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Microsaccade-rate indicates absorption by music listening

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ABSTRACT

The power of music is a literary topos, which can be attributed to intense and personally significant experiences, one of them being the state of absorption. Such phenomenal states are difficult to grasp objectively. We investigated the state of musical absorption by using eye tracking. We utilized a load related definition of state absorption: multimodal resources are committed to create a unified representation of music. Resource allocation was measured indirectly by microsaccade rate, known to indicate cognitive processing load. We showed in Exp. 1 that microsaccade rate also indicates state absorption. Hence, there is cross-modal coupling between an auditory aesthetic experience and fixational eye movements. When removing the fixational stimulus in Exp. 2, saccades are no longer generated upon visual input and the cross-modal coupling disappeared. Results are interpreted in favor of the load hypothesis of microsaccade rate and against the assumption of general slowing by state absorption.

1. Introduction

1.1. Trait and state absorption

"… music with its movements penetrates the arcanum of all the movements of the soul. Therefore, it captivates the consciousness which (…) is carried away itself by the ever-flowing stream of sounds." Hegel, 1835-38/1975, p. 906 In Georg Friedrich Hegel's lectures on aesthetics this state of deep involvement with music listening is discussed as a key component of an aesthetic experience. And Hegel does not stand alone with this view. From the antique myths on Orpheus to current listening practices, being drawn into the music had almost always been regarded as a sought-for form of musical experience (Scruton, 1997). However, being deeply involved can be related to many different stimuli and activities. In the domain of psychology, several constructs have been conceptualized to examine these states (e.g., Agarwal & Karahanna, 2000). One of the most prominent constructs is absorption as a state and trait (Tellegen, 1981; Tellegen & Atkinson, 1974). Whereas elaborated questionnaires have been developed to measure trait absorption (Jamieson, 2005; Tellegen & Atkinson, 1974), there has been less emphasis to advance measures for state absorption. The goal of our project was to find a quantitative way to reveal state absorption in the context of music listening by using eye tracking.

Substantial work on trait as well as state absorption came from Auke Tellegen, including a commonly used questionnaire on trait absorption: the Tellegen Absorption Scale (Tellegen & Atkinson, 1974). Trait absorption as a construct gained in importance with its relation to other traits like imaginative involvement (Hilgard, 1979) and openness to experience (e.g., Glisky, Tataryn, Tobias, Kihlstrom, & McConkey, 1991; McCrae, 1993), the latter being one out of five dimensions of personality (*The Big Five*; Costa & McCrae, 1985, 1992). The construct of state absorption pioneered models that depict states of deep mental involvement, such

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as presence, immersion, flow or cognitive absorption (Agarwal & Karahanna, 2000). Those mental states are directed to virtual reality (e.g. Lombard & Ditton, 1997; Minsky, 1980), physical activities (e.g., Csikszentmihalyi, 1990), or activities regarding information technologies such as computer programs (e.g., Agarwal & Karahanna, 2000).

Trait and state absorption have also been demonstrated to relate to hypnotizability or hypnotic states (Tellegen & Atkinson, 1974; see Roche & McConkey, 1990 for a review). This relation points to the fact that absorption belongs to the family of altered states of consciousness. In fact, state absorption as a phase of absent self-awareness has been suggested to cover one of four dimensions to categorize the variety of altered states of consciousness (Vaitl et al., 2005). Interestingly, a biological marker has been discovered for absorption as personality trait within the dopaminergic neurotransmitter system, affecting a receptor that is also related to drug consumption like LSD (Ott, Reuter, Hennig, & Vaitl, 2005).

1.2. *Music listening experience and trait as well as state absorption*

In the last years, a series of compendiums addressed the topic of intense music listening experiences. Those publications stressed music as a stimulus that moves us in a particular way (Bicknell, 2009), evokes strong experiences (Gabrielsson, 2011), is related to emotions in a powerful manner (Huron, 2006; Juslin & Sloboda, 2001), induces altered states of consciousness (Aldridge & Fachner, 2006), and promotes specific psychological states like absorption, dissociation and trancing (Herbert, 2011a). However, the term *absorption* within the context of intense music listening experiences is rather underrepresented (Herbert, 2011 b). Likewise, quantitative research on music and absorption is sparse. Trait absorption correlates with felt pleasure during music listening episodes (Rhodes, David, & Combs, 1988). It increases the intensity of music-induced emotions and specifically felt sadness (Kreutz, Ott, Teichmann, Osawa, & Vaitl, 2007), and correlates with the preference to listen to sad music (Garrido & Schubert, 2011). State absorption by music increases reaction time to an unrelated auditory signal (Snodgrass & Lynn, 1989). The intensity of absorption states is related to the ability of being hypnotizable, with high hypnotizable persons gained stronger absorption levels during music listening (Snodgrass & Lynn, 1989). Self-reported absorption levels induced by classical music were higher for persons favoring classical music (Snodgrass & Lynn, 1989), indicating that musical preferences play a major role for induction of musical absorption. However, there is also indirect evidence on musical absorption: Schäfer, Fachner, and Smukalla (2013) reviewed a multitude of empirical evidence showing changes in time and space perception by music listening. Results were interpreted in favor of state absorption or altered states of consciousness. Interestingly, trait absorption and the intensity of state absorption by music listening not necessarily correlate (Herbert, 2011 b).

1.3. *Absorption and attentional capacity*

One aspect of the construct absorption appears in both aspects, state and trait, and is also important in the related constructs of immersion, flow and cognitive absorption: This is the role of attention. State absorption has been defined as a “state of ‘total attention’ during which the available representational apparatus seems to be entirely dedicated to experiencing and modeling the attentional object” (Tellegen & Atkinson, 1974, p. 274). This kind of attention involves “a full commitment of available perceptual, motoric, imaginative and ideational resources to a unified representation of the attentional object” (p. 274). Trait absorption is then the “ability to operate diverse representational modalities synergistically so that a full but unified experience is realized” (p. 275) and can be “interpreted as a capacity for absorbed and self-altering attention” (p. 276).

This capacity definition allows us to interpret the construct absorption within working memory theories. Working memory is a system to encode, maintain, and retrieve information. It coordinates processing and storage of information (e.g., Baddeley, 2000). Attention is an integral part of working memory (e.g., Engle, 2002), serving as a capacity that limits ongoing processing, e.g. as a resource and/or bottleneck (e.g., Cowan, 1995). Working memory models diverge slightly on how attention is implemented. In an early working memory model attention served as a supervisory system that controls ongoing processing in modality-specific sub systems (Baddeley, 2000; Baddeley & Hitch, 1974). Later models assume a focus of attention that can be voluntarily directed to relevant information and is strongly related to keeping representations in an active state (e.g., Cowan, 1995, 2005; Oberauer, 2010). In one line of research working memory capacity is equated with controlled attention (Engle, 2002; Kane, Bleckley, Conway, & Engle, 2001). Importantly, models converge on the fundamental function of attention for ongoing information processing.

Note that state absorption is not identical with object processing in working memory. For instance, state absorption is characterized by an altered sense of reality (Tellegen & Atkinson, 1974, p. 274). It is experienced as thoroughly pleasurable or satisfying, and is investigated here in an aesthetic context.

There are several possibilities to measure processing load in performance tasks. Quantifying cognitive load (e.g. in terms of processing steps per time as in Barrouillet, Bernardin, & Camos, 2004) for musical processing a priori appears difficult in the context of music processing, as load depends on chunk size. Individual chunking abilities decidedly depend on listener’s hearing experiences and familiarity with the music. Hence, we discarded the idea of a direct manipulation. We selected microsaccade rate as an indirect measure for two reasons: First, microsaccades are linked to (spatial) attention and cognitive load. Second, only recently researchers demonstrated cognitive load effects independent from the visual input of a task (Gao, Yan, & Sun, 2015; Siegenthaler et al., 2014; see also Dalmaso, Castelli, Scatturin, & Galfano, 2017, for a related account). We planned to contribute to this line of research by replicating cross-modal interactions and extending effects of microsaccade rates to the music domain. One study showed increased fixation durations, when music accompanied film or scene perception (Schäfer & Fachner, 2014), encouraging us to study cross-modal coupling in the context of intense music listening.

1.4. Eye-tracking, attention and cognitive load

In normal viewing conditions our gaze can be characterized as a sequence of fixations and saccades. During fixations, we have the subjective experience that our eyes are rather stable. Our experience only partly resembles what we know from measuring eye movements. Eyes are never completely still, but are constantly moving. These fixational movements show three characteristic components: Drift, tremor and microsaccades (see Rucci & Poletti, 2015, for a review). Drift is a rather slow motion carrying the retinal image across only moderate distances. Tremor is a movement of high frequency that is superimposed on the meandering drift movement. Microsaccades are eye movements of high velocity, resembling the goal-directed eye-movements of intentional saccades, but are executed without awareness. In fact, saccades and microsaccades follow the same main sequence, a parametric relation between amplitude and velocity (Zuber, Stark, & Cook, 1965). This strongly suggests that microsaccades and saccades share a common generator. There is further neural (Hafed, 2011) and behavioral evidence (Otero-Millan, Troncoso, Macknik, Serrano-Pedraza, & Martinez-Conde, 2008) to support this conclusion, but functional differences have been demonstrated as well (Sinn & Engbert, 2016).

Importantly, microsaccades are related to two constructs substantial to our investigation: (1) (spatial) attention as well as (2) cognitive processing load. First, microsaccades index the direction of spatial attention shifts in visual cuing paradigms (Engbert & Kliegl, 2003; Hafed & Clark, 2002; Laubrock, Engbert, & Kliegl, 2005; Pastukhov & Braun, 2010; but see Horowitz, Fine, Fencsik, Yurgenson, & Wolfe, 2007) and the mode of focusing versus dispersing attention spatially (Pastukhov & Braun, 2010). The effect of an attention shift has also been demonstrated in the auditory modality, indicating cross-modal coupling of the senses (Rolfs, Engbert, & Kliegl, 2005).

