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Prof. Dr. Dr. Karl Hörmann zum 80. Geburtstag

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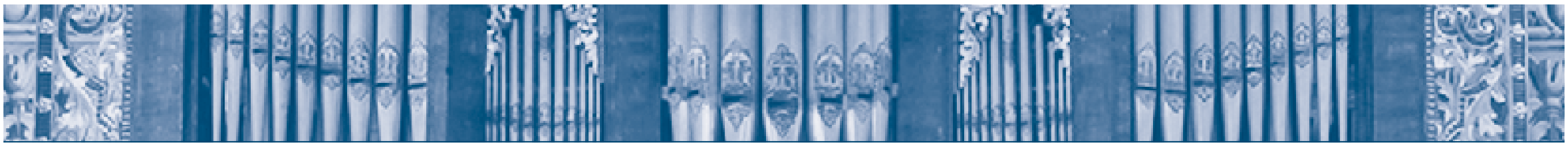

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Karl Hörmann
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mtk@bkmt.de

Mitherausgeberin und Redaktion
Yolanda Bertolaso
mtk@kuenstlerischetherapien.de

Mitherausgeber
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Inhalt

Colored timbres. Do crossmodal correspondences between musical instrument sounds and visual colors rather depend on pitch instead of timbre?

Saleh Siddiq[1], Isabella Czedik-Eysenberg[1], Jörg Jewanski[1,2], Charalampos Saitis[3], Sascha Kruchten[1], Rustem Sakhabiev[4], Michael Oehler[5] & Christoph Reuter[1]

Abstract

Crossmodal correspondences between music and color gained much attention from researchers. Especially mappings of pitch to colors were investigated, while mappings of timbre to color garnered less interest. A short review over historic and recent studies on timbre-color mappings is given. An empirical study with 40 participants who were asked to match 60 musical instrument sounds with 38 colors was conducted in order to shed light on the underlying factors of the assignment of musical instruments' sounds to colors. The question is if timbre-color matchings depend on timbre or if participants indeed resort to pitch as dominating factor. Despite notable interindividual inconsistencies, the results reflect some of the more common associations of colors and musical instruments, e.g., red/yellow and trumpet sounds. However, the influence of timbre was found to be less robust than the influence of pitch. The most reliable relation was the well known tendency to match lower pitches with darker colors and higher pitches with bright colors. As starting point for future research, the results were qualitatively compared with the sensations of one synesthete.

Keywords: musical timbre, musical instrument, color, crossmodal correspondences

Farbige Klangfarben. Hängen intermodale Analogiebildungen zwischen den Klängen von Musikinstrumenten und visuellen Farben eher von der Tonhöhe oder von der Klangfarbe ab?

Zusammenfassung

Intermodale Analogiebildungen zwischen Musik und Farbe haben bei Forschern viel Aufmerksamkeit erregt. Insbesondere wurden Zuordnungen von Tonhöhe zu Farben untersucht, während Zuordnungen von Klangfarbe zu Farbe weniger Interesse fanden. Es wird ein kurzer Überblick über historische und aktuelle Studien zu Klangfarben-Farben-Zuordnungen gegeben. Eine empirische Studie mit 40 Teilnehmern, die aufgefordert wurden, 60 Musikinstrumentenklänge 38 Farben zuzuordnen, wurde durchgeführt, um die der Zuordnung von Musikinstrumentenklängen zu Farben zugrunde liegenden Faktoren zu erhellen. Die Frage ist, ob die Zuordnung von Klangfarbe zu Farbe von der Klangfarbe abhängt oder ob die Teilnehmer eher auf die Tonhöhe als dominierenden Faktor zurückgreifen. Trotz bemerkenswerter interindividueller Inkonsistenzen spiegeln die Ergebnisse einige der häufigsten Assoziationen von Farben und Musikinstrumenten wider, z. B. rot/gelb und Trompetenklänge.

