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Crossmodal Correspondence between Music and Ambient Color Is Mediated by Emotion

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Abstract

The quality of a concert hall primarily depends on its acoustics. But does visual input also have an impact on musical enjoyment? Does the color of ambient lighting modulate the perceived music quality? And are certain colors perceived to fit better than others with a given music piece? To address these questions, we performed three within-subjects experiments. We carried out two pretests to select four music pieces differing in tonality and genre, and 14 lighting conditions of varying hue, brightness, and saturation. In the main experiment, we applied a fully crossed repeated-measures design. Under each of the four lighting conditions, participants rated the musical variables 'Harmonic', 'Powerful', 'Gloomy', 'Lively' and overall liking of the music pieces, as well as the perceived fit of music and lighting. Subsequently, participants evaluated music and lighting separately by rating the same variables as before, as well as their emotional impact (valence, arousal, dominance). We found that music and lighting being similarly rated in terms of valence and arousal in the unimodal conditions were judged to match better when presented together. Accordingly, tonal (atonal) music was rated to fit better with weakly saturated (highly saturated) colors. Moreover, some characteristics of the lighting were carried over to music. That is, just as red lighting was rated as more powerful than green and blue lighting, music was evaluated to be more powerful under red compared to green and blue lighting. We conclude that listening to music is a multisensory process enriched by impressions from the visual domain.

Keywords

music, color, lighting, multisensory perception, concert

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1. Introduction

Music enthusiasts may close their eyes while listening to music, to be able to focus on acoustic enjoyment with all their attention, as if visual sensory input would distract them from what they hear and thus limit their listening pleasure. This implies that visual impressions do have the power to change what is perceived in the auditory domain. But is this really the case?

1.1. Audiovisual Crossmodal Correspondence

It certainly seems plausible, as an extensive and rapidly growing body of research is dedicated to examining interrelationships between the five human senses, labeled as ‘crossmodal correspondences’ (see Spence, 2011, for a review). Links between senses have been documented for adults and children of different age and gender (Guerdoux *et al.*, 2014; Maurer *et al.*, 2006), showing that crossmodal experiences should be regarded as universal. Note that they are not to be confused with the rare phenomenon of synesthesia (see Deroy and Spence, 2013, for a review). The term ‘crossmodal correspondences’ refers to sensual impressions that have been found to exert specific reciprocal crossmodal mappings. For instance, in a study by Crisinel and Spence (2010), high-pitched sounds were associated with sweet and sour tastes, while low-pitched sounds were preferably matched with umami and bitter tastants. As to audiovisual mappings, high-pitched sounds were found to be associated with small (Evans and Treisman, 2010) and light objects (Hubbard, 1996), just as certain odors are matched with certain shapes (Hanson-Vaux *et al.*, 2013), colors (Spence, 2020a), or music notes (Crisinel and Spence, 2012). In a recent study, Albertazzi *et al.* (2020) even found robust crossmodal associations between highly complex stimuli, i.e., paintings by Kandinsky and music by Schönberg. However, impressions from different sensory domains were found not only to be readily matched but to crossmodally influence each other. For example, the color of the container (Piqueras-Fiszman and Spence, 2012) can change the perceived taste of beverages, and the visual size of objects alters their perceived weight (Buckingham, 2014; Charpentier, 1981). With regards to interrelations between auditory and visual perception, one of the best-known phenomena is the so-called ‘ventriloquist’ or ‘McGurk effect’. It demonstrates that the visual impression of a speaking mouth has an influence on what we hear and can change the words we understand (McGurk and Macdonald, 1976). Conversely, there is evidence that the auditory perception of a falling object alters the visually perceived size of that object (e.g., Carello *et al.*, 1998; Hauck and Hecht, 2019a).

Auditory stimuli employed in these studies vary widely in their complexity. For example, beep tones of different loudness and pitch are much simpler in structure than impact sounds of falling objects. Music, in turn, is even more complex with its multiple dimensions, such as tempo, mode, tonality, and loudness, as well as different instrumentation and genre. Also, music is much more likely to trigger emotions than are single sounds (see Eerola and Vuoskoski, 2013; Juslin and Sloboda, 2010; Spence, 2020b, for reviews). Short musical excerpts are often employed as stimuli for the examination of crossmodal correspondences when researchers pursue a more practice-oriented approach, involving meaningful multi-element auditory stimuli (Spence, 2019a, 2020b). As such, music stimuli have been found to exert an influence on, inter alia, odor (Velasco *et al.*, 2014), taste (Crisinel *et al.*, 2012; Hauck and Hecht, 2019b), haptic experience (Imschloss and Kuehnl, 2019), and cognitive performance (Kämpfe *et al.*, 2011).

In the visual domain, distinct emotional reactions are commonly evoked by different colors (e.g., Gilbert *et al.*, 2016; Suk and Irtel, 2010; Wilms and Oberfeld, 2018). Correlations between emotional outcomes and color have been reported for all of the three basic colorimetric dimensions, which are hue, saturation, and luminance. For example, concerning hue, there is evidence that red goes along with higher arousal than green and blue (e.g., Elliot, 2019; Walters *et al.*, 1982, but see Castell *et al.*, 2018). Similarly, highly saturated vivid colors have been reported to be more arousing than low-saturated pale colors (Suk and Irtel, 2010; Valdez and Mehrabian, 1994; Wilms and Oberfeld, 2018; Zieliński, 2016). Furthermore, brighter colors were found to be associated with positive emotions and darker colors with negative emotions (e.g., Barbiere *et al.*, 2016; Hemphill, 1996, but see Schloss *et al.*, 2020). Color has been found to be a highly influential stimulus as regards crossmodal interactions. For instance, research results indicate an influence of color on taste experience (Morrot *et al.*, 2001; Spence, 2019b), temperature evaluation (Huebner *et al.*, 2016; Spence, 2020c), odor perception (Zellner, 2013), and purchase decisions (Labrecque *et al.*, 2013). The color of the ambient lighting is also a considerable factor in architectural design (see Spence, 2020d, for a review).

1.2. Aim of the Study

In this study, we want to investigate the relation between color and music. A considerable number of findings suggests robust crossmodal correspondences between these two types of sensory input (e.g., Barbiere *et al.*, 2016; Palmer *et al.*, 2013; Sebba, 1991; Whiteford *et al.*, 2018). Studies show that brighter, warmer, and more saturated colors are matched with faster music in major modality, whereas darker, cooler, and less saturated colors are matched with slower music in minor modality (e.g., Palmer *et al.*, 2013; Sebba, 1991). To find out which color is associated with which type of music, the method of choice often includes the task to match excerpts of music pieces with color patches, as was also the case in an often-cited study by Palmer and colleagues

(2013). Whereas these crossmodal mappings are relatively well examined, there is hardly any research about the crossmodal influence that color and music perception might exert on each other. A rare example is a study by Bhattacharya and Lindsen (2016) in which the authors showed that listening to music excerpts can modulate brightness judgments of visual stimuli presented on a screen. After listening to music that had been validated to convey positive emotions, participants rated gray squares to be brighter than after listening to music that conveyed negative emotions. The way of presenting color stimuli on a self-luminous display Bhattacharya and Lindsen (2016) applied here is one of the common presentation techniques in crossmodal color research (e.g., Lindborg and Friberg, 2015; Palmer *et al.*, 2013), together with color patches and scales printed on paper or cardboard (e.g., Valdez and Mehrabian, 1994, see also Suk and Irtel, 2010). Interestingly, the presentation of colored ambient lighting has been neglected so far.

On this basis, we ask the following research questions. First, is there a crossmodal influence of the hue, saturation, and luminance of colored ambient light on the evaluation of music pieces? We hypothesize that music evaluation will change according to the mood associated with the color of the ambient light. We assume that ratings will trend towards the unimodal ratings of the respective lighting. Thus, a given music piece should be rated more powerful when the ambient color that accompanies it is judged as powerful when presented in isolation. Such transfer effects have already been shown for other applications, e.g. for the effect of color on the evaluation of interior space. Yildirim *et al.* (2011) reported that participants rated large-scale pictures of a red-painted living room to be more arousing, stimulating, and exciting compared to blue or gray wall paint.

Second, are there ambient colors that fit better with certain music pieces than others? As described earlier, both music (e.g., Costa, 2004) and color (e.g., Wilms and Oberfeld, 2018) have been shown to systematically trigger specific emotions as a function of their stimulus characteristics. Therefore, music–color researchers oftentimes suggest a mediating function of emotions as an explanation for crossmodal correspondences (e.g., Palmer *et al.*, 2013; Whiteford *et al.*, 2018). Besides emotional congruency, also semantic congruency has been found to be decisive for the matching of multimodal stimuli (cf. Evans and Treisman, 2010; Marks, 2004; Sun *et al.*, 2018; Walker, 2012). Accordingly, we hypothesize that our stimuli will be perceived as better fitting together if they evoke similar emotions in separate presentations and if they are associated with similar semantic attributes.

To test these hypotheses, we designed two pre-tests and one main experiment with three separate samples. In the pre-tests, participants evaluated lighting stimuli and music stimuli separately and produced baseline ratings on dimensions such as harmony or power. Moreover, in the case of music, we took these ratings to choose the music pieces for the main experiment. There, participants rated the music pieces according to the same dimensions under different lighting conditions.

2. Material and Methods

2.1. Sample

In total, 60 participants volunteered for the experiment. Six data sets were removed from the sample due to attention deficit hyperactivity disorder ($n = 1$), deficient color perception ($n = 2$), or a large number of extreme values ($n = 3$). The remaining 54 participants (25 female; age $M = 26.33$, $\mathrm{SD} = 11.38$) were mainly psychology students or psychologists ($n = 50$). Two participants with slightly impaired vision and one with slight hearing impairment were kept in the sample because their data did not deviate from the data of the other participants. All other participants had normal or corrected-to-normal vision and did not report any hearing deficiencies. All participants reported being non-synesthetes. Color vision was tested using the Ishihara (2010) color vision deficiency test (Test Plates 1, 4, 7, 13, 15, and 20) presented under a D65 standard illuminant. Musical expertise in the sample was below the average ($M = 69.74$, $\mathrm{SD} = 20.93$, 28th percentile; norm: $M = 81.58$, $\mathrm{SD} = 20.62$), with 41 participants scoring below and 13 above average in the General Musical Sophistication Test, which is a short version of the Goldsmith Musical Sophistication Index (Gold-MSI; Schaal *et al.*, 2014).

2.2. Apparatus and Stimuli

2.2.1. Setup

The experiment took place in a darkened laboratory room. The room was illuminated through four color-adjustable LED panels, controlled by an Optiplex 980 Core i5 PC (Dell, Round Rock, USA) using Python 2.7.13 (www.python.org). The LED panels were arranged in a square with a surface area of 114 × 114 cm and mounted to the wall, centered at seated eye height. By placing a white table in front of the wall, and white partition panels to either side, a booth was created. The participant sat at the white table (see Fig. 1) at a distance of 100 cm between the participant's eyes and the LED panels. The audio stimuli were presented on two loudspeakers (5″ Studio Reference Monitors, ESI Audiotechnik GmbH, Leonberg, Germany), which were placed to the left and right of the listener, respectively, at an approximate distance of 78 cm to the respective ear.