Second, several studies showed a decrease of microsaccade rate by cognitive load. Two of them manipulated cognitive load independently of the visual features of the task. Siegenthaler et al. (2014) measured fixational eye movements during mental arithmetic, showing that task difficulty dampened microsaccade rate. In their study, they compared difficult subtraction and easy mathematical addition. Gao et al. (2015) replicated the inhibiting effect of arithmetic processing on microsaccade rate in a refined design. Microsaccade inhibition was particularly pronounced during the calculation phase and inhibition was released just after the verbal response.

Effects of load are accompanied by studies showing specific cognitive processes to be related to microsaccades. For instance, microsaccade rate is linked to deviant detection in the visual (Valsecchi, Betta, & Turatto, 2007) as well as auditory oddball task (Valsecchi & Turatto, 2009). The effect occurred only if deviants had to be counted and not in a passive perception condition, indicating that the reduced microsaccade rate might be related to memory updating (e.g., counting) rather than to attentional distraction alone. In addition, in the pro- and antisaccade task microsaccades were suppressed during the preparatory interval before stimulus onset (Watanabe, Matsuo, Zha, Munoz, & Kobayashi, 2013). The decrease was more pronounced in the antisaccade task, which requires inhibition of a reflexive saccade and programming of a voluntary saccade and therefore needs more cognitive control (Unsworth, Schrock, & Engle, 2004). Microsaccade rate is also related to manual response preparation in a simple reaction time task. If a response is required in comparison to the no-response control, microsaccade rate decreases (Betta & Turatto, 2006). In two experiments microsaccade rate was related to memory encoding (Dalmaso et al., 2017). Participants had to remember the color (one out of two possibilities) or the content of a five-digit string. When the to-be-encoded visual stimulus disappeared, microsaccade rates dropped followed by a rebound effect and a return to baseline afterwards. This signature is typical for display changes. Importantly, the rebound effect was more pronounced for digit encoding in comparison to color encoding. A second experiment compared encoding of a two- versus five-digit string. Again, the rebound was higher for the longer digit string, indicating that task difficulty was linked to the oculomotor system. Together, these studies indicate that microsaccade rate is related to working memory processes such as memory updating, inhibition and cognitive control, as well as to different memory encoding processes.

1.5. The present account: Eye tracking accompanied by musical feature extraction

We applied eye tracking during music listening. We selected musical excerpts from a variety of styles. Participants listened to those excerpts. Their task was to immerse themselves into the music and rate their absorption level afterwards. The variety of musical styles should increase variance of absorption levels within participants. We then used microsaccade rate as predictor for absorption states applying linear mixed effect models.

Using eye tracking allows us to collect pupil and blinking data as well. At first sight those variables might complement microsaccade rates. The pattern of pupil dilation correlates with task difficulty (Kahneman & Beatty, 1966), music induced arousal (Gingras, Marin, Puig-Waldmüller, & Fitch, 2015), and attentive musical listening (Kang & Wheatley, 2015). Blink rate is often modulated but not reliably decreased by load (Goldstein, Bauer, & Stern, 1992). However, in the context of our study predictions on blinking activity are difficult. Blinking activity distorts the fixation episode and microsaccade measurements. We asked participants to avoid blinking, making predictions about spontaneous blinking activity problematic. If anything, an increase of pupil dilation and a decrease of blinking activity might indicate absorption via processing load.

However, microsaccade rate might be related to some basic music features in a simple way. For instance, acoustic startle by loud noise affects eye reactions and the motor system (Davis, 1948). Then, musical irregularities or mean differences in sound intensity might affect eye reactions and the motor system as well. We decided to include some musical features in our analysis in addition to eye parameters. We planned measurements of the sound intensity (root mean square, RMS, of amplitude), brightness or spectrum (spectral centroid and contrast density in different frequency bands), tempo (beat-per-minute, annotated by hand), and number musical irregularities (novelty index). We decided on a small selection of features for several reasons: First, a huge variety of musical features is available for extraction but many features are highly correlated. Correlations between predictors make them less interpretable. In fact, we had to reduce our list further because of high correlations (see Method part). Second, linear mixed models are sensitive to Type I errors. Hence, we deliberately kept the number of predictors to a minimum of carefully selected features. Third, it has been demonstrated that a low number of features, e.g. four, can already predict the perception of emotional expression in music pretty well (Saari, Eerola, & Lartillot, 2011), indicating that an increased number of extracted feature not always improves results in music perception. The final list in our study included RMS of amplitude (energy), spectral centroid (brightness), and novelty.

To sum, microsaccades are related to cognitive resource allocation. A decrease in microsaccade rate indicates cognitive load. In our studies, we applied eye tracking during music listening. State absorption has been defined as object processing. We measured state absorption by subjective ratings and processing load indirectly by microsaccade rate. We then aimed to predict absorption ratings by microsaccade rate. We added measures of pupil dilation and blinking activity as a complement. To differentiate absorption from other states, we also included subjective ratings on felt valence, arousal, liking and familiarity. In addition, we extracted some key musical characteristics for each musical piece and explored whether those musical features would contribute to the models additively to the eye measures.

2. Method Experiment 1

2.1. Participants

Thirty-one participants were tested. Their age ranged between 20 and 30 (M = 24). Sixteen of them had normal, 15 corrected to normal vision. Twenty-two were female. Twenty-seven were students from a diverse range of departments from Goethe University Frankfurt. None were professional musicians. None of them reported hearing problems. They took part in exchange of 10 Euro per hour.

2.2. Apparatus

Data collection took place in a sound attenuated booth, equipped with a 24-inch Monitor (resolution 1920 × 1080, refresh rate 144 Hz), eye tracker (Eye Link 1000 from SR Research), and Neumann KH 120 A G loud speakers. Data were recorded binocularly with a sample rate of 500 Hz. A chin- and head-rest supported the head of the participants. The experiment was programmed using Psychopy (1.82.01) on a Windows PC.

2.3. Materials

2.3.1. Music selection and editing

We composed a stimulus pool of high diversity, both of musical style (blues, country, hip hop/rap, classical music, jazz, metal, pop, reggae, rock, soul, traditional German Folk, world music) and emotional connotation (spanning the two-dimensional arousal (high/low) - valence (positive/negative) space). We decided on instrumental music to avoid any confounding effect of language processing. As control, we included 14 trials in silence whereat no music was exposed.

A trained sound engineer created the stimuli by editing and processing the audio files using the AVID PRO TOOLS 10 digital audio workstation. We chose excerpts of 43–61 s. length (M = 52 s.) that represented the character of piece as a whole. Silence trials lasted 60 s. We took particularly care to make the listening experience smooth throughout the experiment by mainly three moves: (i) We created excerpts based on the musical phrases. (ii) Whenever harmonically possible, we edited the original ending of a song/piece as ending for the stimulus. (iii) If the original had a fade out, we created an artificial ending by processing the end of the musical phrase with a reverb effect, a technique commonly employed for radio with the goal to “soften” the ending and avoid disruption of musical absorption. After the editing process, the stimuli were exported as digital files in wave format with a sampling rate of 44.100 Hz and a depth of 16 Bit. To adjust strong differences in loudness, we applied the normalization algorithm EBU R128 onto the wave files (Belkner, r128gain.sourceforge.net; 17.02.2015). Subsequently, some excerpts had to be amplified by +/−3 to 5 dB again, to keep the character of the music. For instance, a soft piano piece would sound unnaturally loud when adjusted to the same loudness level than metal music. See Table A1 in the Appendix A for a list of musical pieces from which the excerpts were taken.

2.3.2. Self-assessment/questionnaires

The listening experience of each excerpt was rated on five dimensions as soon as the music ended: Felt absorption (“I was entirely involved in the music”), felt valence and felt arousal (Self-Assessment Manikin, Bradley & Lang, 1994), felt liking (“I liked the music”), and familiarity (“I knew this music very well”). All ratings were collected using a 7-point Likert Scale (1 = *fully disagree* and 7 = *fully agree*).

In addition, we collected some data on individual music preferences (14 musical styles), on a range of psychological functions music can fulfill (eight functions, e.g., social identity, mood regulation, etc.) as well as trait absorption (German version of the Tellegen Absorption Scale, Ritz & Dahme, 1995). None of these ratings contributed to ratings of state absorption.

2.4. Procedure

The experiment took part in two sessions, with 35 trials in each session composed of 28 trials with music and seven in silence.

Each session took about 90 min. Trials were arranged in seven blocks. Each block contained one silent trial and one trial from each of the four quadrants of the pre-assigned valence-arousal-space. Moreover, assignment of musical pieces to blocks was randomized.

Participants were seated in a sound attenuated booth. A 9-point calibration procedure was applied to adjust the camera of the eye tracker. Instructions were written and asked participants to immerse themselves into the music as best as possible, while making clear that we expect this not always to be the case. Participants were asked to reduce blinking to a minimum during the trials. They adjusted their preferred volume of the loudspeakers using three music examples, generated in an analogue way than the experimental excerpts. Each trial started self-paced by pressing the space bar, upon which a black dot (radius: 0.15°) appeared centrally on the gray screen. Participants were asked to fixate this dot throughout the trial. In the first 1200 ms a fixation check routine ensured that calibration was still sufficient (deviations from the dot center had to be $< 1°$). Upon successful fixation check the music or the silent period started. When finished, evaluation of the listening experience followed by five ratings. Upon key press the next trial started. The calibration procedure was repeated at about every fifth trial.

2.5. Data treatment

2.5.1. Missing recordings

Due to technical failure and outlier measures (e.g. when the distribution showed extra-ordinary fixation durations) we rejected 85 trials (3.92%). For the remaining data, a sophisticated treatment of the blink periods and recording loss was applied to analyze pupil dilation as well as microsaccade rate. We defined gaze loss by the following criteria: (i) missing pupil data from one or both eyes, (ii) strong fluctuations of pupil area (> 20 units per sample), (iii) gaze position out of screen. In addition, we included two samples before and after gaze loss periods into the loss interval, because the measurement would not be reliable at the edges of the loss period. Data with monocular blinks were regressed onto each other. Binocular blinks were interpolated with a cubic spline using 10 samples before and after the blinking period. For the cubic spline, we set the data to "not-a-number", when eyes were closed for longer than 500 ms. We then applied a low pass filter of 12 Hz.

