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The Color of Music: Emotion-Mediated Associations to Bach's *Well-Tempered Clavier*

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Three experiments tested the proposal that music–color associations are mediated by emotional connotations as suggested by Palmer and collaborators (2013, 2016). Experiment 1 asked participants to choose 1 of 8 saturated colors for excerpts of 24 Preludes from Bach's *Well-tempered Clavier*. Half of these excerpts were presented again for color choices, together with excerpts from another 12 Preludes. Participants were also asked to judge whether or not they had heard the excerpts before in the experiment. The color choices grouped together Preludes according to tempo, mode, pitch height, and attack rate. Participants included nonmusicians, musicians, absolute pitch (AP) possessors, and music–color synesthetes. Color choices followed the same general pattern across groups, and were more similar than chance when the excerpts were repeated and, to a lesser extent, when the excerpt was different but in the same key. No recognition advantage was found for synesthetes or possessors of AP. Experiment 2 asked participants to rate the colors on a number of emotion scales. Experiment 3 asked them to rate the excerpts from the Preludes on the same emotion scales, and found that the emotion ratings grouped together Preludes according to tempo, mode, pitch height, and attack rate as in Experiment 1. Finally, the color choices in Experiment 1 could be predicted by the color–emotion ratings in Experiment 2 and the music–emotion ratings in Experiment 3. These results support the proposal that music–color associations can be accounted for by the correlations between music and emotion, and color and emotion.

Keywords: cross-modal associations, music cognition, color, emotion, synesthesia

Associations between music and color, and cross-modal associations in general, have been understood in a variety of ways. One view is that, because we experience the world through multiple sensory modalities simultaneously, integrating these signals provides us with richer and more precise information on which to act (Parise & Spence, 2013; Spence, 2011). Cross-modal associations, for example, between the color of a fruit and whether or not it tastes ripe, are normal and adaptive for integrating information across the senses. Three types of cross-modal associations that have been identified are structural correspondences (originating in the neural processing), statistical correspondences (reflecting regularities in the world), and semantically (primarily verbally) mediated correspondences (Spence, 2011).

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Walker and colleagues (Walker & Smith, 1984; Walker, Walker, & Francis, 2012) have proposed a system of amodal, conceptual terms that apply across sensory modalities to account for cross-modal associations. These draw on basic features of bodily actions, gestures, and vocalizations. For example, common to hearing and sight are fast versus slow, high versus low, bright versus dark, and small versus large. Such cross-sensory correspondences may be bidirectional and symmetrical, or asymmetrical with the association in one direction being stronger than in the other, or even unidirectional. Hearing a high sound might lead one to expect that a small object is the source, but a small object would not necessarily lead one to expect a high sound. Walker (2016) describes how the theory might apply to music, going beyond associations to simple tones varying in pitch height, loudness, and/or timbre, to possible factors operating at compositional levels of melody and tempo.

One issue that arises in the literature on cross-modal associations is what the relationship is between these associations and the phenomenon of synesthesia, in which a trigger stimulus ("inducer") causes automatic, perception-like experiences ("concurrent") in a different modality. Although cross-modal associations have been found to be consistent across individuals, the focus in research on synesthesia tends to be on individuals under the assumption that the particular correspondences would be idiosyncratic. Hundreds of different types of synesthesia have been identified, with a history of scientific reports going back to the 1800s (Galton, 1883; see Jewanski, 2013; Ward, 2013 for reviews). Recently, it has been suggested that synesthesia may be subject to the same rules that govern normal patterns of cross-modal associations, differing mainly in its automaticity but less in its phenomenology (Marks, 2013; Simner, 2013; but see Spence, 2011).

Marks (1975) reviewed >100 reports of auditory–visual synesthesia, many of which involved music. He found that some of the associations are regular, systematic, and consistent across individuals. Specifically, there were correlations between auditory pitch and visual brightness (the higher the brighter, and in some studies more yellow), and pitch and visual size (larger with lower), and loudness and visual size and brightness (larger and brighter with louder). Marks described devices invented to present colors to accompany music, such as an organ built by Scriabin that mapped tones and colors so that, for example, C was accompanied by red, and D accompanied by yellow. Associations between musical notes and/or keys and colors are quite common in synesthetes and a case study demonstrated stability over time (Carroll & Greenberg, 1961). However, as noted by Marks, the specific mappings tend to vary across individuals, so that C might be red to one synesthete and white to another. Other, also idiosyncratic, associations have been reported between color and musical instruments, such as trumpet and scarlet, and flute and blue, and the music of particular composers, such as Chopin and purple, Mozart and green, or specific works by composers.

Notable music–color synesthetes include Messiaen, Scriabin, Rimsky-Korsakoff, and Liszt, as well as artists and writers, such as Rimbaud, Baudelaire, Nobokov, Kandinsky, and Hockney (Harrison & Baron-Cohen, 1997; Ward, 2013). The variety of cross-modal associations to music is impressive. Studies report associations between music and visual shapes (Athanasopoulos & Moran, 2013; Bamberger, 2013), musical notation and color (Ward, Tsakanikos, & Bray, 2006), expressive performances and color (Bresin, 2005), and musical genre and color (Moon, Kim, Lee, & Kim, 2014). Associations with color have been suggested as a way to stimulate musical creativity, for creating computer-based visualization of music, and to index song collections for music information retrieval.

Palmer, Schloss, Xu, and Prado-León (2013) proposed the "emotion-mediation" hypothesis that posits that music and color are linked through shared emotional associations. They empirically tested this using both emotion terms and faces with emotional expressions as mediators. Unlike most studies that used isolated tones varying in pitch height, loudness, and/or timbre, they used 18 classical orchestral selections that varied in tempo (slow/medium/fast) and mode (major/minor). They also used 37 colors that were distributed systematically on the three dimensions of color: hue, saturation, and lightness (Palmer & Schloss, 2010). These are theoretically orthogonal, although the saturated yellow appears lighter than the other saturated colors. The eight hues were red, green, blue, and yellow, plus intermediate hues of equal amounts of their neighbors: orange, chartreuse, cyan, and purple. For each selection, participants were asked to choose, in order, the five best colors most consistent with the music, then the five colors least consistent, in order.

Palmer et al. (2013) found that pieces in major mode were associated with more saturated, lighter, and yellower colors. In contrast, pieces in minor mode were associated with less saturated, darker, and bluer colors. In addition, tempo had an effect such that faster pieces were associated with more saturated, lighter, and yellower colors. Effects on the red–green dimension were less apparent. The participants in this study also rated the colors on a number of emotion scales: happy, sad, angry, calm, strong, weak, lively, and dreary. Another experiment showed strong emotional correlations when participants matched emotionally expressive faces to the musical excerpts. A final experiment showed strong emotional correlations when participants matched the emotionally expressive faces to the colors. Thus, associations between all three of these domains followed the same pattern in support of the emotion-mediation hypothesis.

The results were replicated and extended in a later study using single-line piano melodies (Palmer, Langlois, & Schloss, 2016) that were varied systematically in mode and tempo, as before, but also in pitch height and attack rate (the number of notes per minute, what they called note density). They replicated the effects of mode and tempo found earlier, and also uncovered an effect such that melodies with greater attack rate were associated with more saturated colors. Pitch height was associated with lighter colors as had been found in previous studies (Hubbard, 1996; Marks, 1975). The rating on the happy scale was associated with lighter and more saturated colors, especially yellow. Agitated was associated with more saturated reds and yellows, angry with darker and redder colors, and stronger with more saturated colors. These color associations were consistent with those found in the earlier study (Palmer et al., 2013).