[1] Department of Musicology, University of Vienna, Austria
[2] Department Musikhochschule, University of Münster, Germany
[3] Centre for Digital Music, School of Electronic Engineering and Computer Science, Queen Mary University of London, Great Britain
[4] Independent scholar, Rheine, Germany
[5] Department of Musicology, University of Osnabrück, Germany

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Allerdings erwies sich der Einfluss der Klangfarbe als weniger stabil als der Einfluss der Tonhöhe. Der zuverlässigste Zusammenhang war die bekannte Tendenz, tiefe Töne mit dunkleren Farben und hohe Töne mit helleren Farben zu verbinden. Als Ausgangspunkt für zukünftige Forschung wurden die Ergebnisse qualitativ mit den Empfindungen eines Synästhetikers verglichen.

Schlüsselwörter: Klangfarbe, Musikinstrument, Farbe, intermodale Analogiebildung

Introduction[6]

Throughout history, color and music had many points of contact. Since Ancient Greece, the relationship between auditory pitch and visual color was often discussed (Jewanski, 1999), the recurring theme of this relation is the matching of higher pitches with brighter colors and lower pitches with darker colors. It was first reported by the German polymath Athanasius Kircher (1646, p. 67; Jewanski, 1999, pp. 197–219) and, without referring to Kircher, has since been confirmed by several empirical studies (e.g., Wicker, 1968; Marks, 1974, 1987; Marks et al., 1987; Hubbard, 1996; Ward et al., 2006; Haryu & Kajikawa, 2012; Klapetek et al., 2012; Walker et al., 2012; Brunel et al., 2015; Jonas et al., 2017; Getz & Kubovy, 2018; Hamilton-Fletcher et al., 2018; Anikin & Johansson, 2019). The association of auditory pitch and visual brightness can be seen as exemplifying a broader cognitive phenomenon, collectively known as crossmodal correspondences (Spence, 2011, 2019). These are defined as the brain's tendency to preferentially associate certain features of stimuli, or dimensions, across modalities (i.e., the senses). A similar tendency was found in chimpanzees and thus might constitute 'a basic feature of the primate sensory system' (Ludwig et al., 2011, p. 20661). However, it is questionable if such crossmodal correspondences are indeed innate since new associations between previously unrelated sensory dimensions are internalized rapidly and the environment provides plenty of cues regarding the correlation of auditory pitch and visual brightness (Spence & Deroy, 2012, p. 317).

The relationship between musical timbre (often meaning: the 'characteristic sound' of a musical instrument) and visual colors, on the contrary, received less attention from researchers. The following review gives a little insight into the research history of timbre-color mappings.

[6] Jörg Jewanski, one of the authors of this study, attended Karl Hörmann's seminar *Form and Color in Music Education* at the University of Münster in the summer semester of 1982. This course, in combination with Hörmann's monograph *Musikwahrnehmung und Farbvorstellung* (Music perception and color vision; 1982), in particular the chapter on the state of music-related synesthesia research (pp. 28–45), was the starting point for Jewanski's ongoing preoccupation with artistic and scientific interactions between sound and color and with the phenomenon of synesthesia. In particular, Hörmann's reception of Bulat Galeev's writings on color music, the first of their kind in the German-speaking world, is taken up in this article and continued with the integration of the works of Galeev's wife Irina Vanečkina and her student Irina Trofimova.

Early history of timbre-color mappings

'Timbre' is a term that needs some clarification. It was famously labeled by Joseph Carl Robnett Licklider as a 'multidimensional dimension' (1951, p. 1019). As such, it is 'impossible to measure […] on a single continuum such as low to high, short to long, or soft to loud' (McAdams et al., 1995, p. 177). Timbre mainly consists of the spectral attributes of the respective sound but temporal (e.g., transients) and noise components contribute considerably (Stumpf, 1890, p. 516; English summary in Reuter & Siddiq, 2017, pp. 151–152; Siddiq et al., 2018). In fact, timbre applies to single sounds which is obvious in the analogous German term 'Klangfarbe' (literally: 'sound color'). Alexander J. Ellis deliberately translated it as 'quality of tone' within his translation of Hermann von Helmholtz's *'On the sensation of tones'* (1875, p. 36). Mostly, 'timbre' is used in reference to pure tones, single sounds, sound combinations, as well as musical instruments.