2.2.2. Music Stimuli

We used 30-s excerpts of four music pieces as audio stimuli. The duration of 30 s per piece was chosen to give the participants sufficient time to form

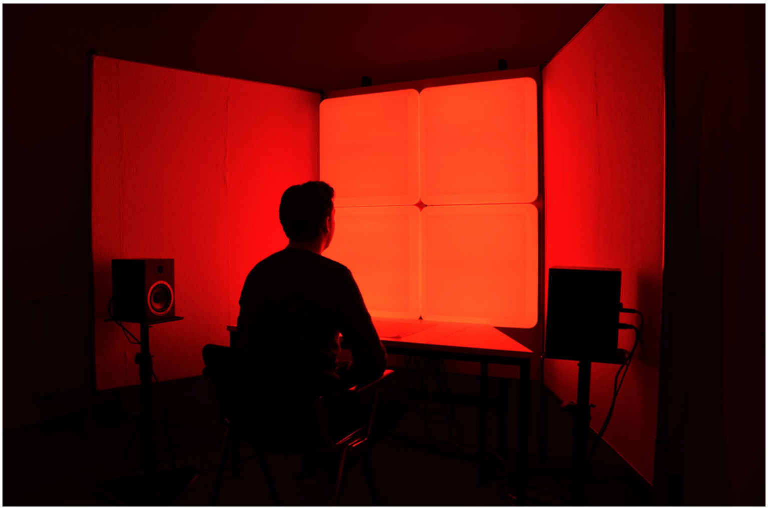

Figure 1. The experimental setup featuring a large square of LED panels and two speakers.

an impression of the music and rate it on the six given scales. At the same time, we wanted to minimize cognitive distortions and, therefore, kept the excerpts rather short. We followed examples of studies that assessed perceived emotions in music with a median stimulus duration of 24 s (see Eerola and Vuoskoski, 2013, for a review). These were two classical and two jazz pieces, one atonal and one tonal piece per genre. The four music pieces were selected based on an online pre-test ($n = 45$, 36 female; age $M = 25.3$ years, SD = 4.24). We selected pieces of the same genre that differed as much as possible in terms of their emotional effects, whereas the pieces of the same tonality should resemble each other. This was the case for ‘*Mack the Knife*’ by Dan Forshaw Trio (tonal Jazz), ‘*Waltz of the Flowers*’ from the ‘*Nutcracker Suite*’ by Piotr Tchaikovsky (tonal classical music), ‘*Pink Pong*’ by the Georg Graewe Quintet (atonal Jazz) and ‘*March*’ from ‘*Three Pieces for Orchestra*’ by Alban Berg (atonal classical music). Details about the recordings can be found in Table 1. The excerpt wav-files were set to an equivalent continuous sound level of about 60 dB using an SPL meter (NTi AL1, Schaan, Liechtenstein).

2.2.3. *Lighting Stimuli*

We presented 14 lighting conditions; two achromatic stimuli and a fully crossed set of different hues (red, blue, and green), luminances (32 *vs* 16 cd/m^2), and saturations (90 *vs* 80%). Table 2 displays the colorimetric values of the presented lighting colors, as measured with a spectroradiometer (Specbos 1201, JETI Technische Instrumente GmbH, Jena, Germany). Just like the audio stimuli, we pretested the lighting stimuli in terms of their emotional value in a laboratory experiment ($n = 30$, 28 female; age $M = 22.43$

Table 1.
List of music pieces presented as audio stimuli

Title	Peter Tchaikovsky: '*Waltz of the Flowers*' from '*Nutcracker Suite*, op. 71a'	Alban Berg: '*March*' from '*Three Pieces for Orchestra*, op. 6'	'*Mack the Knife*'	'*Pink Pong*'
Type	Classical	Classical	Jazz	Jazz
Tonality	Tonal	Atonal	Tonal	Atonal
Artist	Bolshoi Theatre Symphony Orchestra Moscow, Alexander Vedernikov	Goetheborg Symphony Orchestra, Mario Venzago	Dan Forshaw Trio	Georg Graewe Quintet
Recording	2006, Bolshoi Theatre Moscow, PentaTone Music	2009, Konserthuset, Gothenburg, Sweden, Chandos	2014, Stapleford Granary, Cambridge	1977, FMP-Studio Berlin
Excerpt	1:47–2:17 min.	5:35–6:05 min.	0:00–0:30 min.	0:16–0:46 min.
BPM*	60	76	97	75
Instrumentation	Symphony orchestra	Symphony orchestra	Jazz trio (saxophone, bass, drums)	Jazz quintet (trumpet, saxophone, piano, bass, drums)
Key	D major	atonal	C major	atonal
Familiarity**	8	2.51	4.18	1.76
$L_{\mathrm{Aeq\_dt}}$***	62.43	62.31	62.68	64.24

*Beats per minute averaged over 30 seconds; **familiarity assessed in the Pre-Test Music (0 = 'not familiar at all', 9 = 'very familiar'); ***Sound level, A-weighted equivalent with 1-second logging interval.

years, SD = 3.69), in which the lighting stimuli were presented in the same experimental setting as in the main experiment and rated on the same scales as in the lighting-only condition described below.

2.3. Design and Procedure

We crossed the 14 lighting conditions (3 hue × 2 saturation × 2 luminance + 2 achromatic stimuli) with tonality (2) and genre (2 in a repeated-measures design), amounting to 56 conditions. Thus, the participants rated each of the

Table 2.
Colorimetric values of the presented lighting colors for Panel 1 as an example. Values for the other three panels were similar

Hue	Saturation	Brightness	h^* (deg)	S (%)	L^* (cd/m^2)
Red	High	High	45.3	92	32.2
		Low	44.6	91.7	16.2
	Low	High	44.3	80.8	33
		Low	44.5	81.2	16.7
Green	High	High	151.5	91.5	33.1
		Low	152.2	91.7	16.5
	Low	High	150.9	80.7	32.9
		Low	150.6	81.1	16.7
Blue	High	High	290.9	90.8	33.2
		Low	292.1	90.9	17.1
	Low	High	291.2	80.4	33.1
		Low	291.9	80.4	16.8
(Achromatic)		Low		44.5	33.1
		High		40.3	16.6

Columns L^* and h^* display the lightness and hue values according to the CIE L_{Ch} 1976 system (Commission Internationale de l'Éclairage, 2007) calculated from the CIE *XYZ* tristimulus values according to the 10° CIE 1964 standard observer (Commission Internationale de l'Éclairage, 2006). Column S displays the saturation values calculated from the L_{Ch} 1976 chroma (C^*) values: $S = C^*2/(C^*2 + L^*2)1/2 \cdot 100\%$ (cf. Lübbe, 2013). L^*, S, and h^* are specified relative to a D65 white point.

four music pieces 14 times regarding their perceived emotional dimensions ('How harmonic/powerful/gloomy/lively is the music?') and overall liking ('How much do you like the music?'). They also indicated the perceived fit of music and lighting ('How well do music and lighting fit together?'). All items were assessed on 10-point rating scales ranging from 0 ('not at all') to 9 ('very much').

For each participant, the experiment consisted of three blocks, which were presented in a fixed order. In the first block (music and lighting condition — ML), participants rated the four music pieces (30-s excerpts) under each of the 14 lighting conditions on the aforementioned scales. Thus, every lighting condition prevailed for 4 × 30 s = 2 mins. Participants were instructed to give verbal ratings within the 30-s intervals while listening to the music and looking at the LED wall. We presented 30-s intervals of white lighting between the different lighting conditions to enable participants' eyes to re-adapt. During this time, participants did not receive particular instructions but continued to look at the LED wall. The 14 lighting conditions were presented in random

Table 3.
Experimental design and rating scales

ML	MO	LO
Verbal rating of each music with each lighting	Paper/pencil rating of each music under white lighting	Paper/pencil rating of each lighting in silence
56 trials | 40 min.	4 trials | 5 min.	14 trials | 15 min.
–	a. SAM scales (9-pt)	a. SAM scales (9-pt)
	Valence	Valence
	Arousal	Arousal
	Dominance	Dominance
b. Liking (10-pt)	b. Liking (10-pt)	b. Liking (10-pt)
c. Appraisal (10-pt)	c. Appraisal (10-pt)	c. Appraisal (10-pt)
Harmonic	Harmonic	Harmonic
Powerful	Powerful	Powerful
Gloomy	Gloomy	Gloomy
Lively	Lively	Lively
d. Music–lighting fit (10-pt)	–	–
–	e. Familiarity (10-pt)	–
–	–	f. Demographic Data
–	–	g. Gold-MSI short

ML = music and lighting condition; MO = music-only condition; LO = lighting-only condition; SAM = Self-Assessment Manikin.

order, and under each lighting condition, the four music excerpts were also presented in random order.

In the second experimental block, we presented the four music excerpts together with neutral white lighting (D65, luminance: 99.9 cd/m^2, saturation: 45.4%; music-only condition — MO) and asked participants to rate the music on the same scales as in the ML condition. In the third experimental block, participants performed separate ratings for the 14 lighting conditions presented in silence (lighting-only condition — LO). In both blocks, participants rated music appraisal and liking as well as the emotional valence, evoked arousal, and perceived dominance of the stimuli. We employed a 9-point version of the Self-Assessment Manikin scales (SAM scales, cf. Bradley and Lang, 1994).

At the end of the experiment, participants filled in a questionnaire on demographic data as well as a short version of the Gold-MSI (Schaal *et al.*, 2014; see subsection 2.2. *Sample*). Table 3 provides a summary of the study design.

3. Results

We first report the effects of lighting on music appraisal and then the results for perceived music–lighting fit (as collected in the main experiment). As to the influence of lighting on music appraisal, we calculated two repeated-measures multivariate analyses of variance (rmMANOVA). In the first analysis, we considered only the chromatic stimuli to investigate a potential influence of hue. In the second analysis, we averaged the ratings over hue and included the achromatic stimuli, focusing on the effect of saturation. Subsequently, we examined the music-only and lighting-only ratings, which we considered as a baseline for the investigation on music–lighting fit. We then calculated two rmANOVAs on fit ratings, including and excluding achromatic stimuli, as described above for music appraisal. Results for the dependent variable ‘liking’ did not show any significant patterns and are listed in Tables A5 and A6 in the Appendix. We used the Greenhouse–Geisser correction for the degrees of freedom where necessary (correction factor ε; this applies to all subsequent analyses in this article).