2.5.2. Saccadic eye movements

We first detected saccadic movements by the velocity-threshold method of Engbert and Mergenthaler (2006). We defined saccadic movements as valid, when they occurred binocularly (at least one sample overlap). In addition, we rechecked after this procedure that detection of the movement was indeed a saccade and not a blink. This resulted in 140,181 saccadic movements with a mean rate of 1.23/s. ($SD = 0.60$) and a median amplitude of 0.51° viewing angle ($SD = 0.22$). The majority of saccadic movements, 95.29%, had an amplitude smaller than 1.5° viewing angle and might qualify as microsaccades using a very liberal criterion (Martinez-Conde, Macknik, Troncoso, & Hubel, 2009). However, the amplitude of saccadic movements showed a unimodal distribution (Lambda = 6 for saccade detection) and did not separate microsaccades from saccades. Hence, we decided to leave all saccades independent from their amplitude in the data set for further analysis. For simplicity, we will continue to use the term microsaccades for all saccadic movements in Exp. 1. Fig. 1 shows the main sequence and distributions of the raw data.

2.5.3. Pupil dilation

The Eye Link 1000 measures pupil size only arbitrary. Therefore, we calculated mean pupil area during the fixation period (800 ms) and the deviation from this baseline during the trial (up to 60 s.). To de-confound pupil measure from measurement noise due to eye movements, we set pupil measures to "not-a-number" for the time period of saccades and microsaccades. The distribution of mean pupil deviation was normally distributed with a mean of 0.91% ($SD = 0.14$).

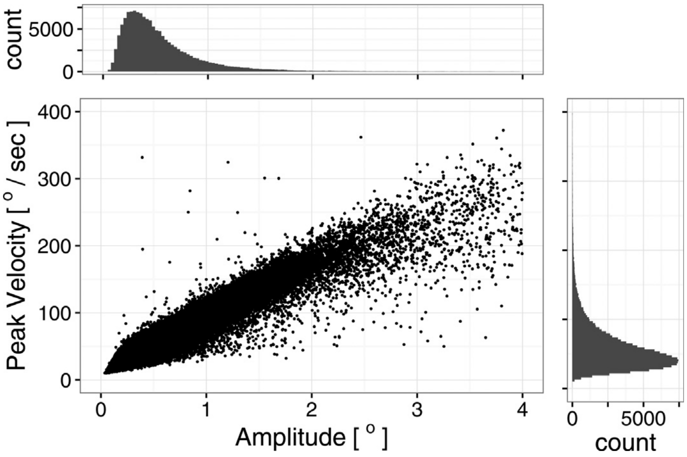

Fig. 1. The main sequence depicting the relation of amplitude and peak velocity for saccades with an amplitude $< 4°$ and peak velocities $< 400°/s$ and the related histograms.

2.5.4. Blink rate

A blink was detected when at least one sample of identified gaze loss periods overlapped in both eyes. After outlier analysis trials showed 7638 blinks, which resulted in a median blink rate of 0.05/s. ($SD = 0.07$). In 21.25% of the trials participants did not blink at all.

2.6. Music feature analysis

For music feature extraction, we applied the *MIR toolbox*, Version 1.6.1 (Lartillot & Toiviainen, 2007), to calculate energy (root mean square, RMS, of amplitude), brightness (spectral centroid), and contrast density in different frequency bands (flux subbands), using a frame length of 25 ms, half overlapping (e.g. Alluri & Toiviainen, 2010). We calculated the mean value for each excerpt, glossing over dynamic changes within the music. This static analysis is a simplification, which is justified by the fact that static means are often sufficient representatives for more fine-grained dynamic changes (Alluri & Toiviainen, 2010). To capture at least one high-level feature, we implemented a novelty index that represents the number of less predictable events like unexpected pitches in the melody or a delayed entry of an instrument. Novelty extraction is particularly sensitive for different choices of parameters. Here, we decided to apply different frame lengths (25–80 ms), kernel sizes (200–250), and thresholds for peak picking (between 0.1 and 0.7). Choices were verified by auditory analysis, which was done by one musically trained expert, who compared the audio file with a visualization of the analysis. The resulting number of peaks was related onto the duration of the musical excerpt. In addition to automatized feature extraction one trained expert annotated musical tempo. High correlations between flux subbands and other measures, e.g. spectral centroid, as well as between tempo and brightness, lead to exclusion of flux features and tempo from the analyses. This left us with the following features: Energy (RMS of amplitude), brightness (spectral centroid), and the novelty index.

2.7. Data analysis

We applied linear mixed-effects models, calculated with the lme4 package for R. We generally chose $t > 2$ as criteria for significance of the fixed effects (e.g., Baayen, Davidson, & Bates, 2008) and calculated p-values by including the Satterthwaite approximation from the package *lmerTest*. On the physiological level, we considered microsaccade rate, pupil dilation and blink rate, on the musical feature level energy, brightness, and novelty as predictors. We decided on linear mixed models as we expected trial numbers for different absorption intensities to vary across participants and music excerpts.

The analysis section splits in two main sections. We will first analyze the effect of music presence (comparing trials with and without music) and the effect of musical features on eye parameter. Music presence was factorized within the model using a treatment contrast. Blink rate could not be fitted with the linear model (as well as a general linear model with the gamma family), because the distribution was extremely right skewed with too many zero blink rates, resulting in non-normally distributed residuals. That is, in this first section we fitted models regarding microsaccade rate and pupil dilation only.

In the second section, we focus on the main question of this study and relate eye parameters as well as musical features to subjective states. Our goal was to find five linear mixed models to predict each of the subjective ratings absorption, valence, arousal,

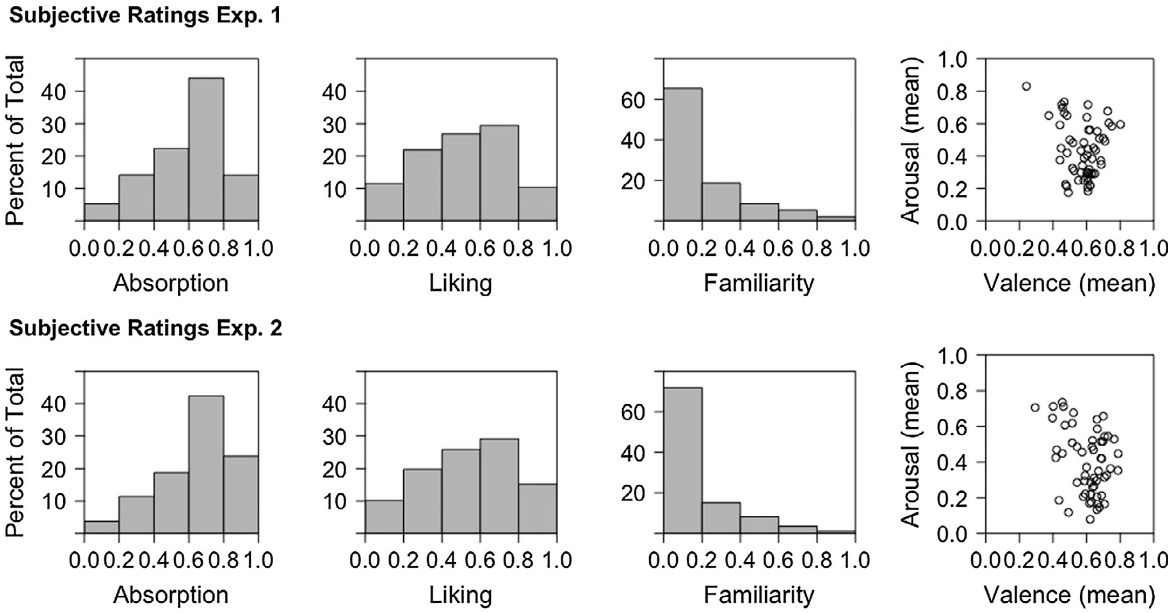

Fig. 2. Distributions of subjective ratings of absorption, liking and familiarity, as well as mean valence-by-arousal ratings for the 56 musical excerpts for Exp. 1 and 2, showing overall high similarity between experiments and a differentiation within experiment.

liking, familiarity (see Fig. 2) by a combination of microsaccade rate, pupil dilation, blink rate, and the musical features energy, brightness, novelty. As the music was mainly unfamiliar to the participants ($M = 0.60$, $SD = 0.99$), a serious regression model was not sensible, so we excluded familiarity from all analyses. This leaves us with the goal to find four regression models.

One sophisticated procedure of model fitting is to start with a maximal model, including all fixed effects as well as all random slopes (Barr, Levy, Scheepers, & Tily, 2013). However, we did not succeed in fitting the full models in Exp. 1. Hence, we decided for the following multi-step procedure (i) include all predictors as fixed effects with a random intercept for participants and songs; (ii) include a random slope for participants for each predictor separately and check whether the goodness of fit increases in comparison to the model result of (i). For model comparisons we applied likelihood ratio tests; (iii) combine significant random slopes from (ii) as long as they increase the goodness of fit; (iv) delete fixed effects with t values below $t < 1.5$; (v) check whether fixed effects with $t \geq 1.5$ improve the model fit; (vi) check whether correlations between effects can be forced to zero (which was never the case); (vii) check whether the model was over-parameterized (using the *rePCA* function in the *RePsychLing* package, which is analogue to a principal component analysis of the random effects, see Bates, Kliegl, Vasishth, & Baayen, 2015). This was the case for the arousal model. But a reduction of the number of random slopes solved this problem.

3. Results of Experiment 1

3.1. Effect of music or musical features on eye parameter

In a first step, we checked for effects of music in general on our physical markers. We fitted two linear models, predicting microsaccade rate or pupil dilation by the fact that music was present or not. The models included random intercepts and slopes for participants. The fixed effect of music presence was not significant in the microsaccade model, demonstrating that music had no general effect on microsaccade rate, $t = -1.09$, $p > 0.05$. But the fixed effect was significant in the pupil model, $t = 4.62$, $p < 0.0001$. Pupils dilated with music from 0.88 to 0.92%, which corresponds to an increase of pupil dilation by 4.55%.