However, when using the word 'timbre', we often think of a concept of identity, i.e., a sound with a meaning such as the sound of, e.g., the bassoon (i.e., defining the bassoon). Of course, there is no such thing as 'the sound of the bassoon', since no two bassoons sound alike and one bassoon does not produce two tones that sound the same (Houtsma, 1997, p. 105). Currently, a change in thinking seems to happen, where the concept of timbre as identity of an entire instrument is broken down to smaller levels, e.g. registers (Reymore et al., 2023, pp. 271–272). A more refined terminology was proposed, taking all the different levels into account (Siddiq et al., 2018, pp. 414–415).

But since the motivation of researchers is often unclear and 'timbre' is inconsistently applied to entire instruments and isolated sounds, we here terminologically collapse 'timbre-color' and 'instrument-color' mappings. Moreover, for the scope of this article, the term 'timbre' applies to both, the sound quality of single sounds as well as the sound character of musical instruments. A strict separation in this context would be more tedious (for the writer and the reader) than it would be beneficial.

To our knowledge, the first reported mapping of a musical instrument and a color is the matching of the trumpet and the color red (or rather scarlet), as described by the British philosopher John Locke (1690, p. 199). The first mapping 'system', containing several instruments and colors, was developed by the German painter Johann Leonhard Hoffmann. He explained the harmony of a painting through examples of music (Hoffmann, 1786, pp. 56–58). The Swiss composer Joachim Raff was well aware of the multitude of timbres a musical instrument produces over the span of its pitch range. He deliberately matched each instrument with several colors (Raff, 1854, letters 22 and 24, pp. 166–175, 186–194).

The first explanation of timbre-color mappings was provided by the Czech philosopher Joseph Wilhelm Nahlowsky. He thought matchings would arise due to the same effect certain tones and colors had on the soul (Nahlowsky, 1862, pp. 147–148). E.g., the flute has a similar soft, enthusiastic, dreamlike effect on the soul as the blue sky, whereas the trumpet has the same radical effect as bright red. Wilhelm Wundt, a German psychologist, supported Nahlowsky's method of creating associations, and complimented:

> *'The low pitch tone, regarded as pure sensation, presents no relationship to the dark color, but, due to the same earnest kind of feeling attached to both of them, we transfer this to the sensations, which seem to be related to us now.' (Wundt, 1874, p. 452; translated by the authors)*

Without referring to Nahlowsky or Wundt, more recent publications fall into line with the idea that the relation of auditory percepts (e.g., music) and visual percepts (e.g., colors) are mediated by feelings, emotions, or mood (Olbert et al., 1942; Barbiere et al., 2007; Holm et al., 2009; Palmer et al., 2013, 2016; Lindborg & Friberg, 2015; Whiteford et al., 2018).

In 1943, roughly a century after Raff, the US-American composer Arthur Lange published an elaborate system of timbre-color mappings. Lange mapped a range of colors onto many (orchestral) instruments from dark colors (mostly purple and brown) at the low pitch register to bright colors at the high pitch register (mostly yellow and white). He created a set of 'tone-colors' (black, shaded, purple, brown, red, orange, blue, green, yellow, white) and stated that the 'analogy between visual color and the musical tone-color it describes is based on the psychological reaction they both create in common' (Lange, 1943, p. 2). Based on this theory he developed an orchestration system, known as Spectrotone, that, in turn, defines the relations between (or combinations of) different timbres based on color similarities (ibid, pp. 12–25).

Empirical studies on timbre-color mappings

There is actually a longer history of empirical studies on timbre-color mappings than we are aware of today. But, unfortunately, studies from the 19th and 20th centuries were often lacking crucial methodological information. In stark contrast to the standardized stimuli we are used to from contemporary studies, authors usually did not disclose (and most likely were not concerned with) any specific color spaces or values. Also, information on the nature and/or manner of presentation of the 'auditory' stimuli was provided sparsely. Moreover, they never referred to one another and thus did not spark a lasting line of research and have since fallen into oblivion.

The first empirical study investigating the mapping of timbres to colors was published as early as 1883 by the US-American psychologist and educator Granville Stanley Hall. Twenty-one out of 53 children described the sounds of certain instruments as colored. Tested and re-tested on a weekly basis, hue, intensity and saturation varied considerably within the same individuals as well as across the group. The author described the results as 'forms of association or analogies of sensation' (Hall, 1883, pp. 265–266). Specifics on the presentation of the stimuli were not provided. On the one hand, the colors were named freely by the participants without constraints and/or standardization by means of a list or palette. On the other hand, it is unclear whether the musical instruments were only referred to by name or actually played.