3.1. *Effects of Lighting on Music Appraisal*

3.1.1. *Chromatic Colors*

We first consider the effects of hue on the music appraisal ratings. Upon visual inspection (see Fig. 2), music was perceived as more powerful (panel b) and livelier (panel d) under red lighting, and less powerful and lively under blue lighting. Under green lighting, the ‘Powerful’ and ‘Lively’ ratings did not change, whereas ‘Gloomy’ ratings went down (panel c). The ‘Harmonic’ ratings were largely unaffected by the variation of hue (panel a). A 3 (hue) × 2 (saturation) × 2 (luminance) × 2 (tonality) × 2 (genre) rmMANOVA with the four rating dimensions as the dependent measures failed to reveal a significant multivariate main effect for the factor hue, $F_{8,208} = 1.92$, $p = 0.059$, $\eta^2 = 0.069$. *Post-hoc* rmANOVAs (univariate approach) with the same factorial design run separately for each dependent variable showed that none of the ratings was significantly affected by the manipulations of hue, $F_{2,106} \leqslant 2.81$, $p \geqslant 0.065$, $\eta^2 \leqslant 0.05$.

There were also no significant main effects for saturation, $F_{4,50} = 1.7$, $p = 0.165$, $\eta^2 = 0.12$, and luminance, $F_{4,50} = 0.78$, $p = 0.541$, $\eta^2 = 0.059$, but a significant hue * tonality interaction, $F_{8,208} = 2.03$, $p = 0.045$, $\eta^2 = 0.072$. The *post-hoc* rmANOVAs showed that this interaction was mainly driven by the ‘Powerful’ ratings, $F_{2,106} = 6.14$, $p = 0.003$, $\eta^2 = 0.104$. The effect of hue on the ‘Powerful’ ratings was opposite depending on the tonality of the piece of music, with the maximum difference under green lighting (cf. Fig. 3). For the remaining appraisal dimensions, the hue * tonality interaction was clearly not significant, $F_{2,106} \leqslant 2.28$, $p \geqslant 0.107$, $\eta^2 \leqslant 0.041$). The complete results of the described analysis are listed in Table A1 in the Appendix.

3.1.2. *Chromatic and Achromatic Colors*

Since the ratings were largely independent of hue, we averaged the ratings under chromatic lighting across hues for the further examination of saturation

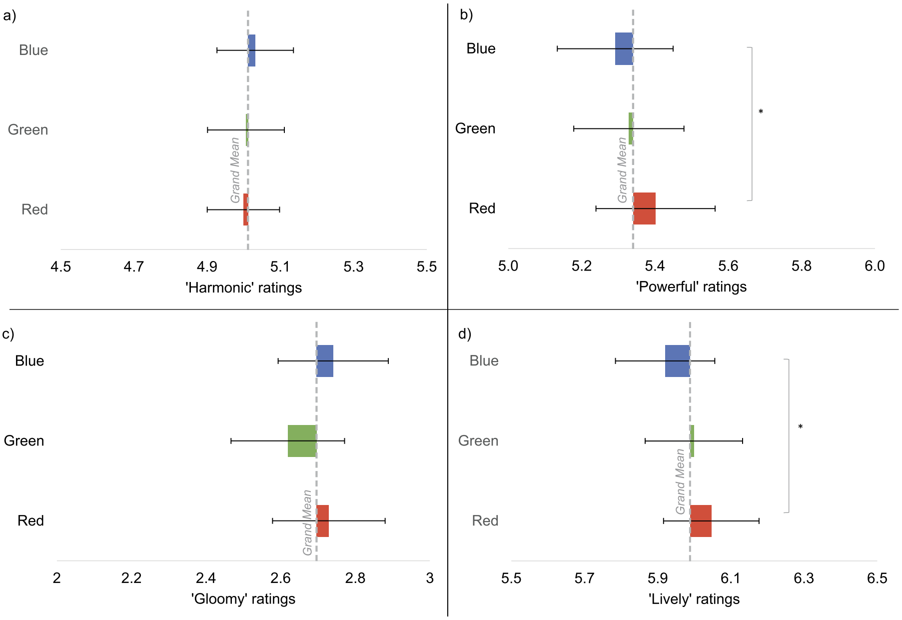

Figure 2. Mean music ratings for appraisal dimensions as a function of hue. Columns show the deviation from the Grand Mean per dependent variable. Error bars show ± 1 SEM. Asterisks indicate significant differences ($p < 0.05$) determined by *post-hoc* paired-samples t-tests (Powerful: $\Delta_{\mathrm{M\_red–blue}} = 0.11$, $p = 0.044$; Lively: $\Delta_{\mathrm{M\_red–blue}} = 0.13$, $p = 0.026$).

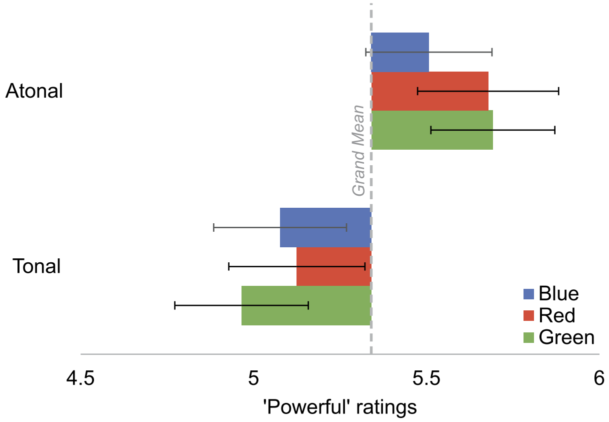

Figure 3. Mean 'Powerful' ratings for tonal and atonal music as a function of hue. Columns show the deviation from the Grand Mean per dependent variable. Error bars show ± 1 SEM.

and luminance. We also included the two achromatic lighting conditions as a third saturation level in the analysis. Figure 4 shows that music appraisal ratings varied according to the saturation level of the lighting color, especially

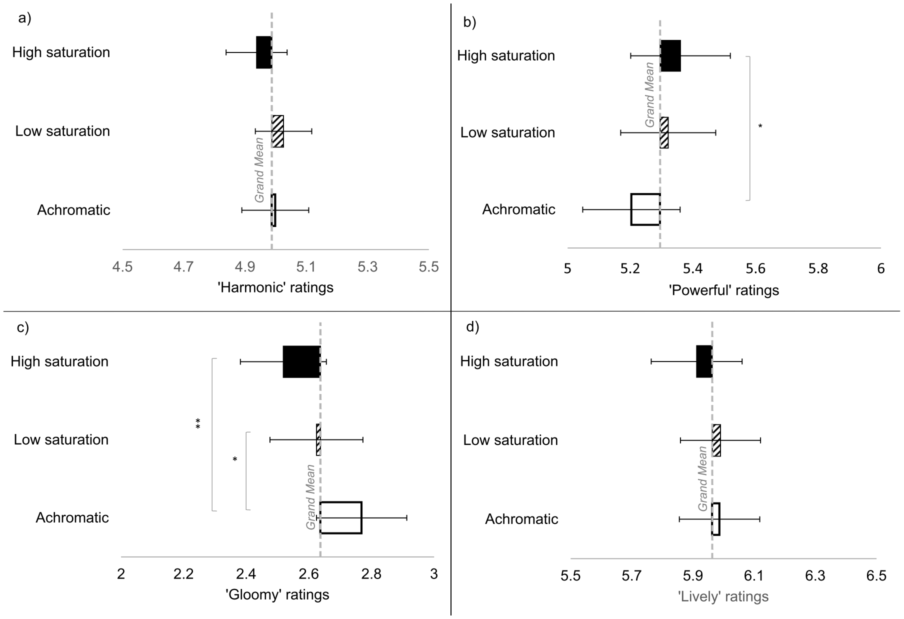

Figure 4. Mean ratings for music appraisal as a function of saturation. Columns show the deviation from the Grand Mean per dependent variable. Error bars show ± 1 SEM. Asterisks indicate significant differences (*, $p < 0.05$; **, $p < 0.01$).

for ‘Powerful’ and ‘Gloomy’ ratings. A 3 (saturation) × 2 (luminance) × 2 (tonality) × 2 (genre) rmMANOVA on the four rating dimensions revealed a significant main effect of saturation, $F_{8,208} = 2.22$, $p = 0.027$, $\eta^2 = 0.079$. According to the *post-hoc* rmANOVAs, this effect was mainly driven by the ‘Powerful’ ($F_{1.47,90.24} = 1.9$, $p = 0.042$, $\eta^2 = 0.065$) and ‘Gloomy’ ratings ($F_{1.68,90.24} = 6.64$, $p = 0.004$, $\eta^2 = 0.111$). Paired-samples t-tests (two tailed) showed that the music pieces were perceived more powerful under high-saturated lighting compared to achromatic lighting ($\Delta_{\text{M\_high-achromatic}} = 0.157$, $p = 0.031$, $\Delta_{\text{M\_high-low}} = 0.039$, $p = 0.309$, $\Delta_{\text{M\_low-achromatic}} = 0.117$, $p = 0.08$, cf. Fig. 4b). Also, music was perceived gloomier as saturation was lower ($\Delta_{\text{M\_high-low}} = 0.144$, $p = 0.01$; $\Delta_{\text{M\_high-achromatic}} = 0.25$, $p = 0.003$, $\Delta_{\text{M\_low-achromatic}} = 0.106$, $p = 0.132$, cf. Fig. 4c). Univariate effects of saturation for the ‘Harmonic’ and ‘Lively’ ratings missed significance (Harmonic: $F_{1.70,90.24} = 1.9$, $p = 0.161$, $\eta^2 = 0.035$; Lively: $F_{1.57,83.40} = 1.02$, $p = 0.350$, $\eta^2 = 0.019$, cf. Figs 4a and d).

The MANOVA also revealed a significant saturation * tonality interaction, $F_{8,208} = 2.18$, $p = 0.03$, $\eta^2 = 0.077$. According to the *post-hoc* rmANOVAs, this effect can be traced back to the ‘Harmonic’ ($F_{1.6,86.24} = 4.35$, $p = 0.022$, $\eta^2 = 0.076$) and ‘Lively’ ratings ($F_{1.77,86.24} = 5.68$, $p = 0.006$, $\eta^2 = 0.097$). ‘Harmonic’ ratings for tonal music were higher when saturation was low. For

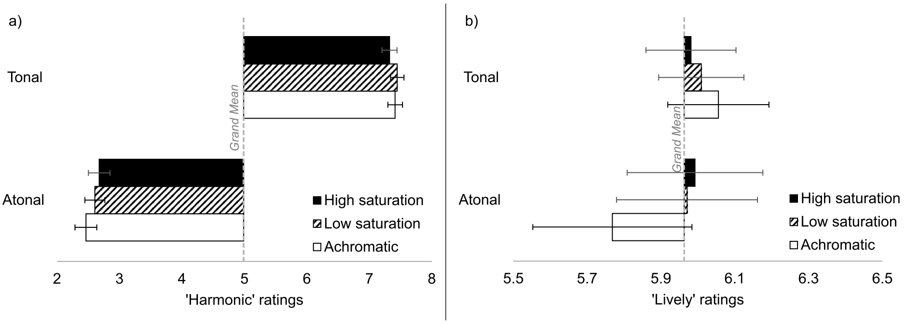

Figure 5. Mean 'Harmonic' and 'Lively' ratings for tonal and atonal music as a function of different saturation levels of ambient lighting. Columns show the deviation from the Grand Mean per dependent variable. Error bars show ± 1 SEM.

atonal music, this relation was inverse (see Fig. 5a). 'Lively' ratings were higher for tonal music and lower for atonal music when participants were exposed to achromatic lighting compared to saturated lighting (see Fig. 5b). Ratings of the music pieces remained largely unaffected by the variation of luminance. In the MANOVA, there was neither a significant main effect for luminance, $F_{4,50} = 1.73$, $p = 0.158$, $\eta^2 = 0.122$, nor any significant interaction involving luminance (see also Appendix, Fig. A1 and Table A2).

