops). These relationships are symbolized by circular arrows because embodiment proposes reciprocal interactions (Niedenthal, 2007). Mind and body are ‘entangled’ (Noë, 2023), and Noë argues from a phenomenological perspective that especially art and aesthetics are in support of an understanding of human nature that goes beyond materialism. Correspondingly, ‘embodied’ means that the mind influences the body and, reciprocally, the body influences the mind. This reciprocity may be interpreted in a dualistic manner (Hendricks, 2024) or by referring to phenomenological enactivism and ‘radical embodiment’ (Thompson and Varela, 2001).

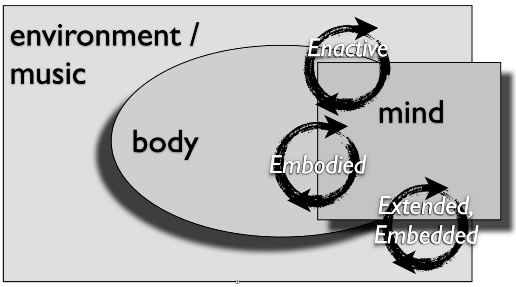

Figure 1. Schema of 4E cognition on relationships between mind, body, and environment.

1.3. Hypotheses

In general and based on the mentioned psychophysiological responses to music and the theory of 4E cognition, we expected that self-reported aesthetic experiences and emotions would be linked to the physiology measured during the segments, consistent with the notion of the embodied mind. This 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 reported above, 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 addressed such experience–physiology links at the level of pieces. We expected that the linkage would differ between the three staged pieces, from which the segments originated. 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 between experience and physiology. 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.

Finally, in the discussion section we will interpret the empirical findings in the light of 4E cognition and, more generally, of the mind–body relationship, which provides the essential background for any definition of consciousness.

2. Methods

2.1. Participants and setting

The research project 'Experimental Concert Research' has the goal of investigating concert experience with a multidisciplinary approach connecting 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 the Pierre Boulez Saal and the Radialsystem concert hall. The music presentations of the concerts, not counting the pauses, had durations between 65 and 75 minutes. 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 ensembles were string quintets with two violinists, two violists, and a cellist.

The procedures and data acquisition adhered to the principles of the Declaration of Helsinki and ethics regulations in Germany and was approved by the Ethics Council of the Max-Planck Society. The possible participation in the study was announced in local media and on the concert hall websites. Interested persons could book tickets for a concert either as a regular visitor of the concert or as a study participant. All visitors opting for participation were given information material, and those 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 44 years (SD = 17.2). 57.7% of participants were female, 41.8% male, 0.5% preferred not to say.

2.2. Musical stimuli: segments

The present analyses concern participants' responses (physiological and self-reported) to musical segments of the respective concert. The complete concert was partitioned into 96 different segments, which were defined beforehand by the investigators as meaningful phrases of the presented music. The duration of segments was on average 38 seconds (SD = 8.4, range 17–53). During each concert, musicological 'loggers' had 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 on his or her individual terminal (here, an iPad tablet), a few minutes after the concert, with audio-visual replays of eight of the segments, thus implementing a stimulated-recall procedure. The segments were presented on the tablets as short video excerpts of the ensemble who had played the concert just attended, and the participant viewed the video and listened to the music with headphones.

After each replay, the participants assessed their appreciation and experience of this specific music segment using rating scales. Three of the eight segments were pre-selected by the researchers ('index segments'), four segments were selected because of each individual participant's physiology while listening to this segment during the concert, and one segment was drawn randomly from the sample of all (minus the seven already presented) segments. Thus, the selected music segments presented three salient 'index' passages, four passages deemed noticeable because of the participant's physiological responses, and one randomly chosen passage.

2.3. Self-report measures

Standardized surveys before and after each concert were coded using an open-source software for conducting online surveys, which sent scales and questionnaires to the portable tablets of each participant using the wireless network established in the venue (Tröndle *et al.*, 2026. 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 each of the eight musical segments of the concert presented to each participant. This self-report survey consisted of 25 five-point Likert scales. The 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.