Next, we considered trials with music only and built again two linear mixed models predicting either microsaccade rate or pupil dilation by a combination of the musical features energy, brightness, novelty, with random intercepts and slopes of participants and random intercepts for musical pieces. However, random slopes did not contribute to the models. For the microsaccade model all fixed effects were far from significant, t-values were below $t < 1.05$. But in the pupil model we found a fixed effect of energy, $t = 2.62$, $p = 0.011$, indicating that with intensified mean sound intensity pupils dilated. Likely, then, the general effect of music presence on pupil dilation, reported above, was related to sound intensity and the fact that during silence intensity was reduced to environmental noise. Notably, microsaccade rate and pupil dilation were dissociated for music processing in our study.

3.2. Effects of eye parameters and musical features on subjective evaluations

Table 1 reports the significant fixed effects of the four models predicting absorption, valence, arousal or liking from physical markers and musical features. Table 2 gives a pictorial overview of significant fixed and fitted random effects. The effect on absorption was as predicted: Lower microsaccade rate predicted stronger absorption (see Fig. 3, upper left). This should be the case, as we assumed increased absorption to be related to higher processing load and load affects microsaccade rate negatively. In addition, lower blink rate predicted stronger absorption as well. Turning to musical features, only brightness was related as fixed effect to absorption. Lower brightness resulted in enhanced absorption. But including energy and novelty as random slopes increased the fit of

Table 1
Model fits predicting subjective states from eye parameter and music features in Exp. 1.

Model and fixed effects	*b*	*SD*	*t*	*p*
Absorption				
MS Rate	−0.054	0.014	−3.815	0.0001
Blink Rate	−0.333	0.111	−3.003	0.0027
Brightness	−0.027	0.009	−2.103	0.0400
Valence				
MS Rate	−0.047	0.011	−4.166	< 0.0001
Pup. Dil.	0.107	0.042	2.533	0.0115
Arousal				
Energy	0.070	0.016	4.290	< 0.0001
Brightness	0.081	0.017	4.918	< 0.0001
Novelty	−0.041	0.015	−2.737	0.0083
Liking				
MS Rate	−0.082	0.015	−5.448	< 0.0001
Energy	−0.032	0.017	−1.928	0.0582
Brightness	−0.025	0.014	−1.863	0.0677
Novelty	0.033	0.014	2.344	0.0224

Note. Significant fixed effects ($p < 0.05$) as well as tendencies of effects ($|t| > 1.8$, $p < 0.10$) are listed. MS Rate = microsaccade rate; Pup. Dil. = Pupil Dilation.

Table 2
Fixed and random effects in Exp. 1.

	MS Rate	Pup. Dil.	Blink Rate	Energy	Brightness	Novelty	Random Slopes
Absorpt.	—		—		—		Energy, Novelty
Valence	—	+					
Arousal				+	+	—	Energy, Brightness
Liking	—			(—)	(—)	+	Energy, Novelty

Note. MS refers to microsaccade, Pup. Dil. to Pupil Dilation, Absorpt. to absorption; "—" denotes a negative effect, "+" a positive effect and "()" a tendency with $p < 0.10$.

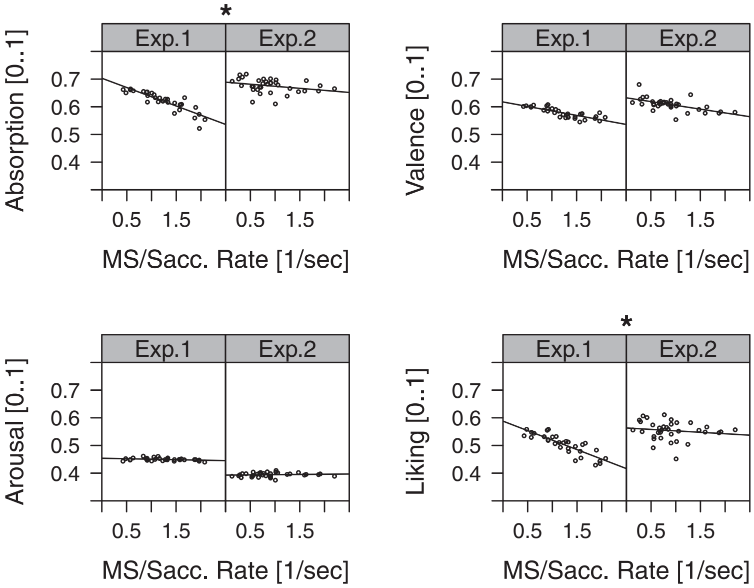

Fig. 3. Relation between individual microsaccade rates and reports of absorption, felt positive valence, felt arousal and liking for Exp. 1 and 2. Plotted means are based on the estimates of the linear mixed effect models, adjusting for variance on participant and musical-excerpt level. We used the *remef* function in R by Hohenstein and Kliegl (2013), to calculate these estimates. The lines are simple regression lines onto those means. The * sign denotes a significant between-experiment difference of the relation between microsaccade rate and the subjective rating, corresponding to Table 6, column RMS * Exp. Note that the means for arousal and valence of Figs. 2 and 3 do not match, Fig. 2 shows the observed means (on the level of musical excerpt) and Fig. 3 the adjusted means.

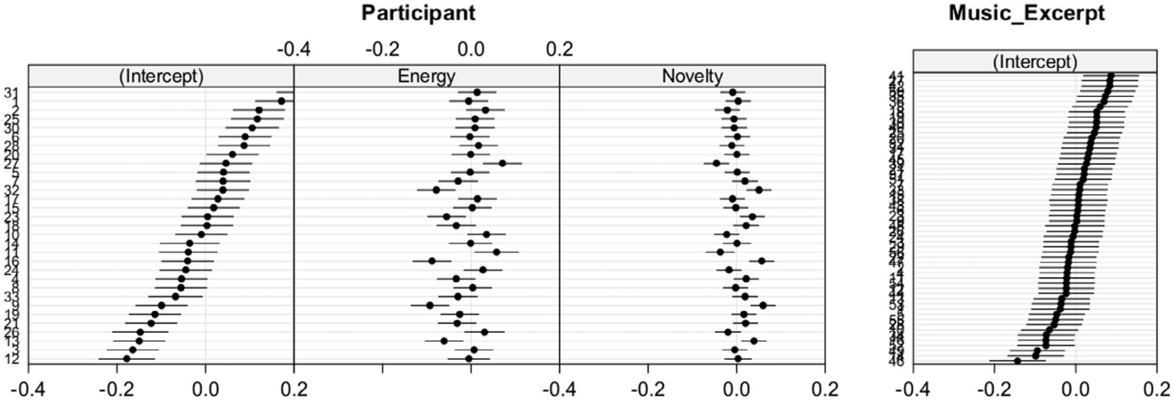

Fig. 4. Caterpillar plots of the random effects for the absorption model for Exp. 1. These plots arrange the random effects by the mean prediction intervals of participants (left part of the figure, 32 lines) or musical excerpts (right part of the figure, 56 lines). Horizontal lines indicate 95% prediction intervals for 32 participants or 56 musical excerpts. The visual comparison of those estimates illustrated that prediction means of musical excerpts overlap more strongly than for participants (the "slope" when connecting the data points is steeper for musical excerpts). The scales of the four subplots indicate that large differences in mean values for participants (random intercept) are related to small individual effects of energy and novelty (random slopes).

the model, $X^2(5) = 52.43, p < 0.0001$, and hence contributed to the absorption ratings on an individual subject level (see Fig. 4).

Notably, microsaccade rate had a small effect in terms of beta weight and the effect of blink rate had a larger beta but also a larger standard deviation (see Table 1). Participants were asked to avoid blinking. The large standard deviation might then be due to the fact that sometimes participants succeeded in inhibition, sometimes not.

Moving on to model predictions for the other ratings, microsaccade rate was predictive as well and in the same direction: Reduced microsaccade rate was linked to more positive valence and liking. Fig. 3 depicts these relations, based on the estimates of the linear mixed effect models (e.g., after removal of between-subject and between-musical excerpt variance). But the pattern of results for other fixed effects diverged. Valence was additionally predicted by pupil dilation. The arousal model included musical features only. Effects of musical features were reversed for arousal and liking. Higher energy and brightness and less novelty predicted arousal. Higher novelty predicted liking. There was also a tendency for lower energy and lower brightness to predict liking, with $p < 0.10$. But the best model fit for liking (with the lowest number of parameters) did not include energy and brightness as fixed effects.

Summarizing the predictive value of microsaccades, lower rate was linked to increased absorption, more positive valence, increased liking, but there was no relation to arousal.

4. Discussion of Experiment 1

We provided first evidence for microsaccade rate to be predictive of state absorption. This subjective state is theoretically linked to enhanced processing of an attentional object (Tellegen & Atkinson, 1974). As such our finding converges with experimental evidence showing decreased microsaccade rates with increased cognitive load (Gao et al., 2015; Siegenthaler et al., 2014). Furthermore, microsaccade rate is linked to felt valence and liking. Exploration of musical features shows a highly distinct pattern of fixed effects predicting different subjective states.

Absorption is a highly pleasurable state (Rhodes et al., 1988), which might explain that microsaccade rate is related to absorption as well as positive valence and liking ratings. Emotional involvement is one important aspect of an aesthetic music listening experience (Juslin, 2013; Scherer & Zentner, 2001). Is microsaccade rate then also indicative of emotional load? Even though we demonstrated a relation between microsaccade rate and felt valence, there was no support of a relation between microsaccade rate and arousal. Whereas valence might best be interpreted as quality spanning negative to positive states, arousal is a quantitative component. Then, arousal rather reflects emotional load. As microsaccade rate did not relate to arousal, it unlikely signals emotional load.