3.2. Unimodal Ratings

Before we come to describing the results for perceived music–lighting fit, we will first refer to the unimodal music-only (MO) and lighting-only (LO) ratings that were made in the second and third blocks of the experiment. These ratings, first made for music under white lighting and then for lighting in silence, serve as a baseline and facilitate the interpretation of the interrelations found in the bimodal conditions. For each stimulus, participants completed the SAM scales in terms of emotional valence, arousal, and dominance (Bradley and Lang, 1994, see section 2. *Material and Methods*), and, additionally, the four rating scales 'Harmonic', 'Powerful', 'Gloomy', and 'Lively'.

3.2.1. Music-Only Ratings (MO)

SAM ratings for the music pieces are shown in Figs 6a and 6b. We can see that valence and dominance were higher, while arousal was lower for tonal compared to atonal music. Panels c and d show the music appraisal ratings. Tonal music was rated more harmonic than atonal music, whereas atonal music was rated more gloomy than tonal music. Comparing genres, classical music received higher ratings for all four dimensions. We calculated two 2 (tonality) × 2 (genre) rmMANOVAs with the SAM ratings as the dependent measures in one and the appraisal ratings in the other analysis. There was a significant effect of tonality on the valence, dominance, arousal, 'Harmonic',

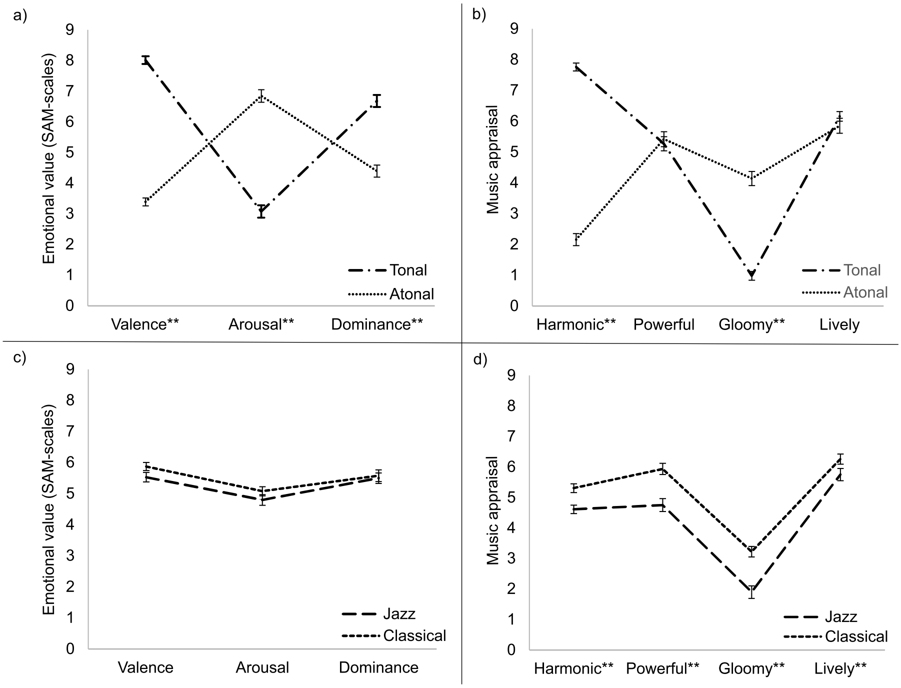

Figure 6. Mean ratings for valence, arousal, and dominance (a, c), and appraisal dimensions (b, d) of music pieces in the MO condition as a function of tonality (a, c) and genre (b, d). Error bars show ± 1 SEM. Asterisks mark significant main effects (*, $p < 0.05$; **, $p < 0.01$).

and ‘Gloomy’ ratings. The factor Genre was significant for all four appraisal dimensions, but not for the SAM ratings. Statistic parameters can be retrieved from Tables A7 and A8 in the Appendix.

3.2.2. Light-Only Ratings (LO)

Valence, arousal, and dominance patterns of the light-only ratings are depicted in Figs 7a to c. Descriptively, valence ratings were higher for blue than for red lighting, while arousal was rated higher for red than for green and blue lighting. In terms of saturation, valence and dominance were higher and arousal was lower for low-saturated and achromatic lighting compared to highly saturated lighting. Likewise, arousal was higher for high compared to low luminance. Panels d to f show the lighting appraisal. Blue lighting was rated to be more harmonic and gloomier compared to green and red lighting, while red and green lighting were appraised as more powerful and livelier than blue lighting. Participants indicated low-saturated and achromatic lighting as more harmonic than highly saturated lighting, while high saturation led to higher ‘Powerful’, ‘Gloomy’, and ‘Lively’ ratings. Lighting of high luminance was rated more powerful and lively, but less harmonic. We calculated two versions

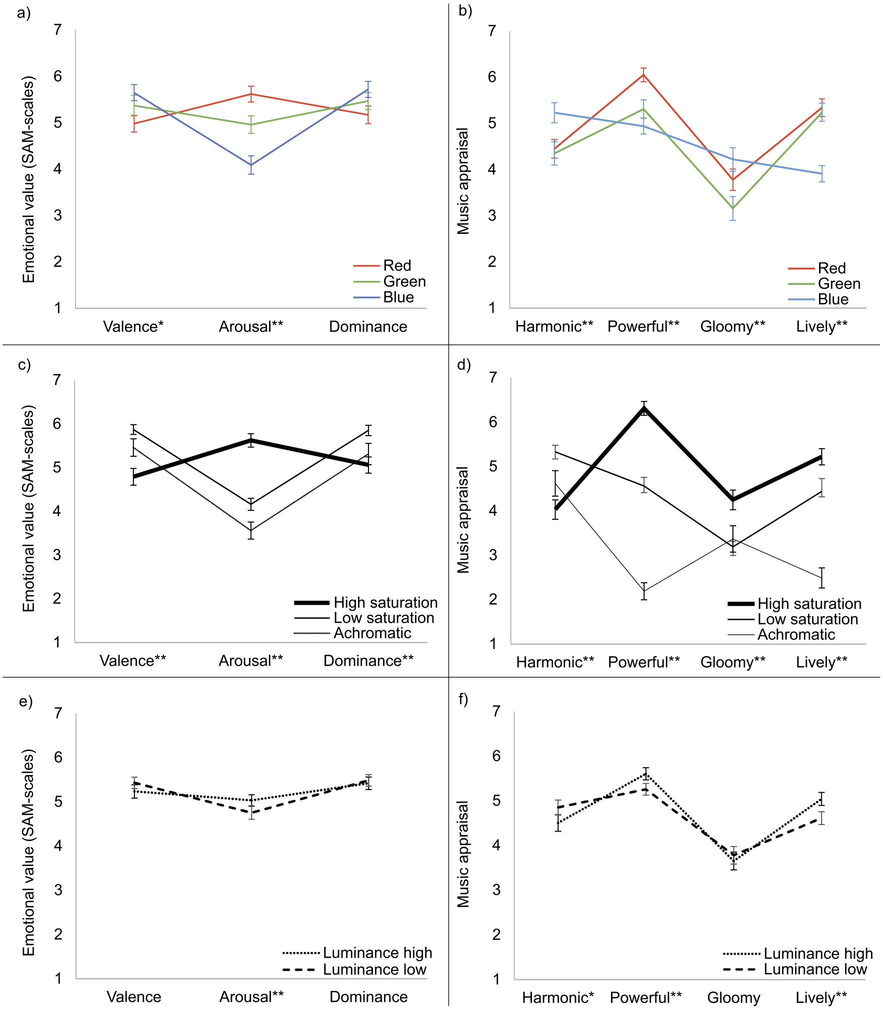

Figure 7. Mean ratings for valence, arousal, and dominance (a, c, e), and appraisal dimensions (b, d, f) of lighting color in the LO condition as a function of hue (a, b), saturation (c, d), and luminance (e, f). Error bars show ± 1 SEM. Asterisks mark significant main effects (*, $p < 0.05$; **, $p < 0.01$).

of a 3 (hue) × 2 (saturation) × 2 (luminance) rmMANOVA with different dependent measures: the SAM ratings in the first, and the appraisal ratings in the second MANOVA. There was a significant effect of hue on valence and arousal ratings, as well as on all four appraisal dimensions, while saturation exerted a significant effect on all dependent measures. As to luminance, tonality significantly influenced arousal ratings, as well as ‘Harmonic’, ‘Powerful’ and ‘Lively’ ratings. Statistic parameters can be retrieved from Tables A9 and A10 in the Appendix).

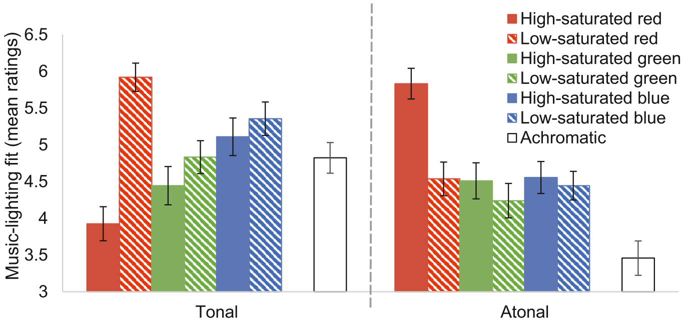

Figure 8. Mean music–lighting fit ratings for tonal and atonal music in combination with ambient lighting of different hues and saturation levels. Error bars show ± 1 SEM.

3.3. Music–Lighting Fit

3.3.1. Chromatic Lighting

We first consider the effects of hue on perceived music–lighting fit. Participants rated atonal music and red lighting to fit better than atonal music and blue or green lighting. In turn, there was a better-perceived fit for tonal music and blue lighting than for tonal music and green lighting (cf. Fig. 8). We calculated a univariate 3 (hue) × 2 (saturation) × 2 (luminance) × 2 (tonality) × 2 (genre) rmANOVA with music–lighting fit as the dependent variable, prospecting for interactions of the colorimetric lighting dimensions with the music dimensions. The interaction hue * tonality missed significance, $F_{2,106} = 2.67$, $p = 0.074$, $\eta^2 = 0.048$. However, there were significant interactions of saturation * tonality, $F_{2,106} = 36.95$, $p < 0.001$, $\eta^2 = 0.411$, and hue * saturation * tonality, $F_{2,106} = 36.95$, $p < 0.001$, $\eta^2 = 0.411$, which indicates that perceived music–lighting fit of tonal *vs* atonal music with lighting color depended largely on the saturation level. We can see in Fig. 8 that low-saturated ambient colors were judged to fit better with tonal music, and high-saturated colors to fit better with atonal music. The latter effect was most pronounced for red. In the figure, achromatic lighting is depicted as a reference, but it was not included in the analysis, as it was not a fully crossed factor. The interaction luminance * tonality was not significant, $F_{1,53} = 0.93$, $p = 0.34$, $\eta^2 = 0.017$, just as any other interaction involving luminance (see Appendix, Table A3). Although there were several significant two-way and three-way interactions involving both tonality and genre, we will not attempt to interpret them here. Note that since there was only one music piece per tonality–genre combination, these interactions are hardly meaningful.