2.4. 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 2). Physiological recordings continued throughout the concert and were stopped at the end of the concert, before the stimulated-recall procedure. 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. Blood-volume pulse was captured by a photo-plethysmographic sensor placed over one finger-tip. 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 to provide phasic skin-conductance response (SCR). The cardiac measures HR and HRV and the respiratory RR are governed by both branches of the autonomous nervous system (ANS) 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 associated with resting, sleepiness, or recreation. SCR is a purely sympathetic signal, prevalent in states of stress, fear, or joy; increase of SCR reflects an increase of sympathetic activation (Birbaumer and Schmidt, 2010; Pocock, Richards and Richards, 2017). It may be noted that the ANS does not differentiate between 'good' and 'bad' arousal, thus not between joy and fear (Eerola and Vuoskoski, 2013). It is also true that the branches of the ANS are antagonistic, yet may be activated in parallel, for instance in states of positively rewarding activity such as flow experiences, where sympathetic–parasympathetic co-activation (Peifer and Tan, 2021) is found. This may be the case in a concert setting when seated safely and comfortably while being aroused by aesthetic experiences.

Figure 2. Sensors for physiological measurement. Photo: Phil Dera.

For the present analyses, each participant's mean physiological values recorded during all 96 segments, including the eight presented segments, were stored. 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 with self-report data contains 20,400 measurements (690 participants, 8 segments per participant, 4 physiological measures, minus 7.6% missing data).

2.5. Organization and infrastructure of data acquisition

Out of the available 96 segments, the eight segments presented to each 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'. After various test runs, the investigators had decided to define each participant's salient segments in relative terms, not using comparisons among all physiological data of the entire concert but only among the data of the respective movement, thus within the local context of each segment. The reason for this was not to favour segments located in the more exceptional (other) movements from the start. Correspondingly, minimum segments of HR, RR, SCR, and HRV were those four segments of each participant which showed the greatest deviation from the averages of HR, RR, SCR, and HRV within the same movement as the segment. Why detecting minima and not maxima? — this was considered equivocal, the *direction* of deviation from the average was to be regarded in the ensuing analyses.

Three 'index segments', one out of each piece, 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 a piece. In three 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 to each participant, three identical for all participants of the concert) were rated in self-report on 25 items in the stimulated-recall procedure.

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 and end times of all segments directly into the central server. Second, the physiologically salient 'minimum 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 a few minutes after the concert, before participants would arrive at the stimulated-recall section of the venue to start the post-concert survey (Figure 3).

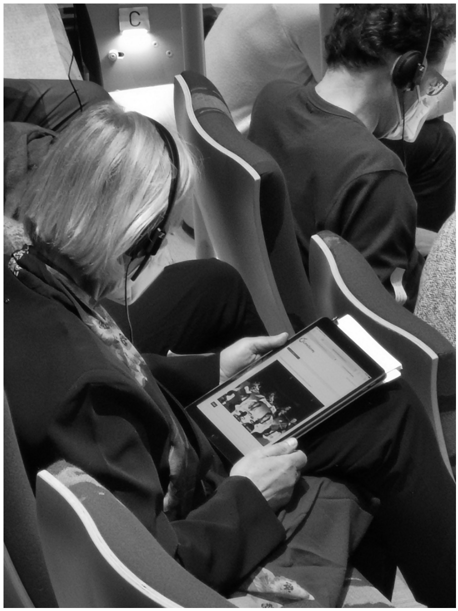

Figure 3. Filling out self-report questionnaires after the concert. Photo: Wolfgang Tschacher.

All data from the physiological recordings and the questionnaire tablets were controlled and synchronized using the central server. The seats with physiological sensors and the server were connected by a wired network because of greater reliability and speed of cabled connections. Immediately after the end of the concert, the physiological data of all participants were processed using the previously developed segment-detection algorithm. All processing steps were fully automated, and the project hardware needed approximately ten minutes to complete processing the data for all participants of a concert. Due to the time pressure, the physiological recording and online segment-detection of physiological signals required decentralized processing as the appropriate hardware architecture. Therefore, the project additionally employed 88 small single-board computers (Raspberry Pi Foundation, UK), to process the physiology recordings in parallel. These computers ran the algorithms for selecting the minimum segments of each participant.

The logger page provided the manual documentation of all 96 segments online during the concert with exact Unix time-stamps of all segments, so that physiologically salient moments could be assigned to segments immediately after the end of the concert, and the videos of all segments were integrated. A detailed description of the project methodology and computational infrastructure is provided by Tröndle and colleagues (2026).