The present study further tests their proposal by determining whether music–color associations can be accounted for by color–emotion and music–emotion associations with a different corpus of music, Bach's *Well-tempered Clavier* (often abbreviated WTC). It also is motivated by an interest in understanding better the musical features that are associated with the colors and emotions. The 48 Preludes and Fugues are the subject of extensive scholarly analysis and criticism (see Ledbetter, 2002, for an extensive bibliography) and have been used in various experimental and computational studies (e.g., Cohen, 1991; Krumhansl, 1990; Longuet-Higgins & Steedman, 1971 and articles cited below). The title refers to the use of a tuning system in which pieces in all major and minor keys are sufficiently in tune (although not necessarily in modern day equal temperament). The first book of Bach's WTC dates from 1722 and contains 24 Preludes and Fugues, one for each of the major and minor keys beginning with C major and moving chromatically in ascending order (e.g., C major, C minor, C# major, C# minor, etc.). It represents diverse styles, such as sonata, dance, fantasia, aria, and invention. The second book of the WTC, organized similarly, appeared 15 years later and included newer styles. An interesting question is whether Bach associated particular characteristics with the different keys. One approach is to consider vocal works, such as operas, that provide clearer information about the nonmusical context, and ask whether certain keys are used disproportionately in different kinds of contexts. Ledbetter (2002) finds some associations, but concludes that clear patterns of extramusical associations to keys are difficult to establish.

One experimental approach that has been taken to understanding the character of the Preludes is to look at cross-modal associations, to color in particular. Two studies by Polzella and collaborators (Polzella & Biers, 1987; Polzella & Hassen, 1997) used 12 of the 24 Preludes from Book I in an experiment asking listeners to choose from among four colors: red, yellow, green, and blue. The first of these studies found red responses were associated with faster tempos and quadruple meter, yellow was associated with major keys, faster tempos, and triple meter, and blue responses were associated with slower tempos. The yellow effect was replicated in the second experiment, but an overall preference for green was also found, possibly related to the particular colors that were displayed (the first study used color words only). Their tempo and mode effects are generally consistent with those of Palmer and collaborators (Palmer et al., 2013; Palmer, Langlois, & Schloss, 2016). The music background of the participants was not described.

Another study of Bach's Preludes used participants with absolute pitch (AP, generally described as the ability to recognize and name a tone sounded in isolation, that is, without context); all were music students or professors of music (Petrovic, Antovic, Milankovic, & Acic, 2012). They heard 12 isolated tones in different octaves, 12 major and 12 minor chords in the middle octave, and the 24 Preludes from Book I, and were asked to select from 13 colors (including black, gray, and white as neutral colors). For the Preludes, they found that faster tempos were associated with orange and yellow, and slower tempos with blue and purple. Preludes in minor keys were associated with blue and purple, and Preludes in major keys with the remaining colors. Again, their findings are consistent with those found more recently with other musical selections (Palmer et al., 2013; Palmer, Langlois, & Schloss, 2016). The participants were grouped into those without synesthesia (8), with partial synesthesia (10), and with complete synesthesia (8). How the groups differ in terms of their music background and specific AP abilities is described, but the color choice results were not broken down according to group.

Experiment 1

The present study tested whether the pattern of music–color associations found by Palmer et al. (2013, 2016) generalizes to another set of musical pieces, and whether these associations are mediated by correlations between music and emotion, and color and emotion. Given this prior research, the variety of styles represented in the WTC, and its systematic organization in terms of keys, we chose it as the source of stimuli in Experiment 1. In phase 1, listeners heard short initial excerpts of 24 Preludes in each of the major and minor keys (Table 1a). Half the Preludes, which will be retested in phase 2, were from Book II of the WTC. They were chosen because they were assumed to be less familiar than the Preludes in Book I. The keys of the Book II Preludes were distributed evenly around the circle of fifths by choosing every other successive key on the circle (e.g., C major and minor, D major and minor, E major and minor, F# major and minor, etc.). We used the eight saturated colors (see Figure 1) from Palmer and Schloss (2010); the RGB values are shown in the Table A1. They were four unique hues (red, green, blue, and yellow) and four intermediate hues (purple, cyan, chartreuse, and orange). Participants were asked to select one of the eight colors that best fit the music.

Next they filled out a demographic questionnaire, during which they reported details of their musical training, whether they have absolute pitch (AP) and, if they have synesthesia, to indicate what kind and describe it in detail. Participants were also asked if they spoke a tone language because a greater incidence of AP occurs in tone language speakers (Deutsch, Henthorn, Marvin, & Xu, 2006; Gregersen, Kowalsky, Kohn, & Marvin, 2001), and nonmusicians who speak tone language learned to identify intervals (a task of relative pitch, RP) more readily than were those who do not speak tone languages (Hove, Sutherland, & Krumhansl, 2010). To anticipate our results, no effect of tone language was found so we do not discuss it further. They were also asked whether they were familiar with the music prior to participating in the experiment, and whether they had learned to play any of the Preludes. Finally, an open-ended question asked them to report how they had assigned colors to the musical excerpts.

In phase 2 of the experiment, participants heard excerpts from the 12 Preludes they had heard in phase 1 (Table 1b, all from Book II). This made it possible to look for self-consistency in color choices on repetitions of the same piece, that is, whether they chose a similar color on the two occasions. They also heard excerpts from another 12 new Preludes (Table 1b, all from Book I) in the corresponding keys. For example, they heard the excerpt from the D major Prelude from Book II in the first phase and they heard the D major Prelude from Book I in the second phase. Because both books of the WTC contain all major and minor keys, it was thus possible to assess the degree of consistency across different pieces in the same key. In a surprise recognition task, they also were asked for each Prelude whether it was one that they had heard before in the first part of the experiment. Thus, the design of the experiment allowed us to examine what colors are chosen for the Preludes, the degree of color consistency, recognition memory accuracy, and whether these measures depend on whether the participant was a nonmusician, a musician, a possessor of AP, and/or a synesthete.

Table 1a and b
Preludes in Phase 1 and Phase 2 of Experiment 1

Phase 1: Color-selection task (a)	
Book II	Book I
C Major	C# Major
C Minor	C# Minor
D Major	Eb Major
D Minor	Eb Minor
E Major	F Major
E Minor	F Minor
F# Major	G Major
F# Minor	G Minor
Ab Major	A Major
G# Minor	A Minor
Bb Major	B Major
Bb Minor	B Minor

Phase 2: Color selection and surprise recognition task (b)	
Old (Book II)	New (Book I)
C Major	C Major
C Minor	C Minor
D Major	D Major
D Minor	D Minor
E Major	E Major
E Minor	E Minor
F# Major	F# Major
F# Minor	F# Minor
Ab Major	Ab Major
G# Minor	G# Minor
Bb Major	Bb Major
Bb Minor	Bb Minor

Method

Participants. A total of 128 volunteers participated in the experiment. Seventy-six participants were tested remotely (for entry into a raffle of 10 $20 Amazon gift cards), while the remaining participants were Cornell University undergraduates tested in a lab context (for course credit). Figure 2 shows a summary of the two groups of participants. Twenty-two participants identified themselves as having synesthesia, which was described to participants as when information from two senses is automatically paired together. Twenty of these participants said they had music–color synesthesia; the other two had color–grapheme synesthesia. For purposes of analysis, four groups of participants that are as nonoverlapping as possible will be considered: music–color synesthetes, AP possessors, musicians without AP or synesthesia, and nonmusicians. The remote participants were referred by other researchers studying absolute pitch and had given their consent to be contacted for future studies; on average they had more musical experience than the participants who were tested in the lab context.[1]

Materials. The study was built using Qualtrics Survey Software. The recording used was J. S. Bach's *The Well-Tempered Clavier* (WTC), *Books I and II* performed by András Schiff (2012). The 36 sound clips were the taken from the beginning of the Preludes listed in Tables 1a and 1b. Each 15-s clip had a three sec fade-out starting 12 sec after the beginning of the music. The colors were the eight saturated colors from Palmer and Schloss (2010) shown in Figure 1.