3.3.2. Chromatic and Achromatic Lighting

As for music appraisal, we averaged fit ratings across hues to examine saturation effects more closely. Again, we handled the achromatic stimuli as a

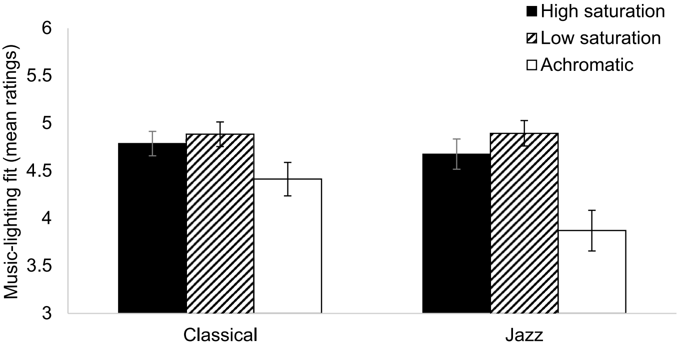

Figure 9. Mean music–lighting fit ratings for different combinations of music and ambient lighting. Error bars show ± 1 SEM.

third level of saturation and calculated a univariate 3 (saturation) × 2 (luminance) × 2 (tonality) × 2 (genre) rmANOVA. The saturation * tonality interaction, $F_{1.41,74.53} = 20.59$, $p < 0.001$, $\eta^2 = 0.28$, and the saturation * genre interaction were significant, $F_{1.5,80.09} = 4.53$, $p = 0.022$, $\eta^2 = 0.079$. Just as low-saturated lighting, achromatic lighting was rated to fit better with tonal compared to atonal music (see Fig. 8). As to genre, achromatic lighting was judged to match with classical rather than with jazz music (see Fig. 9). Just as for music appraisal, all effects involving luminance were not significant for music–lighting fit. The complete results of the described analysis are listed in Table A4 in the Appendix.

3.4. Conjunction of Bimodal With Unimodal Ratings

We related the ratings of music–lighting fit to the separate valence, arousal, and dominance ratings of music and lighting. To illustrate the parallels between LO and MO ratings, we take up again the unimodal SAM ratings and juxtapose those for lighting of different saturation levels and hues with those for music of different genres and tonalities (see Fig. A2 in the Appendix). Atonal music and highly saturated lighting follow a mutual valence–arousal–dominance pattern (arousal higher than valence and dominance), while all other stimuli are rated the opposite way. It becomes apparent that those factor combinations with similar unimodal SAM patterns go along with higher mean ratings of music–lighting fit. Again, the stimuli that were similarly evaluated in terms of their emotional value in the MO and LO conditions, received higher fit ratings when presented in combination in the ML condition.

As to semantic appraisal, we compared unimodal ‘Harmonic’, ‘Powerful’, ‘Gloomy’, and ‘Lively’ ratings for music and lighting (see Fig. A3 in the Appendix). It becomes apparent that atonal music shows a similar pattern to saturated and red lighting, i.e., lower ratings for ‘Harmonic’ and ‘Gloomy’ and higher ratings for 'Powerful' and 'Lively'. Appropriately, fit ratings were higher for the respective stimulus combinations.

4. Discussion

In this study, we examined the interrelationship between music and the color of ambient lighting. Specifically, we were interested in a potential influence of lighting color on music appraisal, and a possible fit of certain colorimetric values with certain music characteristics. To put our research questions to test, we first conducted two pre-tests, to select and pre-evaluate the stimuli that were later applied within the main experiment. In this main experiment, participants were asked to rate music pieces under different lighting conditions in terms of music appraisal and music–lighting fit.

4.1. Influence of Lighting on Music Appraisal

4.1.1. Effects of hue

Music ratings shifted as a function of ambient color. Music was perceived to be more powerful and livelier when accompanied by red lighting and less powerful and lively when accompanied by blue lighting. Under green illumination, tonal music was rated as least powerful. These effects are in line with our first assumption, according to which music ratings would change under colored lighting. As expected, there was a transfer effect from the lighting to music ratings. According to the unimodal ratings in the lighting-only condition, red lighting is perceived to be livelier and more powerful than blue lighting. This finding ties in with previous findings in the field of color research (cf. Elliot, 2019). Moreover, red lighting is more arousing than blue and green lighting, which matches the active connotation of 'Powerful' and 'Lively'. Again, this result is in agreement with the literature (e.g., Rajae-Joordens, 2011). Referring to our finding of music sounding livelier and more powerful in a red environment, we conclude that the characteristics of the ambient light are transported to the music. This mechanism has been detected for stimulus combinations in other sensual domains before. For instance, wine tastes livelier when we are listening to lively music during the wine tasting (Hauck and Hecht, 2019b), coffee tastes sweeter when tasted from a cup with a smooth surface (Carvalho *et al.*, 2020), and lemon scent is more distinct when we see a yellow color patch (Demattè *et al.*, 2009). Our findings extend these crossmodal effects to the interaction of music and ambient color.

4.1.2. Effects of Saturation and Luminance

The present results reveal differences in music appraisal according to the saturation level of the ambient lighting. Music was rated to be more powerful and less gloomy under low- and high-saturated chromatic lighting compared to achromatic lighting. This goes along with saturated lighting being judged as more powerful and less gloomy when rated per se (LO). For the ‘Harmonic’ and ‘Lively’ ratings we found a difference between tonal and atonal music, as tonal music was perceived more harmonic and livelier with decreasing saturation, whereas atonal music was rated less harmonic and lively with decreasing saturation. This interaction illustrates the importance of an appropriate match of music on the one hand and hue and saturation of the ambient color on the other. Luminance, in contrast, did not exert any effect on music appraisal, which is not surprising given that ambient light per se (LO) was appraised similarly across luminance levels. We can see again that some but not all characteristics of the lighting are mirrored in the shift of music ratings.

4.2. Music–Lighting Fit

The examination of perceived music–lighting fit for different combinations of lighting color and music indicated a clear pattern of matching and non-matching stimuli. Fit ratings varied mostly depending on the tonality of the music and the saturation of the ambient color, such that participants rated low-saturated lighting to fit better with tonal music whereas high-saturated colors were judged to go better with atonal music. This relation was especially pronounced for red hues. Furthermore, achromatic lighting was associated with classical rather than with jazz music. We observed that those stimuli were more likely to be judged to fit together that showed a similar pattern in terms of their emotional connotation (SAM scales) when rated alone. As such, atonal music led to higher arousal, but lower valence and dominance ratings, and so did highly saturated and red colors. Achromatic lighting led to higher valence and dominance, but lower arousal ratings, just as classical music did.

4.3. Considering the State of Research

4.3.1. Visual Influence on Music Perception

How do these findings tie in with existing studies of music perception? Other seemingly irrelevant visual impressions can exert a considerable influence on music perception. For instance, the evaluation of a person’s musical performance depends on the availability of visual information, i.e., it is important that the listener can see the musician. In a study by Behne (1994), participants were asked to rate videos of piano players on eight dimensions. The videos showed the picture of four different piano players, but the sound was always the same recording played by one of the pianists. Both musical novices and musically trained participants reported hearing differences among the performances depending on the visual input. For instance, videos showing male pianists were rated more ‘precise’, while videos showing female pianists were appraised as more ‘dramatic’. The results were confirmed in a replication study by Behne and Wöllner (2011). In a more recent work, Vuoskoski *et al.* (2014), employing point-light animations of piano performances as visual stimuli and computer-generated piano sounds as auditory stimuli, created matching and mismatching audiovisual piano performances. Participants were asked to rate the expressivity of a music performance referring to either the visual or the auditory information given. Results showed that auditory expressivity ratings were strongly influenced by the point-lights. Performances were rated significantly less expressive in the 'deadpan' video condition and more expressive when the 'exaggerated' video was shown. Similar results were found in numerous studies investigating the relation of auditory and visual impressions of music presentations (e.g., Thompson *et al.*, 2008; Vines *et al.*, 2006, 2011). In a meta-analysis, Platz and Kopiez (2012) showed that the visual component accounts for an average medium effect size of 0.51 standard deviations with regard to the evaluation of music performances. Even the way how musicians enter the stage can influence the initial judgment of their performance (Waddell and Williamon, 2017); but not only the sight of the performer influences the auditory impression of the musical performance, also visual social cues, such as the audience members surrounding the listener, affect musical experience. For instance, Dotov *et al.* (2021) recently showed in a motion capture experiment that, *inter alia*, the perceived valence and emotional intensity of the music increased with movement energy, which in turn was associated with the visible presence of other persons listening and moving to the music.

4.3.2. Association of Visual and Auditory Stimuli

As to mappings of visual and auditory stimuli, there is evidence that the emotional associations made with each of the stimuli play a crucial role in the perception of audiovisual fit. For instance, Whiteford *et al.* (2018) examined the crossmodal relation of 34 music excerpts from different genres with 37 colors by analyzing data on music-to-color associations, color and music emotions, as well as color and music perception. They found, for instance, that more agitated-sounding music was associated with more agitated-looking colors, which confirmed their postulated emotion mediation hypothesis (see also Barbiere *et al.*, 2016; Lindborg and Friberg, 2015; Palmer *et al.*, 2013). Furthermore, arousal and valence turned out to be mediating factors for music-to-color associations, which is perfectly in line with what we determined for music–lighting fit in the present study. Thus, similar learned emotional associations could be at their root. Emotional mediation has also been found to be decisive for the association of other combinations of sensory input, for instance classical music and the taste of wine (Wang and Spence, 2017), and colors and the scent of fragrances (Schifferstein and Tanudjaja, 2004).

Beside direct emotional associations, less direct semantic ascriptions represent an alternative explanation for the stimulus pairings we found. For instance, in a study by Albertazzi *et al.* (2020), participants were asked to rate paintings by Kandinsky and music by Schönberg on semantic differential scales (Osgood, 1957). In a second task, they were required to pick those paintings and music pieces that they felt to match. It turned out that stimuli judged to be semantically alike were also more likely to be paired. Similar results have even been found for the association of highly-elevated objects and high-pitched sounds in speeded classification, as well as for animals and their vocalizations with children in a Stroop-like paradigm (Thomas *et al.*, 2017). However, not all our findings can be explained by such semantic congruency effects. Some stimulus categories that were judged to fit together, such as atonal music and saturated lighting, indeed show similar unimodal semantic appraisal patterns. However, other 'fitting' combinations do not exhibit semantic commonalities, such as classical music and achromatic lighting.