One potential alternative explanation for the reduction of microsaccade rate needs consideration. Absorption as state of altered awareness might generally slow down the oculomotor system (Amadeo & Shagass, 1963) or reduces muscle tension (Pekala & Kumar, 2000) similarly to hypnosis. The effect of microsaccade rate on absorption might then not be mediated by attentional load, as argued in the context of an attention-related definition of absorption. The effect might be a simple effect of relaxation. One result speaks against this hypothesis: The lacking effect of microsaccade rate on felt arousal. Low arousal maps onto relaxation (Pekala & Kumar, 2000). If microsaccade rate resembles arousal states, there should be a clear positive fixed effect on arousal. But this was not the case.

To pursue the relaxation explanation, we set up a follow-up experiment. In line with Gao et al. (2015) we assume that a reduction in microsaccade rate is the result of a shift of attentional resources from ocular control in the fixation task to mental processing. What did we expect, in case we would remove the fixation task? Microsaccades support proper fixation onto a fixational target by improving visual acuity (e.g., Rucci, Iovin, Poletti, & Santini, 2007), enhancing perception and reducing errors in fixation position (Engbert & Kliegl, 2004). Saccade and microsaccade generation is based on visual target selection and on subsequent translation of the target's position into motor commands (see Hafed, 2011, for the underlying neural processes). When removing visual targets completely, the whole process of visual selection and saccade generation is suspended and saccade generation runs in an autonomous mode. The strong relation between saccade rate and cognitive processing should break up. If saccades are no longer planned due to visual input, cognitive load should have no effect anymore. In contrast, if the reduction in microsaccade rate of Exp. 1 was due to relaxation and a general slowing, we still should find an effect of microsaccade rate on subjective absorption ratings. Relaxation and motor slowing should be independent from processes involved in saccade generation.

We repeated Exp. 1 with one change: We wiped off the computer monitor completely by presenting a gray screen and providing no visual target that could serve as a fixational or saccadic goal. Participants were to move their eyes freely. We decided on this task for other reasons. Free viewing onto a uniformly colored display should provide rather comparable basic results, like a low rate of saccadic movements and a high proportion of microsaccades (Otero-Millan et al., 2008). Repeating the study will also help to clarify the effects of musical features. Notably, musical features like energy, brightness and novelty showed a differentiated contribution to the four models predicting absorption, valence, arousal and liking. In Exp. 2 we aimed to replicate these effects. Changing the visual display should not change directions of musical effects.

5. Method Experiment 2

5.1. Participants

Thirty-five new participant took part in this experiment. They ranged in age from 18 to 32 with a mean of 24 years. Twenty-three of them had normal, twelve corrected-to-normal vision. Twenty were female (14 male, one stated to be both), thirty were students, one from psychology, one from music, one from both (psychology and music), one from musicology. None was a professional musician. None reported hearing problems.

5.2. Material, apparatus, procedure, data treatment

Everything in Exp. 2 was kept the same as in Exp. 1 except for one detail in the procedure. After the fixation check the fixational object – a black dot – disappeared. Subsequently the music started. Participants were instructed to continue looking at the gray screen throughout the trial. Their eyes should not leave the screen, but they were free to move the gaze around.

5.3. Missing recordings

We lost six trials due to technical failure. 123,738 saccadic movements were detected and 3.41% were rejected based on outlier analysis (see Exp. 1), resulting in 191,515 saccadic movements.

5.4. Data analysis

We again will first analyze effects of music presence and musical features, followed by the more central research question of how eye parameter and musical features contribute to absorption, as well as felt valence, felt arousal, liking and knowing. We once more aimed to find five models, predicting each subjective rating by eye parameters and musical features. Similar to Exp. 1 participants did not differentiate on the familiarity rating (see Fig. 2). So, we excluded familiarity from our modeling account again. For the remaining four models, we were able to apply maximal models. To find the best fitting model we first reduced random slope then fixed effects by comparisons of model fits (likelihood ratio tests).

To support our comparative interpretation of the results from both experiments, we analyzed the data by pooling them and fitting a between-experiment factor as its interaction with other fixed effects using linear mixed effect models again. Note, that participants had not been assigned randomly to one or the other experiment, limiting the interpretation of such a between-experiment analysis. However, results of this combined analysis were highly compatible with what can be seen by comparing the separate analysis of experiments.

6. Results

6.1. Data screening: saccadic movements, blinks, pupil dilation

From all saccadic movements 65.38% showed amplitudes below 1.5° (Fig. 5). Again, the distribution of saccadic amplitudes was unimodal. Therefore, no amplitude criterion was applicable to split microsaccades from saccades and all saccades were processes further. Median amplitude of saccadic movements was 1.31°. Mean rate of saccades was 0.91/s.

Overall, raw data differed slightly between experiments. In Exp. 2 fewer saccadic movements were generated, translating to more trials with low rates of saccadic movements. Fig. 6 shows the distribution of rates of saccadic movements in the music trials only, depicting a broader distribution and a shift to occurrences of low rates in comparison to Exp. 1. The median saccade amplitude was more than twice of Exp. 1. In general, those results of lower rates and larger amplitudes match what has been demonstrated in fixations tasks, when the fixational object was removed (Cherici, Kuang, Poletti, & Rucci, 2012; Poletti & Rucci, 2010). Importantly, due to the fact that 2/3 of all saccadic movements featured amplitudes below 1.5°, we succeeded in generating a rather comparable data set for Exp. 1 with a large pool of saccades in the range of microsaccades. However, for simplification, we will use the term *saccades* for all saccadic movements detected in Exp. 2.

Mean pupil deviation from baseline was 0.97%. Note that there was a display change in this experiment. During baseline period, the fixational object (black dot) was visible, during presentation of music it was extinguished. If anything, the change from black

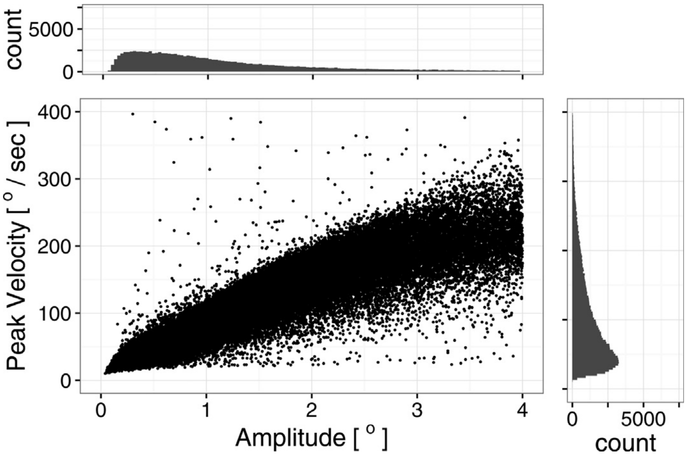

Fig. 5. Main Sequence and histograms of the amplitude and velocity distributions of saccadic movements in Exp. 2.

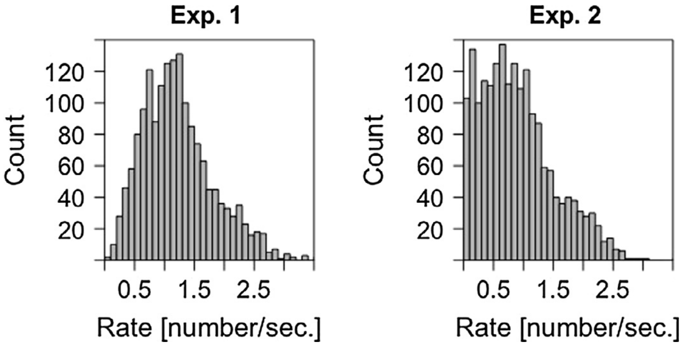

Fig. 6. Distribution of the rate of saccadic movements for both experiments. Here we plotted trials with music only, because our main analysis is based on those. Note, that overall there were less saccades generated in Exp. 2, resulting in more cases of lower rates.

(fixational object) to gray should increase pupil dilation (the deviation would be > 1), which was clearly not the case. We detected 13,263 blinks, resulting in a median blink rate of 0.08/s. The distribution was again extremely right-skewed. Only 15.06% of trials were recorded without a single blink.

6.2. Effects of music in comparison to silent trials and effects of musical features on eye parameters

The effect of music presence, comparing trials with and without music, shows the same pattern as in Exp. 1 (all models included music presence as a fixed effect as well as a random slope for participants). In analogy to Exp. 1 pupil dilated from 0.91 to 0.98% with music, $t = 5.29$, $p < 0.0001$. Again, this strong increase by 7.76% suggests that intense music listening requires processing resources. Investigating the effects of musical features on eye parameter demonstrated that pupil dilation, $t = 2.35$, $p = 0.019$, was related to energy as in Exp. 1 (here, random slopes for musical features did not contribute to the model fit and were removed), supporting the conclusion that the effect of music presence was due to the fact that intensity level was higher for music than the environmental noise in the no-music trials. Different from Exp. 1, there was a tendency for music presence to predict microsaccade rate as well, $t = -1.87, p = 0.070$. With music microsaccade rate decreased. But no effect of musical features could be linked to this effect. All other effects were not significant ($p < 0.05$).

6.3. Effects of eye parameter and musical features on subjective states

6.3.1. Absorption

Our main interest was in the fixed effect of saccadic movements on absorption. Whereas it was present in Exp. 1, it should disappear in Exp. 2. In fact, this was exactly what we found. For a visualization please see Fig. 3. Table 3 reports statistics on the fixed effects and Table 4 depicts fixed and random effects. Fig. 7 shows random effects in the absorption model. The disappearance of the fixed effect of microsaccade rate on absorption was further supported by the analysis of the combined data of Exp. 1 and 2. The

Table 3
Model fits for Exp. 2.