Procedure. Remote participants took the study with their own computers and headphones, and all in-lab participants used a Dell M770 monitor and AKG-K141 headphones. Before starting, all participants gave informed consent for participating in the study, which was approved by the Institutional Review Board at Cornell University. In phase 1, participants heard the excerpts of the Preludes in Table 1a in random order. While listening to each clip, they were presented with all eight colors and asked to select the color that they felt best fit the music. The eight colors on the screen formed a grid 4 wide × 2 high; the placement of the colors was randomized on each trial to minimize response biases. They then completed the demographics questionnaire, which served to separate the two phases of the experiment. In phase 2, participants listened to excerpts from the 24 Preludes shown in Table 1b, half of which they had heard in phase 1 and half they had not. They again chose which color best fit the Prelude. They also were asked whether or not they remembered hearing the music in phase 1 in a forced-choice old/new recognition paradigm. As before, the Preludes were presented in random order, and the colors' positions were randomly assigned.

Figure 1. The eight saturated colors from Palmer and Schloss (2010). The exact RGB values of the colors can be found in the Table A1.

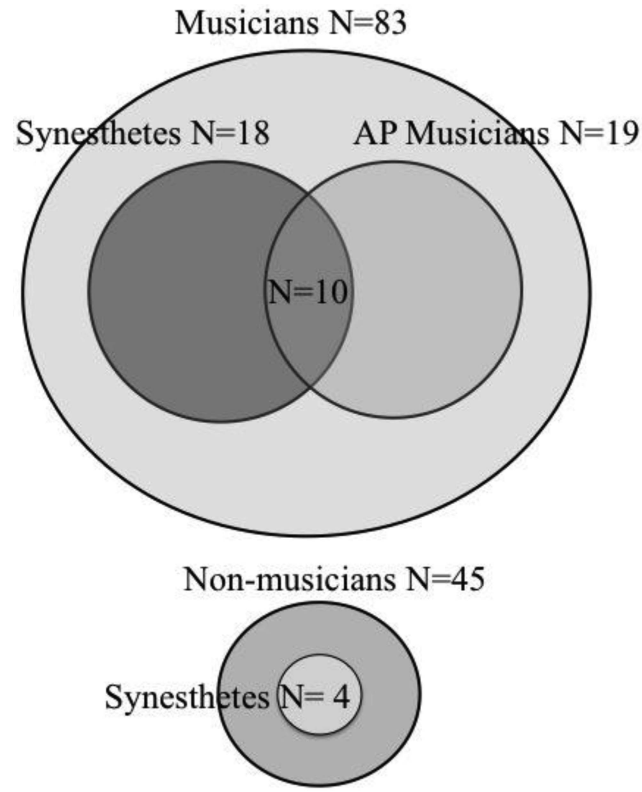

Figure 2. Participant group membership in Experiment 1. There were 83 musicians, of whom 18 had synesthesia and 19 had AP. Of the synesthetes, 10 had AP. There were 45 nonmusicians without AP, four of whom had synesthesia.

Results

Overview of the analyses. Four types of analyses were performed on the data. The first looked at the properties of the music associated with the color choices. The second looked at self-consistency on the choices when the same piece was repeated in

[1] The remote participants (N = 76; 48 women; age M = 30 years, SD = 13.5; range: 14–71) included 61 musicians (years training, M = 12.7 years, range: 1.5–16+, age beginning training, M = 7.9 years, range: 5–18). Seventeen individuals reported being able to play some of the music used in this study. The in-lab group (N = 52; 34 women; age M = 19.4, SD = .99; range: 18–22 years) included 22 musicians (years training, M = 8.9, range: 1.5–16+, age beginning training, M = 8.4 years, range: 5–18). Two individuals reported being able to play some of the music used in this study.

phase 2 (i.e., whether the participant chose a similar color). The third looked at whether participants chose a similar color for Preludes in the same keys in phases 1 and 2 (e.g., for the D minor Prelude in Book II in phase 1 and the D minor Prelude in Book I in phase 2). The last looked at recognition memory accuracy in phase 2.

Color selections. Figure 3 shows the number of participants who chose each color for the Preludes in Book I. The choice to focus on the Book I Preludes was because this provides an even sampling of all major and minor keys, and previous studies have used Book I Preludes exclusively. A clustering algorithm (PROC VARCLUS, implemented in JMP Pro) grouped the Preludes into these five clusters. This algorithm is related to, but not identical to, principal components. It reduces the number of variables by grouping variables together that are similar. It starts with a single cluster, then iteratively splits clusters until no more splits are possible. More technically, at each stage the cluster with the second largest eigenvalue is selected to split into two new clusters. The assignment of its members to one or the other new cluster depends on its correlation with the rotated principal components of the cluster being split. One advantage over principal components is that it aids interpretation by identifying the member that is most representative of each cluster. In this case, the A minor Prelude was most typical of cluster in Figure 3a, the Bb major Prelude was most typical of cluster in Figure 3b, the B minor Prelude was most typical of cluster in Figure 3c, and the E Major Prelude was most