4.4. Limitations and Future Directions

While we successfully demonstrated crossmodal music–lighting associations in the present study, a few limitations need to be considered regarding the methodology and generalizability of our findings. In some cases, only one attribute drove the significant effect (e.g., 'Powerful'), whereas other attributes showed hardly any variation. This shows that the found crossmodal correspondences depend on the character of the respective measure and its multimodal applicability. The attribute 'Powerful' might be more suitable for both music and color than 'Gloomy'. Follow-up studies should include a greater diversity of dependent variables to investigate this issue more broadly. A more principled methodological constraint lies in the necessary limits to the equivalence of the experimental conditions for unimodal and multimodal ratings of music and lighting. We had chosen relative silence — as opposed to an anechoic chamber — as the baseline for lighting-only ratings. And music-only ratings were made in a baseline of white lighting — as opposed to complete darkness. The choice of baseline may have influenced the ratings, although we do not readily see how this could have introduced a systematic bias. Future investigations could address this issue by refining their methods accordingly. Additionally, further research is necessary to explore the robustness and generalizability of the discovered crossmodal connections. As such, follow-ups should explore if the effects can be transferred to other music pieces and music genres, as well as to complete music pieces (as opposed to excerpts) that may exhibit more variability over the course of the piece. It would be interesting to systematically explore the influence of tempo, mode, and instrumentation, just to name a few relevant factors. Especially, music including lyrics compared to instrumental music should be examined in terms of the observed effects.

The results of the present study suggest that the consideration of crossmodal correspondences between music and lighting is a promising way to intensify the listening experience of music. However, our experimental setup differed notably from natural music listening conditions. Further research is needed to determine whether or not the findings can be transferred to other light sources and ways of propagation. For instance, it might make a difference if we are looking right into the light source, if we are sitting in the middle of an illuminated room, or if we are looking at an illuminated stage from afar while sitting in the dark auditorium. Future studies should also consider longer durations for the presentation of lighting colors. We chose the quick variation of music and lighting conditions for practical purposes. Now that the effect has been demonstrated, it seems worthwhile to start exploring more realistic scenarios. We furthermore suggest reflecting on the aspect of chromatic adaptation. After only 40–70 ms of being exposed to colored lighting, we may no longer consciously perceive the lighting color or its initial chromatic appearance anymore, and the process of desensitization can last up to two minutes (Rinner and Gegenfurtner, 2000). Will there still be a crossmodal transfer of lighting characteristics to music appraisal with longer exposure? What happens to audiovisual interaction during the length of a whole song, or even a full-length concert? Will the impact of the lighting decrease, as attention drifts principally to the auditory domain over time? Now that we know that correspondences between music and colored lighting exist, these insights could be extended by conducting field studies that explore crossmodal effects in private and public listening situations.

4.5. Practical Implications

The results demonstrated in this work provide a new perspective on the role that lighting and illumination play in the aesthetic judgment of music. As early as in the 1920s the Hungarian pianist and composer Alexander László discovered the interaction of music and ambient color and composed his first pieces ‘for piano and colored light’. Being a synesthete, he used his personal synesthetic impressions for creating music–color compositions, and therefore invented the so-called ‘Sonchromatoskop’, and later his ‘Color Light Organ’ (Jewanski, 1997). László followed Ostwald’s theory of color (Ostwald, 1917) and systematically transferred musical dimensions into the color dimensions he found in Ostwald’s color wheel. Musical harmonies were visualized via color intervals, the rhythm was translated into shorter or longer color impulses, dynamics were associated with brightness (the louder, the brighter), etc. However, specific tone–color pairings have not been documented.

Another famous musical composition in conjunction with colored lighting is Alexander Scriabin’s ‘*Prometheus*: *The Poem of Fire*’, a so-called ‘light symphony’ first performed in 1962 (cf. Galeyev and Vanechkina, 2001). In contrast to László, Scriabin developed a system of ‘color hearing’ which determined specific pairings of musical tones with colors. For instance, the tone E per se was associated with a whitish blue, E major with sapphire blue, and E flat major with a dark grayish blue (Galeyev and Vanechkina, 2001). Even if it is not clear if Scriabin was a synesthete as well, the described mappings were based on his very personal sense of music–lighting fit. Accordingly, the idea of matching music with certain ambient colors is not novel, but in most cases, its realizations are based on individual preferences and the artistic sense of the creator rather than on evidence for universal crossmodal correspondences.

In a quite different approach, Moon and colleagues (2015) collected data on music mood in a large sample of listeners via a web questionnaire. On that basis, they developed a neural network and a lighting system reflecting the prevailing mood in the music. The system recognized the transported mood and accordingly chose the lighting color, aiming at an enhancement of the respective mood in the listener. However, neither this intensifying effect nor the perceived fit of music and lighting were tested in the study. We propose that the results of the present study should be considered for future developments. Although Moon et al.'s 'mood classification module' has not yet proven to be sufficient for commercial use, the idea of automating the color of ambient lighting according to the music is highly relevant for concert hall illumination (cf. Chen, 2013) as well as for home entertainment systems. The present results suggest that not only mood, but colorimetric and musical dimensions such as hue, saturation, and luminance, and tonality and genre should be studied in that regard. Based on our findings, a system emitting achromatic lighting with classical music and saturated lighting with atonal music would be a great asset.

4.6. Conclusions

We have provided the first demonstration that crossmodal correspondences between music and ambient lighting do exist. Specifically, we provide evidence for associations between music tonality and genre with the saturation and hue of ambient lighting. There are two key findings: Music appraisal ratings are shifted by lighting hue and saturation such that emotional attributions made for the lighting are mirrored and thus enhanced in the ratings. Moreover, music pieces and lighting colors that trigger similar emotional reactions are more likely to be perceived as fitting by the listener. This interrelation is of particular interest for the music event industry, e.g., when it comes to designing the illumination of stages or concert halls.

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Appendix

Table A1.
Results of a 3 (hue) × 2 (saturation) × 2 (luminance) × 2 (tonality) × 2 (genre) rmMANOVA on music characteristics. Multivariate and univariate main effects and interactions

Dimensions of music or lighting		F	df	p	η^2
Multivariates	Univariates				
Hue		**1.92**	**8/208**	**0.059**	**0.069**
	Harmonic	0.24	2/106	0.784	0.005
	Powerful	2.45	2/106	0.091	0.044
	Gloomy	1.58	2/106	0.211	0.029
	Lively	2.81	2/106	0.065	0.050
Saturation		**1.70**	**4/50**	**0.165**	**0.120**
Luminance		**0.78**	**4/50**	**0.541**	**0.059**
Tonality		**167.41****	**4/50**	**0.000**	**0.931**
	Harmonic	572.67**	1/53	0.000	0.915
	Powerful	7.16**	1/53	0.010	0.119
	Gloomy	317.11**	1/53	0.000	0.857
	Lively	0.01	1/53	0.934	0.000

Table A1.
(Continued)

Dimensions of music or lighting		F	df	p	η^2
Multivariates	Univariates				
Genre		**44.08****	**4/50**	**0.000**	**0.779**
	Harmonic	36.55**	1/53	0.000	0.408
	Powerful	70.80**	1/53	0.000	0.572
	Gloomy	93.97**	1/53	0.000	0.639
	Lively	10.03**	1/53	0.003	0.159
Hue × saturation		**1.73**	**8/208**	**0.094**	**0.062**
Hue × luminance		**0.87**	**8/208**	**0.542**	**0.032**
Saturation × luminance		**0.23**	**4/50**	**0.918**	**0.018**
Hue × saturation × luminance		**0.73**	**8/208**	**0.663**	**0.027**
Hue × tonality		**2.03***	**8/208**	**0.045**	**0.072**
	Harmonic	0.23	2/106	0.799	0.004
	Powerful	6.13**	2/106	0.003	0.104
	Gloomy	2.28	2/106	0.107	0.041
	Lively	0.77	2/106	0.466	0.014
Saturation × tonality		**1.55**	**4/50**	**0.203**	**0.110**
Hue × saturation × tonality		**1.46**	**8/208**	**0.175**	**0.053**
Luminance × tonality		**0.92**	**Apr 50**	**0.459**	**0.069**
Hue × luminance × tonality		**0.64**	**8/208**	**0.745**	**0.024**
Saturation × luminance × tonality		**0.45**	**4/50**	**0.775**	**0.034**
Hue × saturation × luminance × tonality		**0.81**	**8/208**	**0.596**	**0.030**
Hue × genre		**0.72**	**8/208**	**0.674**	**0.027**
Saturation × genre		**1.20**	**4/50**	**0.322**	**0.088**
Hue × saturation × genre		**0.75**	**8/208**	**0.647**	**0.028**
Luminance × genre		**2.06**	**4/50**	**0.100**	**0.142**
Hue × luminance × genre		**1.83**	**8/208**	**0.073**	**0.066**
Saturation × luminance × genre		**0.43**	**4/50**	**0.786**	**0.033**
Hue × saturation × luminance × genre		**1.01**	**8/208**	**0.427**	**0.038**
Tonality × genre		**68.16****	**4/50**	**0.000**	**0.845**
	Harmonic	0.02	1/53	0.903	0.000
	Powerful	8.55**	1/53	0.005	0.139
	Gloomy	265.29**	1/53	0.000	0.833
	Lively	4.23*	1/53	0.045	0.074
Hue × tonality × genre		**1.53**	**8/208**	**0.149**	**0.056**
Saturation × tonality × genre		**0.64**	**4/50**	**0.639**	**0.048**
Hue × saturation × tonality × genre		**0.77**	**8/208**	**0.630**	**0.029**
Luminance × tonality × genre		2.39	4/50	0.063	0.160
Hue × luminance × tonality × genre		1.44	8/208	0.180	0.053
Saturation × luminance × tonality × genre		0.23	4/50	0.918	0.018
Hue × saturation × luminance × tonality × genre		1.07	8/208	0.387	0.039

Multivariates refer to Pillai's trace values. Asterisks indicate significant effects (*, $p < 0.05$; **, $p < 0.01$).