Model and fixed effects	*b*	*SD*	*t*	*p*
Absorption				
Blink Rate	−0.232	0.074	−3.159	0.0016
Brightness	−0.031	0.009	−3.339	0.0015
Novelty	0.022	0.009	2.341	0.0229
Valence				
Sacc. Rate	−0.022	0.013	−1.756	0.0794
Blink Rate	−0.148	0.067	−2.212	0.0272
Arousal				
Energy	0.079	0.016	4.877	< 0.0001
Brightness	0.090	0.017	5.365	< 0.0001
Novelty	−0.038	0.016	−2.431	0.0181
Liking				
Pup. Dil.	−0.109	0.045	2.425	0.0155
Blink Rate	−0.271	0.076	−3.564	< 0.0001
Energy	−0.030	0.018	−1.678	0.0983
Brightness	−0.039	0.017	−2.369	0.0213
Novelty	0.044	0.016	2.664	0.0100

Note. Sacc. refers to saccade. Significant fixed effects ($p < 0.05$) as well as tendencies of effects ($|t| \geq 1.7$, $p < 0.10$) are listed.

Table 4
Fixed and random effects in Experiment 2.

	Sacc. Rate	Pup. Dil.	Blink Rate	Energy	Brightness	Novelty	Random Slopes
Absorption			—		—	+	Sacc. Rate Energy
Valence	(—)		—				Energy Brightness
Arousal				+	+	—	Energy Brightness Novelty
Liking		+	—	(—)	—	+	Energy Novelty

Note. Sacc. refers to saccade, Pup. Dil. to Pupil Dilation, "—" denotes a negative effect, "+" a positive effect and "()" a tendency with $p < 0.10$.

disappearance of the fixed effect of saccade rate in Exp. 2 (e.g., Tables 2 and 4, upper row, left cell) should show as a significant negative fixed effect (due to this effect in Exp. 1) and a significant positive fixed effect of the interaction between rate and experiment (due to its disappearance in Exp. 2). Again, this is what we found (e.g., Table 5, first two rows, Table 6, upper row, two leftmost cells). Both analyses, the one based on data of Exp. 2 only as well as the other on the combined data set, point to the same conclusion: There was a reliable disappearance of a fixed effect of saccade rate in Exp. 2.

The interpretation is, that the fixed effect of microsaccade rate on predicting absorption (Exp. 1) is mediated by attentional load and not by a general relaxation or slowing in oculomotor responses. If it was relaxation, then the effect would have occurred in Exp. 2, too.

Turning to the other fixed effects in the absorption models, blink rate predicted absorption reliably in both experiments (significant fixed effects in Exp. 1 and 2 for the separate analyses, Tables 2 and 4, upper row, third column), and a significant fixed effect without interaction in the combined data, Table 6, upper row, fifth and sixth columns). These results indicate that some slowing might have occurred in the motor control of the eyelid. Note that participants were instructed to not blink. Due to this instruction, the interpretation of slowing by reduced blink rate has to be treated with caution. Results might alternatively indicate that this

Table 5
Joint data analysis of Exp. 1 and 2.

Model and fixed effects	*b*	*SD*	*t*	*p*
Absorption				
Sacc. Rate	−0.057	0.012	−4.839	< 0.0001
Sacc. Rate * Exp.	0.048	0.015	3.211	0.0015
Blink Rate	−0.264	0.061	−4.340	< 0.0001
Brightness	−0.026	0.010	−2.733	0.0081
Novelty	0.017	0.009	1.906	0.0619
Valence				
Sacc. Rate	−0.030	0.009	−3.357	0.0008
Pupil Dilation	0.118	0.043	2.742	0.0061
Pupil Dilation * Exp.	−0.122	0.057	−2.156	0.0311
Blink Rate	−0.049	0.098	0.496	0.6196
Blink Rate * Exp.	−0.193	0.118	−1.646	0.0999
Exp.	0.151	0.057	2.634	0.0085
Arousal				
Energy	0.075	0.015	4.949	< 0.0001
Brightness	0.087	0.016	5.464	< 0.0001
Novelty	−0.040	0.015	−2.680	0.0097
Exp.	−0.056	0.026	−2.123	0.0375
Liking				
Sacc. Rate	−0.064	0.013	−5.159	< 0.0001
Sacc. Rate * Exp.	0.059	0.015	3.927	0.0001
Pup. Dil.	−0.095	0.035	2.690	0.0072
Blink Rate	−0.027	0.116	−0.231	0.8176
Blink Rate * Exp.	−0.251	0.136	−1.850	0.0646
Energy	−0.031	0.015	−2.027	0.0466
Brightness	−0.033	0.015	−2.231	0.0295
Novelty	0.039	0.015	2.733	0.0084

Note. Data of both experiments were combined and the factor experiment was included into the modeling account as between-participant factor. This analysis was done to support interpretation when fixed effects differed between experiments. In that case, the fixed effect of the interaction with the factor experiment should be significant. Sacc. refers to saccade, Exp. to the Experiment. Significant fixed effects ($p < 0.05$) as well as tendencies of effects ($|t| \geq 1.7$, $p < 0.10$) are listed. Twice the none significant fixed effect of blink rate was listed because the interaction with the factor experiment was marginal.

Table 6

Pictorial overview of the combined data analysis with experiment as between-participant factor.

	RSM	RSM * Exp.	PD	PD * Exp.	BR	BR * Exp.	Exp.	Ener.	Brigh.	Nov.	Random Slopes
Ab.	—	+			—				—	(+)	RSM Energy Brightness
Va.	—		+	—		(—)	+				Energy Brightness
Ar.							—	+	+	—	RSM PD Brightness
Li.	—	+	+			(—)		—	—	+	Energy Brightness

Note. Pictorial summary of the analysis of the combined data set, including data of Exp. 1 and 2, with the experiment as between-participant factor. RSM = rate of saccadic movements – not differentiating between microsaccades and saccades; Exp. = Experiment; PD = Pupil dilation; BR = Blink rate, Ener. = Energy, Brigh. = Brightness, Nov. = Novelty; Each row represents one model: Ab. = Absorption; Va. = Valence, Ar. = Arousal; Li. = Liking. "—" denotes a negative effect, " + " a positive effect and "()" a tendency with $p < 0.10$. A positive interaction given a negative main effect indicates that the negative fixed effect in Exp. 1 disappeared in Exp. 2 (e.g., RSM & RSM * Exp. in the absorption model, first row). A negative interaction given a positive fixed effect stand for a positive fixed effect in Exp. 1 that disappeared in Exp. 2 (e.g., PD & PD * Exp. in the valence model, second row). A negative interaction term without a significant fixed effect can be translated into no fixed effect in Exp. 1, but a negative fixed effect in Exp. 2 (e.g., BR & BR * Exp. in the valence model, second row). Musical features (energy, brightness, novelty) never interacted with the factor experiment, therefore those columns are spared. The significant fixed effects of experiment show that there were slightly higher valence ratings and smaller arousal ratings in Exp. 2.

instruction was easier to follow with increased absorption. And this might have been independent from the change of procedure (with or without fixational object) between experiments.

The null effect of pupil dilation to predict absorption replicated in Exp. 2 as well (e.g., see missing fixed effect in the absorption models, Tables 2 and 4, no fixed effect and no interaction in the combined data, Tables 5 and 6).

6.3.2. Saccadic movements, blink rate, pupil dilation

Before turning to the results of the musical feature contribution, we briefly report fixed effects of eye parameters predicting other subjective states, that were included in this investigation in a rather exploratory way. Similar to absorption, the fixed effect of saccadic movements on predicting liking disappeared in Exp. 2 (lower row, Tables 2 and 4, negative fixed effect and positive interaction term in the combined data, Tables 5 and 6). However, saccadic movements still predicted valence in Exp. 2 (a fixed effect and no significant interaction in the pooled data, Tables 5 and 6). There was no predictive effect of saccadic movements in both experiments on arousal (Tables 5 and 6).

Whereas blink rate predicted absorption in both experiments, it emerged as predictor only in Exp. 2 for valence and liking (no fixed effect in the combined data set and a marginal interaction, Tables 5 and 6). However, this was only a tendency, as the interaction term in the pooled data was $t < 2$. We report these tendencies, because we believe that they might be potentially interesting for follow-up studies including spontaneous blink rate.

Pupil dilation showed no relation to absorption and arousal in both experiments. Whereas there was a fixed effect to predict valence in Exp. 1 that disappeared in Exp. 2 (positive fixed effect and negative interaction, Tables 5 and 6), there was a stable effect across both experiment for liking.

6.3.3. Musical features

A second important goal of Exp. 2 was to replicate the impact of musical features on subjective ratings. The relation between those features and subjective states should not depend on whether listeners fixated an object or not. We succeeded in this venture. All effects from Exp. 1 replicated in Exp. 2 (Tables 2 and 4). The combined data showed fixed effects and not a single interaction (Tables 5 and 6). This is particularly gratifying, because the pattern of effects was highly distinct for models of different subjective states, e.g. lower brightness predicted absorption, higher brightness arousal, and valence was not affected by brightness. There was one new effect emerging in Exp. 2, resulting in a tendency of a fixed effect in the combined data: Higher novelty predicted absorption (Tables 5 and 6). This finding indicates that state absorption was stronger with more variety in the music, keeping the mind immerged. It might be that a potential effect of novelty was dampened in Exp. 1 because participants could not devote all resources to music processing but still had to fixate actively onto a visual object.

7. General discussion

We pursued the relation between microsaccade rate and induced absorption states by listening to music in two experiments. The underlying rational of the assumed relation links two research fields. State absorption has been defined as allocating resources to process an attentional object (Tellegen & Atkinson, 1974). We argue that when feeling absorbed by intense music listening, attention was allocated to the music. More absorption requires more resource allocation than less absorption. Resource allocation to cognitive tasks has been demonstrated by inhibition of microsaccades (Gao et al., 2015; Siegenthaler et al., 2014). Then, microsaccade rate should also be linked to state absorption. In fact, in Exp. 1 microsaccade rate predicted absorption ratings in a linear mixed model. In Exp. 2, we removed any stimulus and presented a uniformly colored gray screen. Now saccade generation was not related to visual target processing but ran in an autonomous fashion. This should abolish the relation between processing load and saccade rate. As expected, saccade rate was no longer predictive for state absorption. The alternative hypothesis of an effect of motor slowing in Exp. 1 was ruled out. If the microsaccade rate decrease in Exp. 1 simply reflected relaxation, saccade rate should have related to absorption in Exp. 2 as well.