2.6. Statistical analyses

The investigation of segments had descriptive and hypothesis-driven goals. For descriptive statistics we analysed the complete dataset of 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 using Maximum-likelihood factor analysis with Varimax rotation, which condenses the information of the 24 single items to a smaller number of uncorrelated (orthogonal) factors, which then serve as predictors for ensuing regression models. Orthogonality prevents the multicollinearity of predictors, which can bias the results of regression analyses. The test of most hypotheses employed hierarchical regression models with 'participant' as the random effect, so-called mixed-effects modelling. 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 modelling 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 with the item 'I remember this segment'.

The secondary statistical goal of the study was to describe the physiological values measured during the segments. Where appropriate, this was based on the complete dataset independent of self-report data. Exploratory study questions were which physiological differences existed between segments and the movements within the pieces.

3. Results

3.1. 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). Factor analysis was performed on segment evaluations provided 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'). All six factors are orthogonal, which means each factor describes a different and independent dimension of aesthetic experiences and aesthetic emotions.

3.2. 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 with 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 with impressing, beautiful, and physically stimulating. SCR was positively predicted by warming-relaxing and physically stimulating, whereas it was negatively linked with 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 with respect to 'F3-warming', which showed unexpected sympathetic links with SCR.

A 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.

H2 concerned the differences between pieces that may mediate the link between aesthetic experiences and physiology. In the complete dataset (*cf.* Table 8), considerable differences in physiology were found between pieces. We therefore modelled 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).

	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) predicted by aesthetic experiences. Only significant predictors are listed. *N*, number of observations. r^2, explained variance of model. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; **** $p < 0.0001$.

	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. * $p < 0.05$; ** $p < 0.01$; **** $p < 0.0001$.

	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) predicted by aesthetic assessments. Only significant predictors are listed (the SCR model received no significant prediction by assessments). *N*, number of observations. r^2, explained variance of model. * $p < 0.05$; **** $p < 0.0001$.

	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) predicted 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. * $p < 0.05$; **** $p < 0.0001$.

	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 (i.e. the 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. *N*, number of observations. r^2, explained variance of model. ** $p < .01$; **** $p < .0001$.

	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) predicted 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. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; **** $p < .0001$.

	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) predicted 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. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; **** $p < 0.0001$.

	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 the 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. * $p < 0.05$; **** $p < 0.0001$.

	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. * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; **** $p < 0.0001$.

The predictions for the Beethoven piece (which was actually movement 1 of Beethoven's work) were 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 with parasympathetic activation of HRV.

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.

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.

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 modelled 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 with HR in movement 2, but negatively with 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.

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' ($t(5958) = 39.5$, $p < 0.0001$), 'F2-beautiful' ($t(5963) = 2.65$, $p < 0.01$) and 'F6-physical' ($t(5913) = 13.3$, $p < 0.0001$), 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.

3.3. Descriptive and exploratory 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). The first exploratory question 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 modelling 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).

Table 9 describes the differences of segment physiology by movement related to the second exploratory question. 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: $r(10) = 0.82$, $p < 0.01$.

4. Discussion

4.1. Discussion of the empirical findings

Concerning the primary hypothesis of the study ('aesthetic experiences linked with physiology'), multiple associations between factors of aesthetic experience and physiological measures were detected in our large sample of almost 700 participants who altogether provided between 4,400 and 5,300 single ratings on music segments. The majority of these associations were in accordance with expectations: music segments experienced as 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 also by increased SCR. When, in a post-hoc analysis, self-reported valence, that is affectively positive experience, was used as a further predictor of the four physiological signals, all models were significant and consistent with the hypothesis of higher valence linked with increased sympathetic arousal and attenuated HRV. Thus, there was a general tendency for beauty and positive valence to have an exciting effect on audience members.

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, and to 'melancholic' with parasympathetic, activation 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 analysed (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 (higher HRV) in movement Dean-3, but sympathetic activation of RR and SCR in movement Dean-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 of all 96 segments. This dataset showed that sympathetic responses to the Dean piece were significantly smaller than to the Brahms and Beethoven pieces almost throughout. This means that in general the contemporary music was met with less bodily 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 saw a wealth of associations between physiology and self-rated experience, memory, emotion, and cognition — these mental aspects concerning musical presentations were clearly found embodied in physiology, mirroring findings in other art-related contexts such as the fine-art museum (Tschacher and 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 have been 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. Secondly, the data were recorded reflecting the naturalistic environments and affordances of public concerts, which generated a context of high ecological validity. We were studying the embodied mind 'in the wild' instead of in the laboratory (Høffding, Hansen and Jensenius, 2024). 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 recordings of the segment that this participant had viewed and heard undisturbed just before in the concert, a further point emphasizing the validity of the dataset.