Table A2.
Results of a 3 (saturation) × 2 (luminance) × 2 (tonality) × 2 (genre) rmMANOVA on music characteristics. Multivariate and univariate main effects and interactions

Dimensions of music or lighting		F	df	p	η^2
Multivariates	Univariates				
Saturation		**2.22***	**8/208**	**0.027**	**0.079**
	Harmonic	1.90	1.70/90.24	0.161	0.035
	Powerful	3.69*	1.47/77.84	0.042	0.065
	Gloomy	6.64**	1.68/89.03	0.004	0.111
	Lively	1.02	1.57/83.40	0.350	0.019
Luminance		**1.73**	**4/50**	**0.158**	**0.122**
Tonality		**171.2****	**4/50**	**0.000**	**0.932**
	Harmonic	582.02**	1/53	0.000	0.917
	Powerful	5.41*	1/53	0.024	0.093
	Gloomy	306.78**	1/53	0.000	0.853
	Lively	0.36	1/53	0.553	0.007
Genre		**41.82****	**4/50**	**0.000**	**0.770**
	Harmonic	47.55**	1/53	0.000	0.473
	Powerful	79.45**	1/53	0.000	0.600
	Gloomy	85.95**	1/53	0.000	0.619
	Lively	12.21**	1/53	0.001	0.187
Saturation × luminance		**0.96**	**8/208**	**0.469**	**0.036**
Saturation × tonality		**2.18***	**8/208**	**0.030**	**0.077**
	Harmonic	4.34*	1.63/86.24	0.022	0.076
	Powerful	3.12	1.68/89	0.057	0.056
	Gloomy	0.02	1.69/89.46	0.965	0.000
	Lively	5.68**	1.76/93.53	0.006	0.097
Luminance × tonality		**0.511**	4/50	**0.728**	**0.039**
Saturation × luminance × tonality		**0.82**	8/208	**0.590**	**0.030**
Saturation × genre		**1.29**	8/208	**0.250**	**0.047**
Luminance × genre		**0.87**	4/50	**0.491**	**0.065**
Saturation × luminance × genre		**0.53**	8/208	**0.837**	**0.020**
Tonality × genre		**55.9****	4/50	**0.000**	**0.817**
	Harmonic	0.02	1/53	0.881	0.000
	Powerful	7.13*	1/53	0.010	0.119
	Gloomy	227.08**	1/53	0.000	0.811
	Lively	3.23	1/53	0.078	0.057
Saturation × tonality × genre		**0.80**	8/208	**0.600**	**0.030**
Luminance × tonality × genre		**0.43**	4/50	**0.790**	**0.033**
Saturation × luminance × tonality × genre		**1.32**	8/208	**0.237**	**0.048**

Multivariates refer to Pillai's trace values. Asterisks indicate significant effects (*, $p < 0.05$; **, $p < 0.01$).

Table A3.
Results of a univariate 3 (hue) × 2 (saturation) × 2 (luminance) × 2 (tonality) × 2 (genre) rmANOVA on music–lighting fit. Univariate main effects and interactions

Dimensions of music or lighting	*F*	df	*p*	η^2
Hue	10.07**	2/106	0.000	0.160
Saturation	3.11	1/53	0.084	0.055
Luminance	1.41	1/53	0.240	0.026
Tonality	1.74	1/53	0.192	0.032
Genre	0.20	1/53	0.654	0.004
Hue × saturation	2.09	2/106	0.129	0.038
Hue × luminance	2.46	2/106	0.091	0.044
Saturation × luminance	5.54*	1/53	0.022	0.095
Hue × saturation × luminance	0.03	2/106	0.967	0.001
Hue × tonality	2.67	2/106	0.074	0.048
Saturation × tonality	51.76**	1/53	0.000	0.494
Hue × saturation × tonality	36.95**	2/106	0.000	0.411
Luminance × tonality	0.93	1/53	0.340	0.017
Hue × luminance × tonality	1.13	2/106	0.328	0.021
Saturation × luminance × tonality	1.99	1/53	0.164	0.036
Hue × saturation × luminance × tonality	1.81	2/106	0.169	0.033
Hue × genre	2.62	2/106	0.077	0.047
Saturation × genre	0.90	1/53	0.346	0.017
Hue × saturation × genre	0.65	1.70/90.23	0.524	0.012
Luminance × genre	0.62	1/53	0.434	0.012
Hue × luminance × genre	1.55	2/106	0.217	0.028
Saturation × luminance × genre	0.99	1/53	0.325	0.018
Hue × saturation × luminance × genre	2.42	2/106	0.094	0.044
Tonality × genre	55.94**	1/53	0.000	0.513
Hue × tonality × genre	4.54*	2/106	0.013	0.079
Saturation × tonality × genre	14.55**	1/53	0.000	0.215
Hue × saturation × tonality × genre	17.43**	2/106	0.000	0.247
Luminance × tonality × genre	0.00	1/53	0.980	0.000
Hue × luminance × tonality × genre	0.51	2/106	0.605	0.009
Saturation × luminance × tonality × genre	0.03	1/53	0.867	0.001
Hue × saturation × luminance × tonality × genre	1.43	2/106	0.243	0.026

Asterisks indicate significant effects (*, $p < 0.05$; **, $p < 0.01$).

Table A4.
Results of a univariate 3 (saturation) × 2 (luminance) × 2 (tonality) × 2 (genre) rmANOVA on music–lighting fit. Univariate main effects and interactions

Dimensions of music or lighting	F	df	p	η^2
Saturation	13.73**	1.31/69.44	0.000	0.206
Luminance	0.623	1/53	0.434	0.012
Tonality	13.07*	1/53	0.001	0.198
Genre	3.449	1/53	0.069	0.061
Saturation × luminance	1.248	1.49/77.3	0.284	0.023
Saturation × tonality	20.59**	1.4/74.53	0.000	0.280
Luminance × tonality	1.871	1/53	0.177	0.034
Saturation × luminance × tonality	0.819	2/106	0.443	0.015
Saturation × genre	4.53*	1.51/80.09	0.022	0.079
Luminance × genre	0.093	1/53	0.762	0.002
Saturation × luminance × genre	0.553	1.80/95.58	0.559	0.010
Tonality × genre	30.65**	1/53	0.000	0.366
Saturation × tonality × genre	12.96**	2/106	0.000	0.196
Luminance × tonality × genre	2.133	1/53	0.150	0.039
Saturation × luminance × tonality × genre	1.706	2/106	0.186	0.031

Asterisks indicate significant effects (*, $p < 0.05$; **, $p < 0.01$).

Table A5.
Results of a univariate 3 (hue) × 2 (saturation) × 2 (luminance) × 2 (tonality) × 2 (genre) rmANOVA on music liking. Univariate main effects and interactions

Dimensions of music or lighting	F	df	p	η^2
Hue	1.90	1.69/87.82	0.162	0.035
Saturation	0.00	1/52	0.982	0.000
Luminance	0.71	1/52	0.404	0.013
Tonality	84.16**	1/52	0.000	0.618
Genre	0.16	1/52	0.686	0.003
Hue × saturation	0.10	1.71/88.88	0.880	0.002
Hue × luminance	3.30*	2/104	0.041	0.060
Saturation × luminance	1.26	1/52	0.267	0.024
Hue × saturation × luminance	0.26	2/104	0.772	0.005
Hue × tonality	1.13	2/104	0.328	0.021
Saturation × tonality	2.94	1/52	0.092	0.054
Hue × saturation × tonality	1.15	2/104	0.322	0.022
Luminance × tonality	2.17	1/52	0.146	0.040
Hue × luminance × tonality	0.95	2/104	0.392	0.018
Saturation × luminance × tonality	0.03	1/52	0.860	0.001
Hue × saturation × luminance × tonality	0.08	2/104	0.927	0.001
Hue × genre	1.05	2/104	0.354	0.020
Saturation × genre	0.30	1/52	0.586	0.006
Hue × saturation × genre	0.88	2/104	0.420	0.017
Luminance × genre	0.01	1/52	0.935	0.000
Hue × luminance × genre	0.62	2/104	0.540	0.012
Saturation × luminance × genre	0.04	1/52	0.842	0.001
Hue × saturation × luminance × genre	0.40	2/104	0.668	0.008
Tonality × genre	1.99	1/52	0.164	0.037
Hue × tonality × genre	1.29	2/104	0.281	0.024
Saturation × tonality × genre	0.43	1/52	0.516	0.008
Hue × saturation × tonality × genre	0.65	2/104	0.525	0.012
Luminance × tonality × genre	2.21	1/52	0.143	0.041
Hue × luminance × tonality × genre	2.97	2/104	0.056	0.054
Saturation × luminance × tonality × genre	2.50	1/52	0.120	0.046
Hue × saturation × luminance × tonality × genre	0.71	2/104	0.496	0.013

Asterisks indicate significant effects (*, $p < 0.05$; **, $p < 0.01$).

Table A6.
Results of a univariate 3 (saturation) × 2 (luminance) × 2 (tonality) × 2 (genre) rmANOVA on music liking. Univariate main effects and interactions

Dimensions of music or lighting	*F*	df	*p*	η^2
Saturation	0.14	1.38/73.27	0.014	0.039
Luminance	2.36	1/53	0.130	0.043
Tonality	265.84**	1/53	0.000	0.834
Genre	4.52	1/53	0.038	0.079
Saturation × luminance	8.57**	1/53	0.000	0.139
Saturation × tonality	5.11	1.41/74.49	0.017	0.088
Luminance × tonality	2.67	1/53	0.108	0.048
Saturation × luminance × tonality	0.01	1.57/83.44	0.970	0.000
Saturation × genre	1.89	1.64/86.87	0.164	0.034
Luminance × genre	3.68	1/53	0.061	0.065
Saturation × luminance × genre	5.45	1.77/93.83	0.008	0.093
Tonality × genre	0.02	1/53	0.897	0.000
Saturation × tonality × genre	0.43	1/53	0.516	0.008
Luminance × tonality × genre	0.14	1/53	0.714	0.003
Saturation × luminance × tonality × genre	3.83	1.74/92.14	0.031	0.067

Asterisks indicate significant effects (*, $p < 0.05$; **, $p < 0.01$).

Table A7.
Results of a 2 (tonality) × 2 (genre) rmANOVA on SAM-ratings in the music-only condition. Multivariate and univariate main effects and interactions

Dimensions of music or lighting		*F*	df	*p*	η^2
Multivariates	Univariates				
Tonality		**131.95****	**3/50**	**0.000**	**0.888**
	Valence	357.93**	1/52	0.000	0.873
	Arousal	164.42**	1/52	0.000	0.760
	Dominance	36.61**	1/52	0.000	0.413
Genre		**1.96**	**3/50**	**0.132**	**0.105**
Tonality × genre		**0.86**	**3/50**	**0.466**	**0.049**

Asterisks indicate significant effects (*, $p < 0.05$; **, $p < 0.01$).

Table A8.
Results of a 2 (tonality) × 2 (genre) rmMANOVA on music characteristics in the music-only condition. Multivariate and univariate main effects and interactions

Dimensions of music or lighting		*F*	df	*p*	η^2
Multivariates	Univariates				
Tonality		**159.4****	**4/50**	**0.000**	**0.927**
	Harmonic	580.59**	1/53	0.000	0.916
	Powerful	0.225	1/53	0.637	0.004
	Gloomy	230.26**	1/53	0.000	0.813
	Lively	1.78	1/53	0.188	0.032
Genre		**25.81****	**4/50**	**0.000**	**0.674**
	Harmonic	19.66**	1/53	0.000	0.271
	Powerful	44.6**	1/53	0.000	0.457
	Gloomy	43.41**	1/53	0.000	0.450
	Lively	13.2**	1/53	0.001	0.199
Tonality × genre		**23.48****	**4/50**	**0.000**	**0.653**
	Harmonic	0.091	1/53	0.764	0.002
	Powerful	9.76**	1/53	0.003	0.155
	Gloomy	91.94**	1/53	0.000	0.634
	Lively	0.04	1/53	0.845	0.001

Asterisks indicate significant effects (*, $p < 0.05$; **, $p < 0.01$).