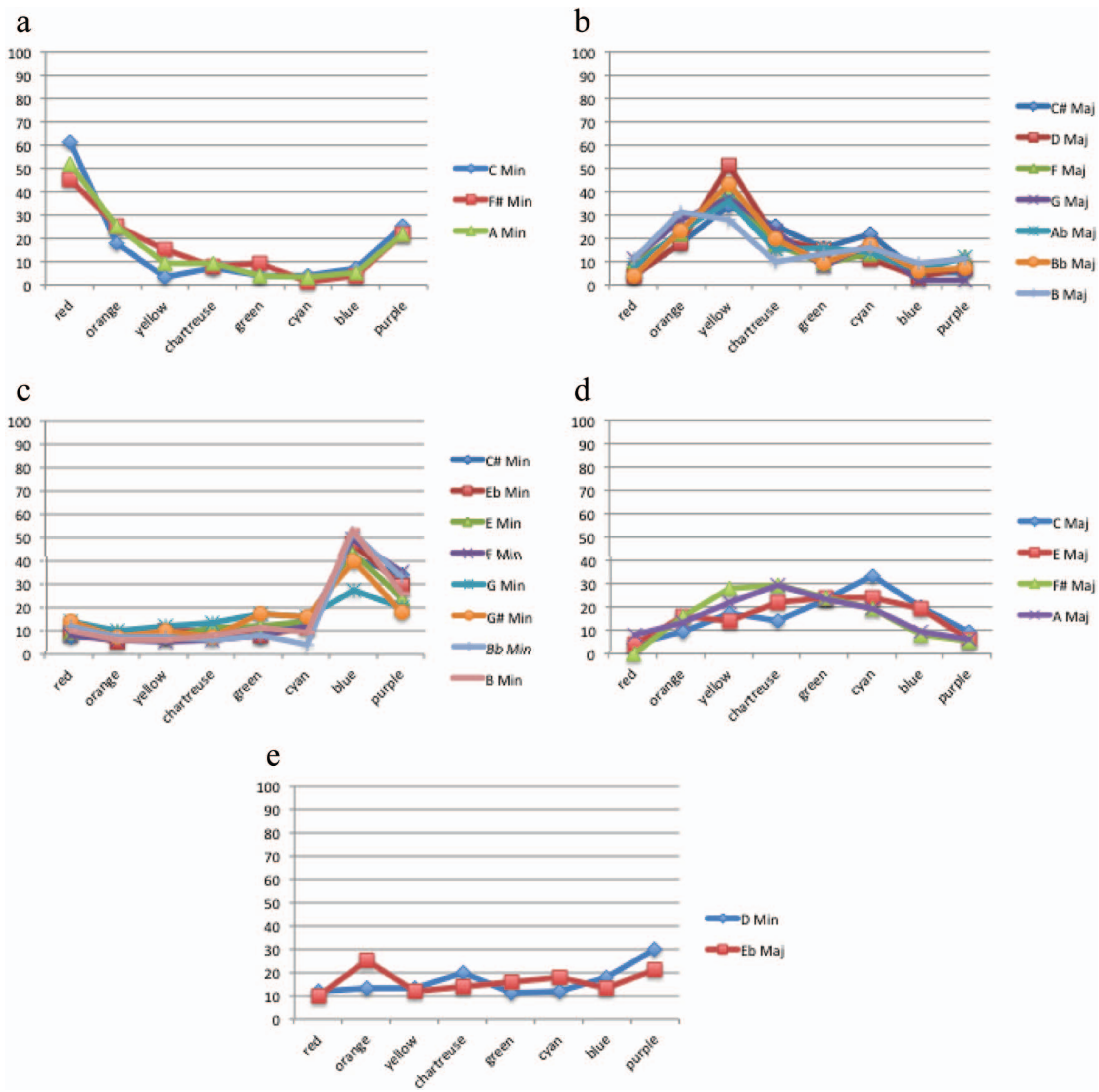

Figure 3. The number of participants choosing each color for each Prelude in Experiment 1. (a) Cluster contains Preludes in minor mode with fast tempo. (b) Cluster contains Preludes in major mode with fast tempo. (c) Cluster contains Preludes in minor mode with slow tempo. (d) Cluster contains Preludes in major mode with slow tempo. (e) Cluster contains two Preludes with slow tempo, one in major and one in minor mode. See the online article for the color version of this figure.

typical of cluster Figure 3d. The proportion of variation explained by the clusters was .855.

The influence of mode and tempo on the first four clusters is evident. The Preludes in Figure 3a with a majority of red choices (with neighbors orange and purple the next most chosen) were all minor Preludes with relatively fast tempos (M = 113 BPM, minimum = 105 BPM, maximum = 123 BPM). The Preludes in Figure 3b with a majority of yellow choices (with neighbors orange and chartreuse the next most chosen) were all major Preludes with relatively fast tempos (M = 117 BPM, minimum = 72 BPM, maximum = 175 BPM). The Preludes in Figure 3c with the majority of blue choices (with the neighbor purple next most chosen) were all minor Preludes in relatively slow tempo (M = 78 BPM, minimum = 62 BPM, maximum = 95 BPM). The Preludes in Figure 3d where the color choices spanned the chartreuse–green–cyan range were all major Preludes with relatively slow tempos (M = 83 BPM, minimum = 72 BPM, maximum = 87 BPM). The two remaining Preludes (in D minor and Eb major) shown in Figure 3e with a relatively flat color distributions were both relatively slow (75 and 78 BPM, respectively).

The grouping shown in Figure 3 was confirmed by a logistic regression predicting group membership by tempo and mode. To examine other characteristics of the music that might be associated with these clusters, three other variables were included. The first was meter, coded as triple or quadruple, which was a factor in color choices in the study by Polzella and Biers (1987). The other two variables were found by Poon and Schutz (2015) to be associated with major versus minor Preludes. One was the average pitch height of the tones weighted by relative duration in the first eight full measures of the piece. The other was attack rate, which was the summed number of attacks within each measure divided by the number of beats in the measure. They used the metronome values (Kalmus Classic edition, edited by Hans Bischoff, Bach, 1883) to compute the number of attacks per second, again for the first eight measures. Meter (triple/quadruple) was not significant in the logistic regression analysis of the present data, but the other four variables were, overall chi-square (df = 16) = 71.6, $p <$ .0001 (mode chi-square (df = 4) = 601.3, $p <$ .0001; meter chi-square (df = 4) = 23.0, $p <$ .0001; attack rate chi-square (df = 4) = 273.3, $p <$ .0001; pitch height chi-square (df = 4) = 30.9, $p <$ .0001).

To look at the consistency across groups, the distribution of colors for each Prelude in Book I was found for these groups: music–color synesthetes, AP possessors, musicians who were neither music synesthetes nor AP possessors, and nonmusicians. The number of participants who chose each of the eight colors for each of the 24 Preludes in Book I was tabulated for each group. All intergroup correlations (with df = 190), shown in Table 2, were significant at $p <$ .0001 when Bonferroni corrected for multiple comparisons. In general, there was considerable intergroup agreement in the color choices. That the music–color synesthetes correlated relatively strongly with the AP possessors may be in part due to the overlapping group members. When the music–color synesthetes were removed from the AP group, the small number of participants remaining (9) produced unstable results. The next highest correlation was between the nonmusicians and musicians without AP or synesthesia, who showed the strongest correlation with the color distributions of all participants as shown in the last row of Table 2.

Color selections: self-consistency across phases 1 and 2 for the same piece. Color consistency was measured using the distance between the colors chosen in phases 1 and 2 of the experiment using the city-block distance in Figure 1. For example, the distance from red to orange = 1, red to yellow = 2, red to chartreuse = 3, red to green = 4, red to cyan = 3, and so forth. On average, the distance between the color chosen for an excerpt in phase 1 and the same except in phase 2 was 1.41. If participants were choosing colors randomly, the average distance between colors would be 2 (if two colors were chosen randomly, on average one time the distance would be 0, two times it would be 1, 2, or 3, and one time it would be 4; see Figure 1). The average value of 1.41 was significantly lower than chance (i.e., more consistent), $t(127) = -15.270$, $p <$ .0001, and this was true for all groups (Figure 4a). Music–color synesthetes and AP possessors were somewhat more self-consistent across phases 1 and 2 than the other groups. However, self-consistency correlated with familiarity with the music, $r(126) = -.300$, p = .0006 (music–color synesthetes M = 4.278, median = 4.5; AP possessors M = 4.474, median = 4; other musicians M = 2.350, median = 1; and nonmusicians M = 1.109, median = .5), so an effect of familiarity cannot be ruled out. It seems unlikely that this consistency is largely due to participants remembering their color choices from phase 1 because they did not know until after the demographics questionnaire that they would hear the Preludes again.