Conducting research with higher degrees of ecological validity has been an ambition for a while. We believe that the present methodological framework comes close to this goal in several respects. It may be assumed that addressing live music, in other words the frame of a concert, is preferable to studying music listeners in the lab (Swarbrick *et al.*, 2019; Wald-Fuhrmann *et al.*, 2021). Smaller differences of aesthetic experiences are found between live and live-streamed concerts (Swarbrick and Vuoskoski, 2023; Kreuzer *et al.*, 2023). Technological progress has created increasingly less obtrusive tools for measuring even complex physiological and behavioural variables. The present study used wearables, thus still depends on fixing sensors for reliable and rather artefact-free measurement; a small control group of participants without sensors, which was included in the context of this research project, showed that aesthetic concert experience was not compromised or biased by these physiological measurements (Tröndle *et al.*, in review). A further point supporting ecological validity is that behavioural measures such as body movement are attainable by video-based motion capture (Tschacher *et al.*, 2023), which is entirely sensor-free, or by accelerometer measures, such as in smartphones (Swarbrick *et al.*, 2024). Even emotional facial expression can be detected by automated facial analysis based on high-resolution video recordings (Weth, Raab and Carbon, 2015).

At the same time, we also became aware of limitations of the present study. Repeated statistical analyses were performed using 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, as the contemporary music was generally estimated less 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, the latter generating shared predictors and models that are easily comparable across pieces. Here we decided for this latter option.

The second issue is that the present results may have been influenced by unrecognized confounders. 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 post-hoc analysis reported above has already shown that especially SCR was correlated to the varying musical tempo of movements.

4.2. Implications for the mind–body debate

The empirical findings were in support of the general expectation that music listening is embodied, leading to the ensuing questions of '4E cognition': how may we conceive of the relationships within the complex system of mind, body, and music? How are *mental* states and processes involved when listening to specific passages of music, thus *physical* stimuli? Which relationships exist between enactive listening and audio features of music segments?

The present study has shown beyond reasonable statistical doubt that *mind* (aesthetic experience, emotions, valence) and *body* (sympathetic and parasympathetic activity) were linked when both were embedded in a *musical* context. Based on the terminology of Figure 1, this speaks for the 'embodied' aspect of the mind–body–music system because experiences and physiology were significantly associated. Findings also speak for the 'enactive' aspect as the attributes of the music stimuli (the composer, the tempo) were found to modulate these mind–body associations.

The reciprocity of the 4E relationships, depicted in Figure 1 by circular arrows, was not directly studied by the present project, as it did not experimentally modify experiences and aesthetic emotions (the mind) to show how this would alter physiology (the body). The present analyses only emphasize that the musical segments used as stimuli influenced both mind and body. Other empirical work on music, however, has suggested for instance that natural variations of listeners' personality traits and affective states have a significant effect on their physiological responses to music (Tschacher *et al.*, 2024). Reciprocity is a topical result of much embodiment research in general psychology. For example, it is well known that depressed mood is expressed by how people move and by their gait patterns; in reverse, experiments showed that changing gait patterns changed aspects of their mood (Michalak, Rohde and Troje, 2015). Many empirical findings suggest that mind–body relationships are generally, including the musical context, very likely bidirectional. Viewed from the embodiment perspective, listening to music is not a passive reception but rather an active (*en*active) engagement with the music (Martin and Nielsen, 2024).

Which of the various notions in the science of consciousness would be consistent with the conceptualization of 4E cognition and the present empirical results? Chalmers (2002), contemplating the place of consciousness in nature, distinguished six different conceptions of the relations between phenomenal experience (consciousness, mind) and physical facts (the body, physical nature): three types of materialism (type-A to type-C), two of dualism (type-D, type-E), and type-F monism. The three materialisms are reductive views that deny mind or consciousness an ontological status, ranging from eliminatory materialism (type-A) to views of 'mind' denoting merely functional and/or representational states or behavioural tendencies of basically material systems. It is quite obvious that any of these reductive materialisms would be at odds with the perspective of embodied cognition: materialism assumes no ontic existence of mind, thus studying the embedding of mind in the body and the physical world would be meaningless in the first place. All physiology–experience links would amount to illusory correlations between different measures of one identical (material) entity. An enactivist view (e.g. Hobson and Friston, 2014) would likewise be untenable in the materialist view, as materialism reduces mental states (such as probabilistic beliefs or qualia) to neural states plus statistics — no room left for an agent's active inference. This would equally hold for enactivist approaches to music therapy (Høffding, Snekkestad and Stige, 2024).