As a supplement, we also asked participants for their felt valence, arousal and liking of the music. Whereas in Exp. 1 microsaccade rate was linked to both, positive valence and liking, in Exp. 2 the fixed effect on valence remained, but the fixed effect on liking was abolished. It seems that with visual stimulus microsaccade rate indicates mental processing changes on other subjective states, not absorption alone.

Support for the reliability of our measures came from inclusion of musical features into our models. Originally, we planned to add five key features to span music effects in an exploratory fashion: Energy, brightness, flux, beat-per-minutes, and novelty as measures for sound intensity, timbre, contrast density, tempo and stimulus complexity. High correlations between those features precluded flux and tempo from linear analysis. In the end, we fitted models including energy, brightness and novelty. Results overlap nicely between experiments with a complex pattern for different subjective states. We presented the same music in Exp. 1 and 2. Changing the visual display should not affect any relation between musical features and subjective states. The effects of musical features on subjective states replicated.

We argue that the effect of microsaccade rate on absorption ratings in Exp. 1 is not due to a general slowing of the system by state absorption. Indirect evidence is the fact that microsaccade rate was linked to absorption but not arousal in Exp. 1 (and saccade rate did not relate to arousal in Exp. 2 as well). Low arousal is equivalent to a relaxed state. If low microsaccade rate indicated relaxation in addition to absorption, there should be a clear positive fixed effect. This was not the case.

Note that even though saccade rate did not predict absorption as fixed factor in Exp. 2, it was a significant random predictor. How can a random slope be interpreted? For some participants, a decrease in saccade rate was indeed associated with increased absorption, but for others the opposite or no relation occurred. When taking the standard deviation into account in Fig. 7, the majority of slopes seemed not to differ from zero. Saccade rates contributed to the models and explained variance between participants, but a fixed effect onto absorption was missing.

Even though the reduction of microsaccade rate with subjective absorption was not related to general relaxation in the oculomotor system, we found in Exp. 2 again some indication of motor slowing, this time in blink rate. However, as participants were instructed not to blink, results are difficult to interpret. Follow-up studies on this issue might be promising to uncover spontaneous blink rate as indicator for subjective states related to aesthetic experiences.

What kind of processing do we assume to take place during intense music listening and absorption? We suggest that our results are best explained by a cognitive processing load. However, emotional involvement is another key aspect of aesthetic musical experience (Juslin, 2013; Scherer & Zentner, 2001, 2008). So, what role does emotion induction play in the relation of microsaccade rate and absorption? There are two aspects to this question in our study. First, our measurement for absorption itself had an emotional aspect. We asked participants to rate how strongly they were immerged into the music. The German choice of word was the verb “einfühlen”. Etymologically this term includes “Gefühl” (engl. Emotion). In philosophical tradition, the noun “Einfühlung” has been linked to project oneself into an aesthetic object (Vischer, 1857, p. 776), which triggers a resonance processes resulting in a positive, affirmative experience or in negative disapproval (Lipps, 1906). By utilizing this term, we allowed absorption to have an emotional connotation. Second, there was a relation between microsaccade rate and felt valence as well as liking, but no support of a relation between microsaccade rate and arousal. Hence, the quality of emotion (valence) as well as liking is related to the subjective state of absorption, all linked by a change in microsaccade rate. Interestingly, there was some overlap between fixed effects for the predictive models of absorption and liking in both experiments. This might be partially due to the fact that absorption and liking ratings correlated highly, $r = 0.64, p < 0.001$ across all participants and trials (n = 1665) in Exp. 1 and $r = 0.62, p < 0.001$, n = 1864 in

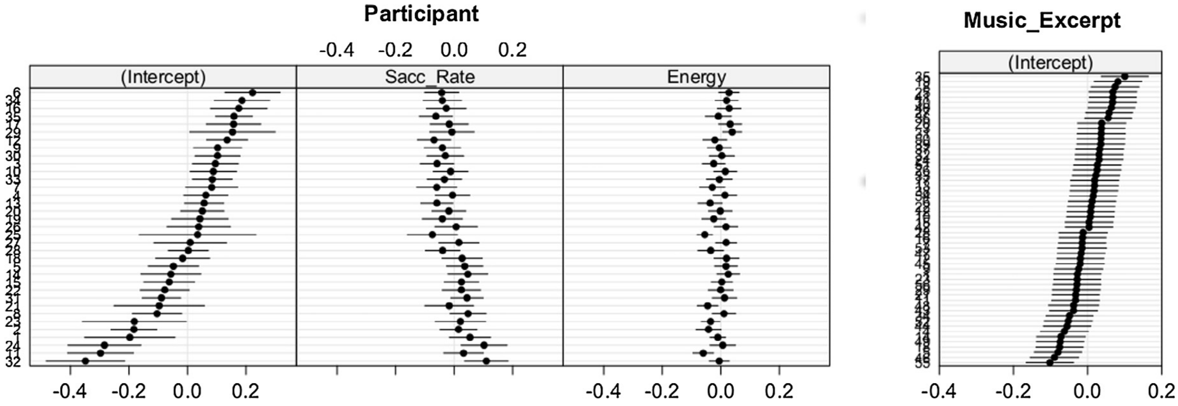

Fig. 7. Caterpillar plots of the random effects for the absorption model for Exp. 2. Horizontal lines indicate 95% prediction intervals for 35 participants or 56 music excerpts. Results from Exp. 2 were highly similar to Exp. 1 with regard to the overlap of prediction means for participants as well as musical excerpts. However, the 95% prediction intervals for participants in Exp. 2 show size differences, that is higher variety in the data between participants. Again, estimates for random slope effects of saccade rate and energy show only very little impact. That is, for both experiments the mean estimates seem to contribute more than the random slopes to the final model.

Exp. 2. But results cannot be fully explained by correlations, as absorption (Exp. 1: $r = -0.42$, Exp. 2: $r = 0.58$) and liking (Exp. 1: $r = -0.61$, Exp. 2: $r = 0.38$) correlated with valence as well (all p's < 0.001), but none of the fixed effects from the absorption or liking model showed in the valence model besides microsaccade rate in Exp. 1 and blink rate on Exp. 2. It might be that absorption as well as valence ratings mediated liking. This would be plausible as in an aesthetic context of music listening absorption is highly related to pleasure (Rhodes et al., 1988).

In this context, it is interesting to note that microsaccade rate has been demonstrated to be linked to reward (Joshua, Tokiyama, & Lisberger, 2015; Okada & Kobayashi, 2014). Music listening is known to activate the reward system as well (Zatorre & Salimpoor, 2013). Then, how does reward contribute to our findings? We demonstrated decreased microsaccade rate with increased absorption, consistent with the load hypothesis. Studies on reward showed increased microsaccade rate with increased reward. However, in these studies microsaccade rates were not recorded during the rewarding experience, but in the interval predicting high versus low reward. Then the studies demonstrate a link between microsaccade rate and reward prediction or expectation. Even though these study designs do not allow for a direct comparison with our findings in the context of the rewarding experiences of music listening, they support our finding that microsaccade generation is linked to pleasurable subjective states.

Recently, it has been demonstrated that microsaccade generation is coupled to heartbeat (Ohl, Wohltat, Kliegl, Pollatos, & Engbert, 2016). The underlying mechanisms are not known at present, but such coupling indicates that bodily processes (in addition to cognitive and emotional processes) influence the visuomotor system. Potential candidates are heart-beat evoked potentials (see Discussion in Ohl et al., 2016). Arousal by music listening is linked to heart-rate changes as well (e.g., Witvliet & Vrana, 2007). Interestingly, there is a link between arousal and microsaccade generation on the neural level (e.g., an area called the pedunculopontine tegmental nucleus, PPTN, has been identified to be involved in arousal as well as microsaccade generation, Okada & Kobayashi, 2014). Then, arousal induced by music listening might affect both, heartbeat and microsaccade generation, or the bodily changes related to arousal might affect microsaccade rate. Given that in our study microsaccade rate was not related to subjective arousal and the fixed effect on absorption showed in Exp. 1 but not Exp. 2, felt arousal or bodily changes likely played only a minor role for our findings.

Even though we argue in favor of the cognitive load hypothesis, there is one supposed caveat. Siegenthaler et al. (2014) offered a reasoning why cognitive load affects microsaccade rate. They argued that fixating a target can be regarded as dual task, which needs cognitive resources. High cognitive load in the (visually unrelated) primary task recruits resources from the dual task. As a result, microsaccade rate decreases. Siegenthaler et al. refer to a specific conceptual model of microsaccade generation for their predictions (Rolfs, Kliegl, & Engbert, 2008). In this model saccade generation is based on activity on a motor map. The central location of the map represents steady fixation, non-central locations depict saccades of increasing amplitude. Within this model Siegenthaler et al. postulate two consequences of reduced cognitive resources for the activation map: the general level of activity decreases (driving the rate) and the distribution of activity broadens (driving amplitude). In fact, Siegenthaler et al. as well as Dalmaso et al. (see footnotes in 2017) reported both, decrease of microsaccade rate and increase of amplitudes in the high load condition. However, Gao et al. (2015) did not report whether amplitude was affected in their refined design (as well as Betta & Turatto, 2006; Valsecchi & Turatto, 2009; Valsecchi et al., 2007). In fact, an increase of amplitude not necessarily follows from the conceptual model of Rolfs et al. (2008). A decrease of amplitude can be derived as well (see Rolfs et al. for their argument of decreased amplitudes by microsaccade inhibition). Also, Rolfs et al. reported one condition, in which the manipulation resulted in an effect of microsaccade rate only and no effect on amplitude. To catch up on this issue in our data we analyzed posthoc the effect of amplitude as well as the size of the area on the screen covered by the eye's trajectory. The later can be interpreted as fixation error and is not implemented in the conceptual model mentioned above, but follows a similar logic. Directing attention towards music processing and away from the fixation task might increase fixation error. For amplitude, we analyzed the median amplitude of saccadic movements during one trial. For fixation error, we applied a box-count analysis (Engbert & Mergenthaler, 2006), in which we placed squared boxes (edge length 0.02°) on the eye's trajectory and calculated the radius of the circular area covering the trajectory. We decided on the radius of 75% of that area to exclude outliers in the eye's trajectory. We then implemented median amplitude or fixation error into the final mixed models of Exp. 1 and 2 to see whether those parameters contributed as fixed effects in our modeling account. However, results were not reliable. In the absorption model of Exp. 1 there was no fixed effect of amplitude ($t = 1.55$, $p = 0.121$) but of fixation error ($t = 2.05$, $p = 0.041$). There was no convincing fixed effect of amplitude ($t = -1.77$, $p = 0.078$) in Exp. 2 (if anything than a reduction of amplitude), but no fixed effect of fixation error ($t = -0.40$, $p = 0.693$). That is, microsaccade rate was not linked to amplitude as tightly as in the Siegenthaler et al. study. The effect of fixation error is compatible with the hypothesis that absorption is related to both, reduced microsaccade rate as well as increased fixation error.