Table A9.
Results of a 3 (hue) × 2 (saturation) × 2 (luminance) rmMANOVA on SAM-ratings in the light-only condition. Multivariate and univariate main effects and interactions

Dimensions of music or lighting		*F*	df	*p*	η^2
Multivariates	Univariates				
Hue		**6.51****	**6/210**	**0.000**	**0.157**
	Valence	3.70*	2/106	0.028	0.065
	Arousal	21.29**	10.78/1030.89	0.000	0.287
	Dominance	3.01	2/106	0.053	0.054
Saturation		**42.10****	**3/51**	**0.000**	**0.712**
	Valence	40.42**	1/53	0.000	0.433
	Arousal	117.59**	1/53	0. 000	0.689
	Dominance	20.2**	1/53	0. 000	0.276
Luminance		**3.18***	**3/51**	**0.031**	**0.158**
	Valence	3.42	1/53	0.070	0.061
	Arousal	9.67**	1/53	0.003	0.154
	Dominance	0.46	1/53	0.500	0.009
Hue × saturation		**6.53****	**6/210**	**0.000**	**0.157**
	Valence	17.53**	2/106	0.000	0.249
	Arousal	12.92**	2/106	0.000	0.196
	Dominance	1.96	2/106	0.142	0.036
Hue × luminance		**4.54****	**6/210**	**0.000**	**0.115**
	Valence	10.68**	2/106	0.000	0.168
	Arousal	8.3**	2/106	0.000	0.135
	Dominance	0.87	10.5/790.25	0.422	0.016
Saturation × luminance		**4.17***	**3/51**	**0.010**	**0.197**
	Valence	5.09*	1/53	0.028	0.088
	Arousal	0.56	1/53	0.459	0.010
	Dominance	9.36**	1/53	0.003	0.150
Hue × saturation × luminance		**0.56**	**6/210**	**0.764**	**0.016**

Asterisks indicate significant effects (*, $p < 0.05$; **, $p < 0.01$).

Table A10.
Results of a 3 (hue) × 2 (saturation) × 2 (luminance) rmMANOVA on music characteristics in the light-only condition. Multivariate and univariate main effects and interactions

Dimensions of music or lighting		*F*	df	*p*	η^2
Multivariates	Univariates				
Hue		__13.38**__	__8/204__	__0.000__	__0.344__
	Harmonic	6.13**	2/104	0.003	0.105
	Powerful	12.48**	2/104	0.000	0.194
	Gloomy	6.881**	10.7/880.3	0.003	0.117
	Lively	23.48**	2/104	0.000	0.311
Saturation		__48.48**__	__4/49__	__0.000__	__0.798__
	Harmonic	43.84**	1/52	0.000	0.457
	Powerful	82.44**	1/52	0.000	0.613
	Gloomy	34.96**	1/52	0.000	0.402
	Lively	22.12**	1/52	0.000	0.298
Luminance		__6.90**__	__4/49__	__0.000__	__0.360__
	Harmonic	7.0*	1/52	0.011	0.119
	Powerful	8.64**	1/52	0.005	0.142
	Gloomy	0.72	1/52	0.399	0.014
	Lively	17.07**	1/52	0.000	0.247
Hue × saturation		__7.75**__	__8/204__	__0.000__	__0.233__
	Harmonic	8.47**	2/104	0.000	0.140
	Powerful	16.62**	2/104	0.000	0.242
	Gloomy	17.35**	10.62/840.24	0.000	0.250
	Lively	3.34**	2/104	0.039	0.060
Hue × luminance		__3.84**__	__8/204__	__0.000__	__0.131__
	Harmonic	9.91**	2/104	0.000	0.160
	Powerful	3.89*	2/104	0.023	0.070
	Gloomy	4.5*	2/104	0.013	0.080
	Lively	0.55	2/104	0.581	0.010
Saturation × luminance		__1.14__	__4/49__	__0.350__	__0.085__
Hue × saturation × luminance		__0.58__	__8/204__	__0.795__	__0.022__

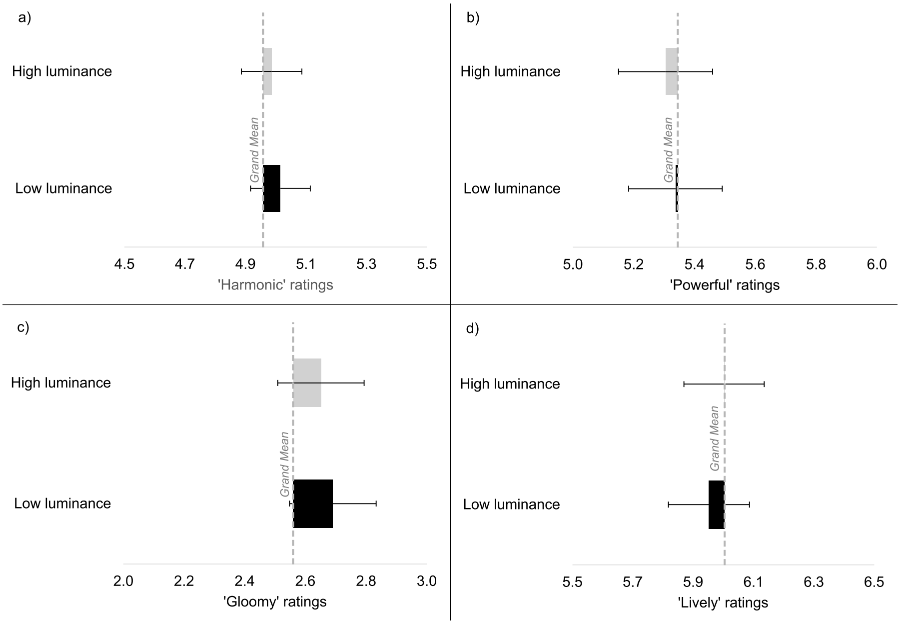

Figure A1. Mean ratings for music appraisal as a function of luminance. Error bars show ± 1 SEM. Baseline data are retrieved from unimodal music ratings under white lighting.

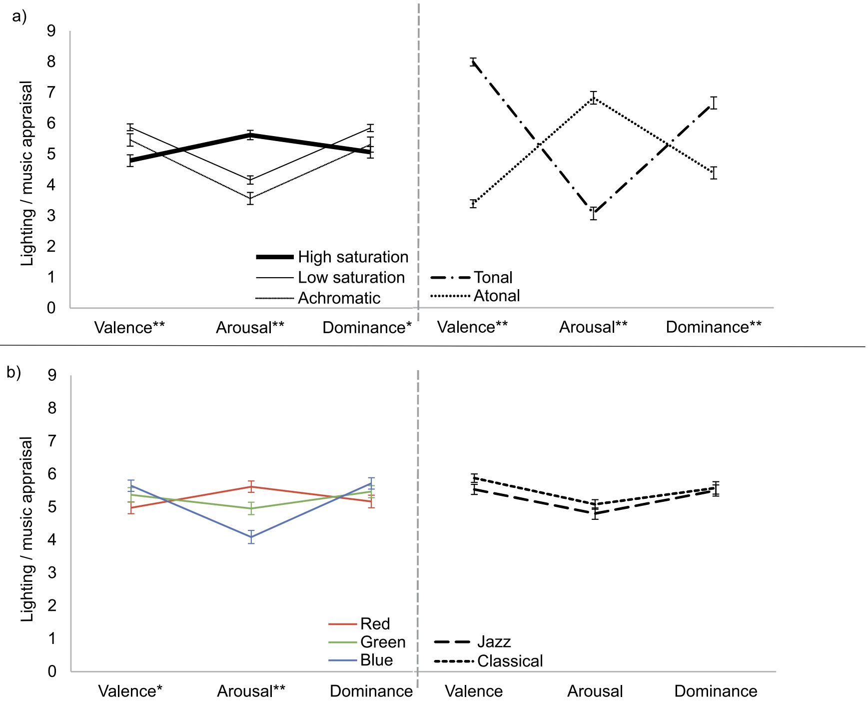

Figure A2. Mean valence, arousal, and dominance ratings in the LO and MO conditions. (a) The LO ratings as a function of saturation juxtaposed to the MO ratings as a function of tonality; (b) the LO ratings as a function of hue juxtaposed to the MO ratings as a function of genre.

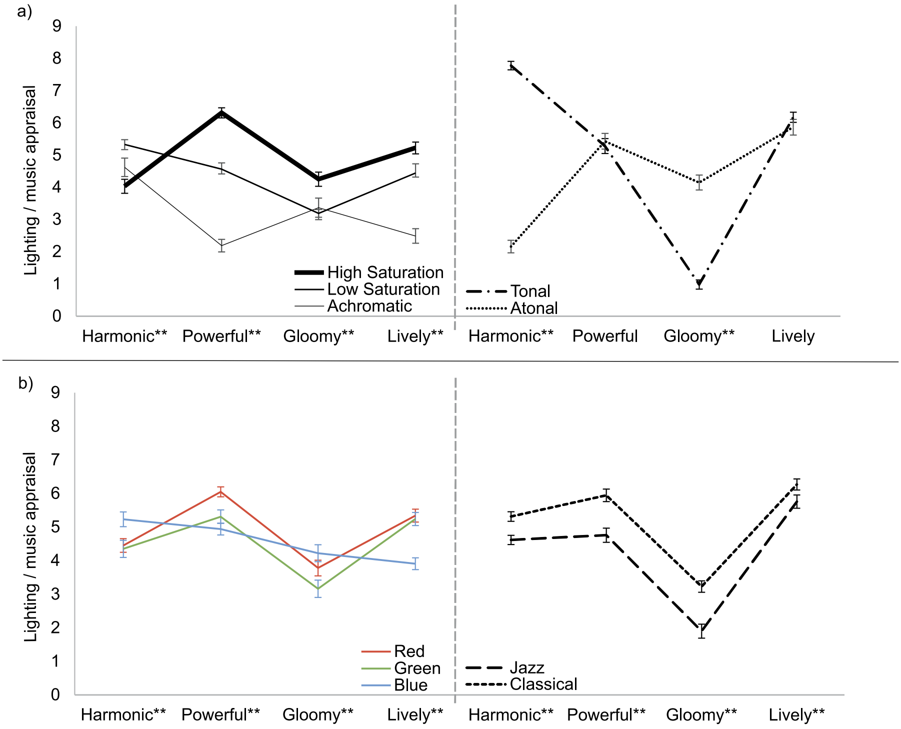

Figure A3. Mean appraisal ratings regarding the dimensions ‘Harmonic’, ‘Powerful’, ‘Gloomy’, and ‘Lively’ in the MO and LO conditions. (a) The LO ratings as a function of saturation juxtaposed to the MO ratings as a function of tonality; (b) the LO ratings as a function of hue juxtaposed to the MO ratings as a function of genre.