Color selections: self-consistency across phases 1 and 2 for the different piece in the same key. On average, the distance between the color chosen in phase 1 and the color chosen for the different piece in the same key in phase 2 was 1.749, which was significantly less than the average distance between colors chosen by chance, $t(127) = 6.593$, $p <$ .0001, and it was significant for all groups of participants (Figure 4b). Participants were less consistent with different pieces in the same key, however, than with the same piece, $t(127) = 7.371$, $p <$ .0001. This can be understood, in part, because although the excerpts from Books I and II were matched in mode (and tonic), the tempos of pieces in the same key did not correlate with one another, $r(10)$ = .176, p = .584. As with self-consistency on the same Preludes, the music–color synesthetes and the AP possessors were more consistent in their color

Table 2
Intergroup Correlation Coefficients (df = 190) of Color Choices in Experiment 1 for the Preludes in Book I

Group	Music–color synesthetes	All AP	Musicians Non-AP Non-Syn	Nonmusicians
All AP	.64 ($p <$ .0001)			
Musicians Non-AP Non-Synesthete	.59 ($p <$ .0001)	.48 ($p <$ .0001)		
Nonmusicians	.44 ($p <$ .0001)	.41 ($p <$ .0001)	.62 ($p <$ .0001)	
All participants	.69 ($p <$ .0001)	.63 ($p <$ .0001)	.94 ($p <$ .0001)	.71 ($p <$ .0001)

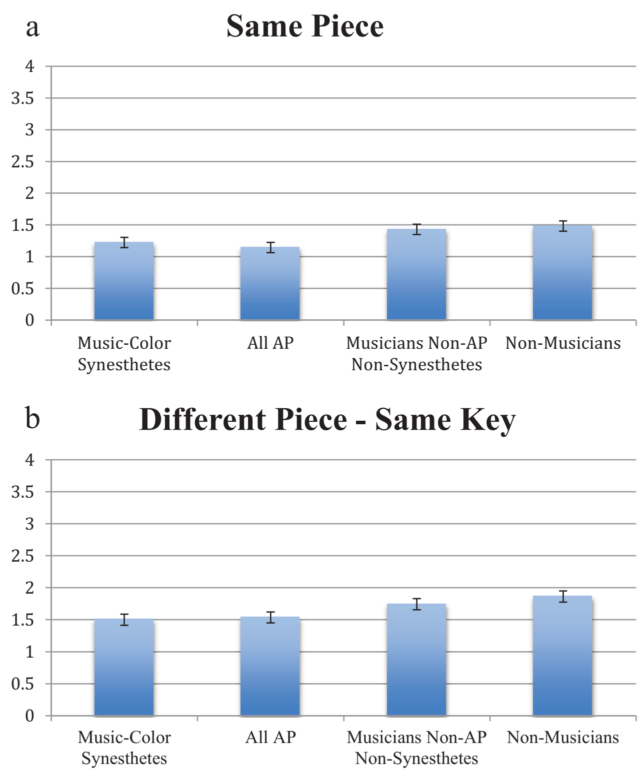

Figure 4. (a) The city-block distance (in Figure 1) between the colors selected in phase 1 and phase 2 (chance = 2) on the same Prelude in Experiment 1. (b) The city-block distance between the colors selected in phase 1 and the different piece in the same key in phase 2. The lower the value, the higher the consistency. Error bars are the standard errors of the mean of each group. See the online article for the color version of this figure.

choices for different Preludes in the same keys. However, again, color consistency correlated with familiarity with the music, $r(126) = -.185$, $p = .0356$, so an effect of familiarity cannot be ruled out. Because these are different pieces of music, the result could not depend on remembering the color choices in phase 1 of the experiment.

Recognition accuracy. To test the accuracy of recognizing previously presented excerpts in phase 2, the hit and false alarm rates were found for each participant, and a signal detection analysis was performed. On average, $d' = .907$ (median = .885), which is significantly greater than 0, $t(127) = 10.671$, $p < .0001$ (see Figure 5). The fact that recognition accuracy was relatively low might be because they did not know during phase 1 that there would be a memory test in phase 2. Because of the skewed distribution, a nonparametric Wilcoxon signed-ranks test was also computed, Signed-Rank = 3336, $p < .0001$. The only significant difference between groups was between musicians without synesthesia or AP and nonmusicians, whether using parametric ($p = .007$) or nonparametric ($p = .004$) measures. No advantage was found for being a music–color synesthete or having AP. Again, familiarity may have played a role in this result; the synesthetes and AP possessors were more familiar with the Preludes prior to the experiment and this may have caused confusion in the old/new recognition task.

Discussion

The Preludes could be divided into four clusters according to the color distributions, that is, the number of participants choosing each of the eight colors for each Prelude. This was true for 22 of the 24 Preludes, the exceptions being two slow Preludes that had relatively flat color distributions. Fast minor Preludes were most often associated with red and its neighbors, fast major Preludes were most often associated with the color yellow and its neighbors, and slow minor Preludes were most often associated with the color blue and its neighbors. Four slow major Preludes were generally associated with colors in the chartreuse–green–cyan range. The color distributions were similar across the different groups: the music–color synesthetes, the AP possessors, the musicians without either synesthesia or AP, and the nonmusicians.

Palmer et al. (2013) found the same effects of tempo and mode on the blue–yellow dimension and replicated it in their more recent study (Palmer et al., 2016). In this second study, they also found effects of attack rate and pitch height. We replicated these effects for the Bach Preludes, using the measures provided by Poon and Schutz (2015). In their studies of a subset of the Preludes in Book I and a smaller selection of four primary colors, Polzella and collaborators (Polzella & Biers, 1987; Polzella & Hassen, 1997) also found an association between red and faster tempos, blue and slower tempos, and yellow and major keys; we did not find their effect of meter (triple/quadruple) possibly because we used the entire set of Preludes. Petrovic et al.'s (2012) study with AP possessors found, as here, faster tempos were associated with orange and yellow, and slower tempos with blue and purple. Preludes in minor keys were also associated with blue and purple. Thus, a number of effects have been found consistently across studies varying in the musical materials used, the procedure, the number of color choices offered, and the music backgrounds of the participants.

Experiment 1 found better than chance self-consistency in color choices across phases 1 and 2 of the experiment when the same Prelude was played twice. That is, the participants tended to choose similar colors when hearing the excerpt again. This was true for all groups, but participants with synesthesia and AP were somewhat more self-consistent. It may be that being able to associate a piece with a color synesthetically, or associating a piece with the name of the tonic tone, facilitated the self-consistency.

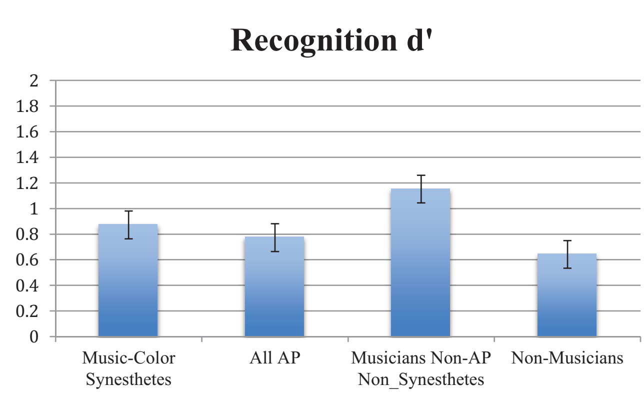

Figure 5. Recognition accuracy in phase 2 of Experiment 1. See the online article for the color version of this figure.

However, these two groups were also more familiar with the music than the other two groups, so familiarity may have also played a role. The participants in all groups were also more consistent than chance when choosing colors for different Preludes in the same key (from Books I and II). The colors tended to be more distant than when the same Prelude was repeated, possibly because the tempos of corresponding keys in Books I and II are quite different. The degree of consistency found nonetheless is interesting in light of the question of whether Bach associated particular characteristics with the different keys as discussed by Ledbetter (2002).