Absorption is highly related to another altered state of consciousness: mind-wandering. We cannot exclude the possibility that our participants sometimes were mind wandering instead of being absorbed. However, we argue that our result of a reduced microsaccade rate is unlikely due to mind-wandering. First, whereas attention is directed "outward" to the absorption inducing stimulus (Tellegen & Atkinson, 1974), attention is directed "inward" during mind-wandering episodes and decoupled from processing of external events (e.g., Smallwood, Beach, Schooler, & Handy, 2008). We demonstrated that musical features had plausible effects on rated absorption. Clearly, music as a stimulus was attended and processed. In addition, the literature on eye behavior and mind-wandering provides mixed results. For instance, in the context of text reading both was demonstrated, either a general slowing, e.g. increased fixation durations (Reichle, Reineberg, & Schooler, 2010) or a specific acceleration by a decrease of fixation durations indicating shallower semantic processing (Schad, Nuthmann, & Engbert, 2012). Often increased motor activity occurred in mind-wandering episodes, e.g. increase of blink rate during text reading (Smilek, Carriere, & Cheyne, 2010) or a visual fixation task (Grandchamp, Braboszcz, & Delorme, 2014). Research with questionnaires on states of inattention and spontaneous mind-wandering demonstrated a general increase of motor activity by those state (Carriere, Seli, & Smilek, 2013). Hence, regarding microsaccade rate no clear prediction can be derived from what is known from the literature on mind-wandering. Second, we stressed the difference between absorption and mind wandering in the task instructions. Absorption was described as a state, where listeners were fully engaged with and drawn into the music in contrast to being indulged in daydreams, fantasies or reminiscences. Hence, participants were informed about the difference. Their ratings should indicate absorption and not mind-wandering. Then, we argue that in our study microsaccade rate was rather related to absorption and less likely to mind-wandering.

The very specific effects of musical features converge nicely with reports from the emotion literature particularly for arousal states. For instance, higher pitch level (measured with fundamental frequency, we used spectral centroid) was associated with arousal (Scherer & Oshinsky, 1977). More often than arousal and valence, concrete emotional categories are investigated. Here, a low versus high sound level differentiates between negative low versus high arousal states like sadness and anger as well as between positive low versus high arousal states like tenderness and happiness (see Juslin & Lindström, 2010 for an overview). In a similar way, low arousal is associated with dull timbre and low pitch, high arousal with sharp timbre and high pitch. Differently from our results valence has also been related to musical features like sound intensity and timbre/pitch. In our experiments those features were not predictive. Interestingly, we found some effects of musical features on liking, despite the fact that musical preferences are highly individual. For instance, loudness has been reported to be negatively related with preference in some studies, but inverted-u-shaped or not at all in other studies (see Finnäs, 1989, for a summary of differential effects of musical features in different populations). Complexity in terms of irregularities sometimes follows the inverted-U relation with liking (Finnäs, 1989), but has also been demonstrated to be negatively related (Glasgow, Cartier, & Wilson, 1985). With our selection of music and a random student sample we consistently demonstrated and replicated linear effects of energy, brightness and novelty on liking, on a level of $p \leq 0.10$.

To our knowledge there is only one other study on the effect of music on eye movements, showing reduced saccade rates for scene or film perception when adding music in comparison to the music absent condition (Schäfer & Fachner, 2014). These authors did not find an effect of music preference, indicating that differences in music processing were not associated with distinct eye movement behaviors. However, mean fixation duration differed between neutral and preferred music by 46–103 ms. Using an eye-tracker with a sampling rate of 60 Hz might have blurred fine-grained effects of differential musical processing.

Finally, we need to raise the direction of our regression account. Our goal was to predict subjective ratings by objective and quantitative measurements of eye movements. As such, we decided on microsaccade rate as predictor and absorption as dependent variable. This account allowed us to add several eye parameters as well as musical features within one and the same model. Resulting fixed effects depict independent contributions between those predictors, e.g., both, blink and microsaccade rate predicted absorption in Exp. 1. Musical features added such independent contribution as well. By deciding on these models, we do not wish to express microsaccades to be the cause of absorption. This is unlikely the case for two reasons. First, microsaccades are linked to attentional processing. Attention allocation is only one feature of an absorption experience, and unlikely sufficient to induce absorption. The relation might be more complex and features of the attentional object, the listener and the context will determine the subjective experience, too. Second, we believe that the direction of dependencies is likely not fixed. Musical absorption might affect microsaccade rate, a reduced microsaccade rate might also trigger processing of the music and hence absorption. Cause and effect might work in a circular fashion.

To sum, we provided first evidence for microsaccades to indicate subjective states like absorption. Our study raises of course many questions. Further studies need to detect the specific role of attention in state absorption, like the act of attention allocation or staying continuously focused. Different contributors have to be evaluated, e.g. emotional processing (including reward), cognitive evaluations, and bodily processes. However, our study provides an important finding. Aesthetic experience is a highly complex and individual state, difficult to investigate with objective and non-invasive methods. We provide first evidence for cross-modal couplings, which seemed to be an easy-to apply tool to reveal more about musical aesthetic experience.

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Appendix A

See Table A1.

Table A1
List of musical stimuli.

Musician/Composer	Title	Musical Style	SP OffSet in dB
Neurosis	Casting Of The Ages	Metal	3
John Fahey	Steamboat Gwine Round de Bend	Folk	0
Fleetwood Mac	Albatross	Blues	0
Billy Strange	If I Were Free	Country	0
Eckbank Zithermusi	Simmerl	German Folk Music	−5
Four Tet	She Moves She	Electronica	−3
DJ CAM	Mad Blunted Jazz	Hip Hop	0
Miles Davis	So What	Jazz	0
Euge Groove	Movin On	Pop	0
Ansel Collins & Dalton Browne	West Of The Sun	Reggae	0
Jeff Beck	Serene	Rock	0
King Curtis	The Stranger *(No Strings)*	Soul	0
Zakir Hussain	Zakir	World Music	−5
György Ligeti	Poème Symphonique for 100 Metronomes	Classical Music	−5
Big Bill Broonzy	Hey Hey	Blues	0
Chet Atkins	Caravan	Country	0
Jimmy Bryant and Speedy West	Frettin' Fingers	Country	0
Blasmusik Oberstaufen	Castaldo-Marsch	German Folk Music	3
Roman Flügel	Gehts noch (Bsherry RMX)	Electronica	3
Duke Ellington	Take The A Train	Jazz	0
Sonny Clark Trio	Junka	Jazz	−3
The Octopus Project	Truck	Pop	0
Boards of Canada	Dayvan Cowboy	Rock	0
Joe Satriani	Satch Boogie	Rock	3
Cliff Nobles	The Horse	Soul	0
Commodores	Machine Gun	Soul	0
Äl Jawala	Unzer Toirele	World Music	0
Duofel	No Caminho das Pedras	World Music	−3
Henry Mancini	Reflection	Blues	0
Koflgschroa	Sofia	German Folk Music	0
Trentemøller	Nightwalker	Electronica	0
DJ Krush	Kemuri Untouchable Mix	Hip Hop	3
Bohren & der Club of Gore	Destroying Angels	Jazz	−3
Thelonious Monk	Round Midnight	Jazz	0
Erik Satie	Trois Gymnopédies No 1	Classical Music	−5
Death	Voice Of The Soul	Metal	0
Kenny G	Songbird	Pop	0
Joe Gibbs & The Professionals	Third World	Reggae	−3
Funkadelic	Maggot Brain	Rock	0
Adrian Younge	Shot Me In The Heart (Instrumental)	Soul	0
Anouar Brahem	Vague E la nave va	World Music	−3
Dhafer Youssef	Ascetic mood	World Music	−3
Stephan Micus	Blossoms in the Wind	World Music	0
John Fahey	Wine and Roses	Folk	0
Justice	Stress	Electronica	3
Mouse on Mars	Hi Fienilin	Electronica	3
DJ Shadow	Stem Long Stem	Hip Hop	3
Flying Lotus	Riot	Hip Hop	5
Tied & Tickled Trio and Billy Hart	Lonely Woman_Exit La Place Demon_The Electronic Family	Jazz	−3
Dmitri Schostakowitsch	Klaviertrio No 2 (Op 67) Allegretto	Classical Music	3
Voodoo Glow Skulls	Los Hombres No Lloran	Reggae	0
Kyuss	Jumbo Blimp Jumbo	Rock	3
Russian Circles	Lebaron	Metal	5
James Brown	Devils Den Live	Soul	3
Krzysztof Penderecki	Den Opfern von Hiroshima	Classical Music	0
Apocalyptica	Hyperventilation	Metal	3

Note: SP = sound pressure; from those musical pieces excerpts of 45 to 60 s length were selected. Excerpts were adjusted to the same loudness level, and subsequently amplified slightly to keep the character of the music piece. The last column denotes those changes in loudness (see Section 2.3.1).

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