If, following Chalmers' conceptions, we continue towards dualism such as Descartes' (type-D) substance dualism (Hendricks, 2024), it can be readily seen that the approach of 4E cognition concurs with type-D dualism. Mind–matter interactions constitute the core of the four 'E's, and empirical findings substantiating such interactions and their reciprocity would mean valuable knowledge about the mind and its place in nature. Unfortunately (for 4E cognition), substance dualism is being considerably criticized by contemporary philosophers of mind owing to the problems entailed by mind–matter interactions. The causal closure of physics is predominantly considered to be at stake should mental processes be allowed to influence physical processes.

To avoid this problem, type-E dualism represents an epiphenomenal variant of dualism, in which the mind does not act back on its material substrate (Mathieson, 2024). The mind merely 'supervenes' on the body. Yet given this epiphenomenal conception, all the circular causations implied by Figure 1 would have to be substituted by linear causations: 'embodied' would then mean that the body and physiological processes have an impact on the mind, yet there are no reverse impacts. 'Enactive' would be replaced by a sequence of music–body and body–mind causalities. Taken together, the consequences of accepting type-E dualism would likewise be considerable, and destructive, for the theory of 4E cognition and for empirical research on psychological embodiment.

A further type of dualism not discussed by Chalmers is the notion of strong emergence. Mind may be viewed as emerging from the physical complexity of the brain. The interdisciplinary theory of Synergetics (Haken, 1996) describes the self-organized formation of stable patterns, which have novel properties that clearly differ from the properties of the components. Synergetics additionally postulates reciprocal influences between these emergent patterns and the underlying components, thus a kind of circular causality (Haken and Tschacher, 2010) that would allow for mental causation, other than type-E dualism.

Type-F monism is the dual-aspect theory that conceptualizes mind and matter as two complementary epistemic accesses to a single underlying ontic reality, which is neutral with respect to mind and matter (Atmanspacher, 2012). One implication of this monism is panpsychism: all objects (even those we may conceive of as rocks, for instance) should then possess mental or proto-mental properties. Applied to 4E cognition, all the empirically accessible 'E's would consequently become acausal correlations, much as correlations between the flipsides of the same monistic coin. A further implication of dual-aspect monism is that there is no field of science outside philosophy that is currently addressing, or has found access to, the assumed neutral reality of type-F monism. In the light of neutral monism, physics and psychology by definition merely address aspects but never ontologically real entities.

In conclusion, the mind–body–music interactions, which are at the core of an embodiment-informed perspective of music listening and music making, do mesh well with only two mind–matter conceptions, namely with type-D dualism and with the notion of strong emergence as sketched by Synergetics. Both conceptions, like all conceptions in the mind–body debate, have their own critical points and weaknesses. Not unexpectedly, the 'hard problem' of the philosophy of mind (Chalmers, 1995; 2002) has reverberations also in music psychology, if not in psychology in its entirety.

Yet at the same time, the clear findings concerning the physiological embodiment of music point to the health-related potential of music. Many mental disorders are characterized by physiological disbalances, which strongly endorses the practice of music also as a therapeutic medium in neurology and psychiatry (Raglio *et al.*, 2015; Yap *et al.*, 2022). The embodiment perspective also generates new research questions for the study of music. The enactive involvement in musical stimuli is not only a (passive) responding to music but also an active, anticipatory activity, much as the concepts of retention and protention in Husserl's phenomenological philosophy. An empirical analysis of protention is feasible by studying the synchronization of bodily rhythms with time series of musical properties, using available statistical tools such as surrogate synchrony (Tschacher, 2023). Such analyses will allow distinguishing the responsive (retentive) from the anticipatory (protentive, enactive) components of a listener's engagement with music, and thus have the potential to illuminate enactivist assumptions by empirical research.

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