The groups differed from one another in terms of how well they were able to distinguish between Preludes they had heard in phase 1 of the experiment and new Preludes introduced in phase 2. Nonmusicians performed less well than the other participants. Musicians without music–color synesthesia or AP performed better than those with synesthesia and/or AP. It is interesting that synesthesia did not incur a memory benefit, which might have been expected given the previous literature (e.g., Radvansky et al., 2011; Rothen & Meier, 2009, 2010; Rothen, Meier, & Ward, 2012; Smilek et al., 2002; Ward, Hovard, Jones, & Rothen, 2013). This might be due to differences between our study and most of those reported in the previous literature; we used a surprise recognition task and music as opposed to visual stimuli. However, it seems most likely, given that the disadvantage was found for both the synesthetes and the AP possessors, their familiarity with the Preludes before the experiment made it difficult for them to distinguish between whether they had just heard it, or whether it sounded familiar because of their prior experience.

The music–color synesthetes were similar to the other groups in all four measures in the experiment: the pattern of color choices, self-consistency in color choices over time, generalization to another piece in the same key, or recognition memory accuracy. It may be that larger differences would be found if the task were altered to offer more fine-grained color choices. Additionally, the synesthetes were not tested to confirm the strength of their synesthesia, although a number of them offered detailed accounts of vivid perceptual experiences. Additionally, the fact that participants were instructed to judge which color best fits the music may have focused the synesthetes' attention on the qualities of the music rather than on their internal experience triggered by the music. Thus, larger effects of having synesthesia might be found with different methodologies.

Experiments 2 and 3 test whether the pattern of color associations, which was fairly consistent across the groups, can be accounted for in terms of the emotion-mediation hypothesis (Palmer et al., 2013). The recent study by Poon and Schutz (2015) made a similar proposal. They suggested that Bach may have varied low-level acoustic characteristics associated with happy and sad speech. They found that Preludes in major mode were two semitones higher in pitch height on average and 29% faster in attack rate than minor Preludes. As noted above, pitch height and attack rate, together with tempo and mode, also were factors in determining to which of our clusters a Prelude belonged. The Preludes from the Well-tempered Clavier vary in many other characteristics, such as arpeggiation and chromaticism, so it is interesting to note the consistent effects of these basic dimensions.

Experiment 2

Experiments 2 and 3 focus on the possibility that the music–color associations found in Experiment 1 are mediated by the emotional associations of the colors and the music, as suggested by Palmer et al. (2013, 2016). In order to clarify the emotional associations to the eight colors, Experiment 2 presented the colors for ratings on a number of emotion scales. Experiment 3 then presents the Preludes for association on the same emotion scales, and the results are combined to determine whether the color–emotion associations in Experiment 2 and the music–emotion associations in Experiment 3 can account for the music–color associations in Experiment 1.

Method

Participants. Twenty-six undergraduates from Cornell University participated in the experiment for course credit and were run individually in the laboratory. They were not selected according to musical background.

Materials. The eight colors were the same as in Experiment 1, and the equipment was that was used for the in-lab participants in Experiment 1.

Procedure. After giving informed consent, the eight colors were presented in random order in a Qualtrics survey. Participants rated the eight colors on nine emotion scales: lively, happy, positive, weak, calm, sad, negative, strong, and angry (taken from D'Andrade & Egan, 1974; Palmer et al., 2013) on a scale from 0 to 10. The order of the emotion scales varied randomly on each trial.

Results and Discussion

Table 3 shows the average ratings for each color on the emotion scales. Red rated highly on strong and angry, orange rated highly

Table 3
Average Ratings for Each Color on the Emotion Scales in Experiment 2

Color	Strong	Angry	Negative	Weak	Sad	Calm	Positive	Happy	Lively
Red	8.19	7.00	5.08	0.58	2.27	1.00	3.42	3.00	4.92
Orange	5.35	3.46	2.92	2.15	1.69	2.19	5.46	6.15	6.12
Yellow	4.27	1.62	1.81	3.08	1.12	2.77	6.85	6.96	7.00
Chartreuse	3.73	1.58	2.92	4.15	2.54	4.04	4.85	4.96	5.15
Green	4.42	1.04	1.69	2.35	2.31	5.42	6.69	5.81	6.19
Cyan	3.65	0.46	1.50	2.92	2.58	6.54	6.08	5.58	4.58
Blue	4.23	0.88	2.42	2.81	4.23	7.15	5.38	4.12	4.08
Purple	6.23	1.92	2.50	1.88	3.65	4.31	5.04	4.77	5.38

on happy and lively, and yellow rated highly on positive, happy, and lively. Chartreuse was similar, although the ratings for chartreuse tended to be lower overall. Green was also rated highly on positive, happy, and lively, and also calm; the ratings for cyan were similar although lower on lively. Blue was rated high on calm and positive, and purple was similar, although also rated highly on lively and strong. In general, the color–emotion associations agree with previous results (D'Andrade & Egan, 1974; Palmer & Schloss, 2010; Palmer et al., 2013, 2016).

A principal components analysis was done on the data in Table 3 in order to visualize and understand better the relationships between the color scales. For each color, the average rating across subjects on the nine color scales was computed. The principal components analysis (in JMP Pro) used the correlations between the emotion ratings. Vectors pointing in similar directions represent colors that correlate more strongly on the emotion scales. The result, shown in Figure 6a, indicates that the emotional associations individuals make to the colors are sufficiently regular to recover the full color wheel, although with less separation than might be expected in the chartreuse–green–cyan range. In a similar way, a principal components analysis was done on the emotion terms with the result shown in Figure 6b. As can be seen, the organization of the emotion terms generally corresponds to variation in valence and arousal, but with angry, strong, and negative associated with similar colors. Note that pairs such as happy–sad are not necessarily diametrically opposite; this kind of result has also been found for music (Vines et al., 2011).

Experiment 3

Experiment 3 investigated whether we could predict the music–color associations (Experiment 1) by color–emotion associations (Experiment 2) and music–emotion associations (Experiment 3). Participants in this experiment rated excerpts of each of the Preludes on the same emotion scales as Experiment 2. One question is whether the emotion ratings produce the same clusters of Preludes found in Experiment 1. Another question is whether the distribution of color choices in Experiment 1 can be mathematically derived from the color and emotion ratings of Experiment 2 and the music and emotion ratings of Experiment 3.

Method

Participants. Twenty-eight undergraduates from Cornell University (22 women; age $M = 19.75$, $SD = 1.80$, range 18–25) participated in the experiment for course credit. In total, there were 21 musicians whose musical experience ranged from 1 to 27 years experience (summed over different instruments), $M = 13.19$. The average age at which the musicians began musical training was 7.05 (range: 3–16). Of the musicians, six had absolute pitch. There were three synesthetes, two musicians with sound to vision associations, and one nonmusician with vision to taste associations. Participants' prior familiarity with the music in this experiment averaged 3.63 on a scale of 1 to 10, and eight of the musicians knew how to play some of the Preludes in the experiment. They were run individually in the laboratory.

Materials. The excerpts from the 36 Preludes from both phases 1 and 2 of Experiment 1 were used, and the equipment was the same as in Experiment 2.

Procedure. After giving informed consent, participants rated the excerpts on the nine emotion scales from Experiment 2: lively, happy, positive, weak, calm, sad, negative, strong, angry on a scale from 0 to 10. Excerpts from the Preludes were presented in random order in a Qualtrics survey, and the order of the emotion scales was randomly reassigned on each trial.

Results and Discussion

Table 4 shows the average rating on the emotion scales for the excerpts from each Prelude in Book I. These ratings were analyzed using the same clustering algorithm as Experiment 1 and produced the clusters shown in Figure 7. It clusters together Preludes that have similar ratings on the emotion scales. Cluster membership was exactly the same as that shown in Figure 3, except that now the two Preludes that had relatively flat color distributions (D minor and Eb major, which are both slow) cluster with the slow major Preludes in Figure 7d. The proportion of variation explained by clustering is .907. This result supports the idea that the music–color associations found in Experiment 1 can be explained by the links from music to emotion and from emotion to color. However, it suggests a slightly different emotion interpretation for the fast, minor Preludes, which was closely associated with strong, a result

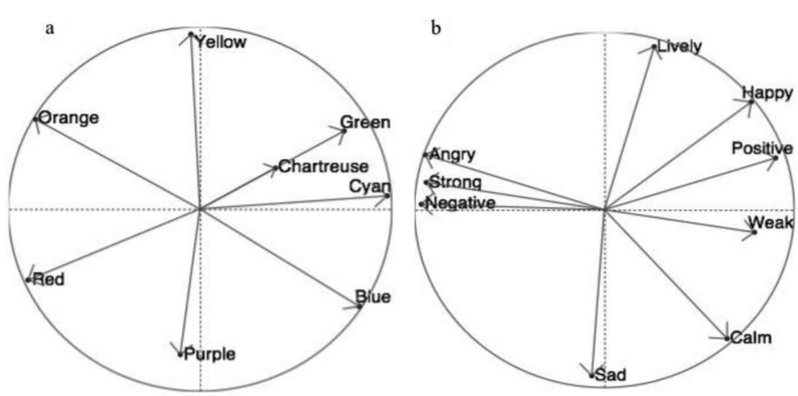

Figure 6. Principal components analysis revealing (a) a two-dimensional map of colors based on emotional associations, and (b) emotion space recovered from color associations.

Table 4
Average Ratings for Preludes in Book I on the Emotion Scales in Experiment 3

Key	Strong	Angry	Negative	Weak	Sad	Calm	Positive	Happy	Lively
C Maj	2.64	0.61	0.79	1.63	2.43	6.59	6.00	5.32	4.57
C Min	7.39	5.07	3.50	0.43	1.89	0.75	1.96	1.54	5.29
C# Maj	3.21	0.71	0.79	1.11	0.71	3.50	5.89	5.93	7.04
C# Min	1.79	1.11	2.96	2.79	5.50	5.61	1.50	0.96	1.79
D Maj	4.39	0.89	0.70	0.68	0.43	1.61	6.32	5.93	8.39
D Min	3.39	2.04	1.93	2.25	3.25	4.11	2.75	2.68	3.64
Eb Maj	4.07	0.93	1.43	1.18	1.56	4.68	5.15	4.32	4.36
Eb Min	1.39	1.32	4.64	4.29	7.61	5.61	0.82	0.71	1.36
E Maj	1.39	0.50	1.00	2.21	2.04	6.46	5.07	3.93	3.39
E Min	2.04	1.07	3.07	3.07	6.43	4.89	1.00	0.93	2.11
F Maj	5.21	1.07	0.64	0.61	0.68	1.71	6.29	6.00	8.14
F Min	1.68	1.19	3.48	3.14	6.93	5.93	1.22	0.75	1.21
F# Maj	2.82	0.57	0.71	1.43	0.93	4.00	5.82	6.43	6.04
F# Min	6.93	2.79	1.93	0.46	1.21	1.54	3.61	3.46	7.14
G Maj	5.25	1.75	1.50	0.71	0.68	1.00	5.21	4.33	7.96
G Min	2.82	1.18	3.32	1.79	5.14	4.25	1.68	1.36	3.32
Ab Maj	4.78	0.39	0.54	1.04	0.93	2.73	6.93	7.11	6.35
G# Min	1.86	0.79	3.71	2.74	6.19	6.11	1.57	1.44	1.46
A Maj	2.82	0.46	0.96	2.07	1.79	4.18	5.57	5.54	5.71
A Min	7.00	3.75	3.29	0.54	1.56	1.11	2.71	2.21	7.29
Bb Maj	3.71	1.21	1.00	0.93	0.82	1.86	6.11	5.68	7.86
Bb Min	3.21	2.82	4.11	3.61	7.93	4.64	0.71	0.54	1.39
B Maj	4.48	1.30	1.21	0.79	0.96	2.11	6.37	6.25	7.96
B Min	3.08	2.19	4.21	3.74	6.96	3.96	0.96	1.11	1.32

also found by Palmer et al. (2016). Otherwise, the fast major Preludes are rated highly on positive, happy, and lively, the slow minor Preludes on sad and calm, and the slow major Preludes on calm, positive, happy, and lively.

The final analysis tests whether the music–color associations can be explained by multiplying the matrix of music–emotion ratings in Experiment 3 (see Table 4) with the color–emotion ratings in Experiment 2 (Table 3, Transposed). Consider, for example, the Prelude in C. When the vector on its emotion ratings, <2.64, .61, .79, 1.63, 2.43, 6.59, 6.00, 5.32, 4.57> (ordered strong, angry, negative, weak, sad, calm, positive, happy, lively), is multiplied by the vector of color on the emotion ratings for green <4.42, 1.04, 1.69, 2.35, 2.31, 5.42, 6.69, 5.81, 6.19> the result is 158.2. In contrast, if the vector for the Prelude in C major is multiplied by the vector of color on the emotion ratings for red <8.19, 7.00, 5.08, .58, 2.27, 1.00, 3.42, 3.00, 4.92> the result is 101.9. This predicts that green would be chosen more often than red for this Prelude. All together, the predicted colors for this Prelude have the vector <101.9, 134.0, 149.8, 131.7, 158.2, 152.3, 148.5, 140.2> (ordered red, orange, yellow, chartreuse, green, cyan, blue, and purple), and it can be seen that the highest predicted colors are green and cyan. The number of participants in Experiment 1 who chose these colors for this Prelude was <4, 9, 17, 14, 23, 33, 20, 9> (shown in Figure 3), with most choosing green and cyan, and the correlation with the predicted colors is $r(6) = .78$. When this is done for all Preludes the average correlation is .72 (range: .21–.97). The lowest two correlations are for the Preludes (*d* minor and Eb major) that had relatively flat color distributions; when these are excluded the average correlation is .76 (range: .45–.97). The corresponding results when the nonparametric test of Spearman's rho was used are: average all Preludes $\rho = .67$ (range: −.08–.99), excluding D minor and Eb major average $\rho = .73$ (range: .38–.99). Thus, two results lend support to the idea that emotion–color associations can be accounted for by emotional connotations: that the Preludes cluster similarly by color choices and emotional ratings, and the prediction of color choices for the music based on the music to emotion, and color to emotion correlations.

Conclusions

The main goal of this study was to determine the extent to which music–color associations could be accounted for by emotional associations to the musical excerpts and to the colors. Following the approach taken by Palmer et al. (2013, 2016), after obtaining color associations to the musical excerpts in Experiment 1, we obtained judgments of both the colors (Experiment 2) and the music (Experiment 3) on a number of emotion scales. Experiment 2 showed that an orderly representation of colors could be recovered from the emotion associations, and an orderly representation of emotions could be recovered from the color associations. The music–emotion judgments grouped the Preludes in the same way as in Experiment 1, with the exception of two Preludes that had relatively flat color distributions in Experiment 1. Moreover, the music–color data of Experiment 1 could be predicted by the color–emotion and music–emotion data in Experiments 2 and 3; a color was frequently chosen for the musical excerpt if it had similar emotional connotations as the color. These results argue that emotional connotations are largely sufficient to account for the music–color associations found in Experiment 1.

These emotional connotations of colors are established, according to the ecological valence theory, by emotional responses to colored objects (Palmer & Schloss, 2010). They suggest that emotional connotations of colors and music could arise from a variety of sources. For example, they suggest that neural encoding

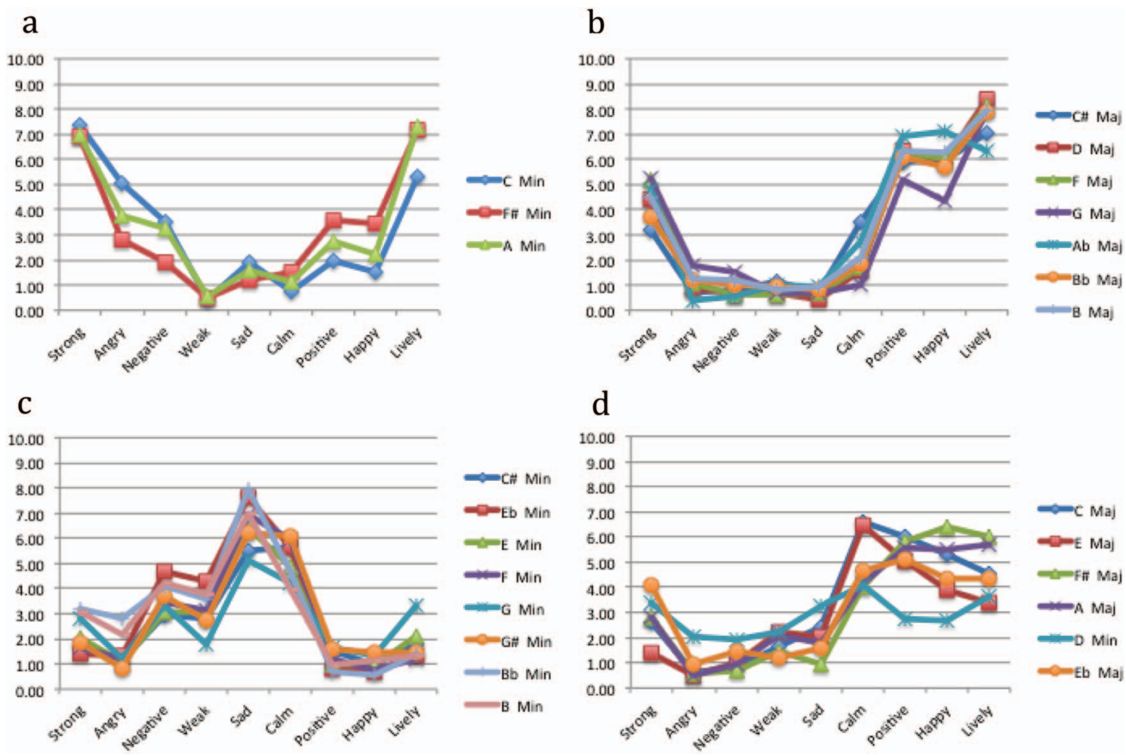

Figure 7. The ratings of each Prelude on the emotion scales in Experiment 3. (a) Cluster contains minor Preludes with fast tempo. (b) Cluster contains major Preludes with fast tempo. (c) Cluster contains minor Preludes with slow tempo. (d) Cluster contains major Preludes with slow tempo and one minor Prelude with slow tempo. See the online article for the color version of this figure.

of emotional associations between the two may be similar. Additionally, statistical regularities may exist when coexperiencing colors and music with particular emotional associations (such as in film and other media). Lastly, they suggest that there may be systematic semantic commonalities in terms of how individuals conceptualize the emotional content of music and colors. In line with this, the emotional connotations of a stimulus have been shown to statistically predict color choices more accurately than any other dimension of the stimulus (Ward, 2004). Stimuli with a negative emotional connotation consistently yielded darker, desaturated color associations, and stimuli with a positive connotation yielded significantly lighter, more saturated color associations.

Walker and colleagues suggest that cross-modal associations between stimuli may reflect reciprocal interactions with a set of amodal, conceptual features that are not necessarily of an emotional character (Walker & Smith, 1984; Walker et al., 2012). They demonstrate that stimuli from different domains access common connotative meanings along dimensions of height, size, strength, and activity. This generates associations, for example, between high-pitched tones and bright visual stimuli (see Walker, 2016, for other examples with musical tones). Similar patterns of association have also been found in 3–4-month-old infants, suggesting that such cross-modal correspondences may be innate (Walker et al., 2010).

Finally, Experiment 1 found relatively small effects of synesthesia, AP, or musical training on the colors chosen for the musical excerpts. The excerpts of the Preludes fell into four clusters according to their color associations, whether in the red, yellow, blue, or green range. Cluster membership was reliably predicted by mode, tempo, pitch height, and attack rate. The groups of participants were also similar on the degree of self-consistency on the same excerpt (whether a similar color was chosen when the excerpt was repeated), generalization to a different excerpt in the same key, or recognition memory accuracy. It would seem, then, that the systematicity of music–color associations operates at a more general level. We note, however, that different experimental methods might uncover greater effects of being a synesthete or possessing AP.

Thus, the similar results for the synesthetes and the remaining participants found here generally support the view that synesthesia may be subject to some of the same rules that govern normal patterns of cross-modal associations (Marks, 2013; Simner, 2013), although perhaps different in origin or automaticity. The pattern of color–emotion associations noted above (Ward, 2004) was found for both synesthetes and nonsynesthetes. A subsequent study looked at color associations to different pitches played by different instruments (Ward, Huckstep, & Tsakanikos, 2006). This study found that the synesthetes were more self-consistent in their color choices in a 2–3 month retest than were nonsynesthetes, and their color choices were also more precise. Despite these differences, both synesthetes and nonsynesthetes used the same scheme for mapping sounds to colors. Higher tones were associated with lighter colors and richer colors were associated with piano and string tones than were sine waves. From this they concluded that synesthetes follow some of the same principles used in normal cross-modal perception rather than possessing a special pathway connecting auditory and visual areas.

The present results, and those of Palmer and colleagues (Palmer et al., 2013, 2016), suggest that similar principles extend to complex musical patterns, and that some of the important characteristics of music associated with cross-modal associations are mode, tempo, pitch height, and attack rate. Although the present experiments examined the role that emotions may play in mediating music–color associations, other types of mediators might also contribute to cross-modal associations to music. Additional semantic associations likely play a role, and perhaps even structural and statistical associations. Another direction to be explored in future research would be to consider other musical features that might influence associations from music to other domains. Possible candidates include melodic contour, harmonic patterns, chromaticism, and rhythmic figuration. This kind of analysis would extend our current understanding of how musical patterns evoke extramusical associations.

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Appendix

Colors Used in Experiments 1 and 2

Table A1

RGB Coordinates for the Colors Used in This Study (Palmer & Schloss, 2010)

Color	R	G	B
Red	209	48	55
Orange	255	152	71
Yellow	255	203	83
Chartreuse	148	203	80
Green	0	204	114
Cyan	0	204	203
Blue	39	154	200
Purple	158	54	197

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