A more nuanced study was published by US-American educator Evelyn L. Mudge in 1920. Fifty students were asked to report the respective colors or brightness values they associated with certain tones, keys, nine musical instruments, and musical compositions (Mudge, 1920, p. 342). Regarding instruments, the results were for example: 24 out of the 50 students associated the piano with a wide range of colors and brightness values. On the other hand, 35 students overwhelmingly associated the violin with blue, violet and related colors. Mudge provided the following explanation:

> *'A high tone or a high pitched instrument is generally associated with bright colors or lighter grays, while a low tone or a commonly low pitched instrument suggests dark color and brightness values. There appears also to be a relation between the timbre of an instrument and the richness of color associated with its tone.' (ibid, p. 345)*

As with Hall, Mudge did not disclose whether the instruments were indicated by name only or actually presented acoustically, nor did she provide any specifics regarding the colors or their presentation.

A study conducted by the Russian musicologist Leonid Sabaneev examined 'the relation between sound and color' (Sabaneev, 1929). Sabaneev let 250 participants match pitches with colors from a table, 'which represented Helm-

	most frequently matched colors			sum (1–3)	other colors
	no. 1	no. 2	no. 3		
flute	31.7	22.5	19.2	73.4	26.6
glockenspiel	55.7	15.6	12.3	83.6	16.4
piano	32.2	19.8	17.4	69.4	30.6
panpipe	25.8	21.7	20.0	67.5	32.5
strings	39.3	23.0	14.8	77.1	22.9
trumpet	36.9	21.3	13.1	71.3	28.7

Figure 1 Short table of Emmett's results

No. 1–3: the three most frequently selected colors, with the absolute number of selections given in the color swatch. 'Sum (1–3)': aggregate of No. 1–3. 'Other colors': Number of residual selections

holtz's colour cone [...] and included every possible shade' (ibid, p. 268; for the color triangle, see Helmholtz, 1924, p. 145). Sabaneev provided a detailed list of findings, assigning participants to different types of associations. The interesting takeaways linked to our topic are that 218 participants matched high registers with bright colors and low registers with dark colors, while only 47 participants matched colors with timbres. Sabaneev explicitly refrained from giving a 'complete exposition' of his methods (Sabaneev, 1929, p. 268) but still shed some light here and there. Although the names and tones of the (auditory) stimuli were not provided, Sabaneev pointed to the importance of how the (auditory) stimulus is presented:

> *'It is evident that two sets of associations are involved here, the one arising from the direct sensation produced and the other from the name of the tonal phenomenon. Thus the name C major yielded a certain colour association.' (ibid, p. 268)*

The colors, on the other hand, were presented by means of a table representing Helmholtz's color cone. The experiment was repeated several times to separate inconsistencies from stable impressions. To our knowledge, this was the first time in the history of timbre-color experiments that both a standardized color palette was utilized and multiple trials were conducted for intrapersonal consistency.

In 1994, music educator Karin E. A. Emmett published the most detailed 'Western' study thus far. A total of 122 children (6–14 years of age) were asked to assign one of six provided colors (blue, yellow, green, red, black, white) to six different versions of the same musical piece. Each of these six otherwise identical versions of J. S. Bach's Invention No. 1 from the Two-Parted Inventions, BWV 772, was played on a different instrument (flute, glockenspiel, piano, panpipe, strings, trumpet). For the sake of simplicity, we collapsed the results into a comprehensive quintessential overview: Figure 1 shows the three most frequently selected colors for each instrument overall. Please note, the colors shown are generic because specific values were not provided.

As can be seen from Figure 1, there is a distinct preference for blue (six selections), green (five), and yellow (four), in apparent independence of the musical instrument (Emmett, 1994, p. 142). If only the very first of the three selected colors for each instrument is taken into account, just three colors (blue, green, yellow) appear at all. Interestingly, instruments with unequivocally dissimilar timbral ranges were yet matched with the very same color (e.g., piano and trumpet).

A possible interpretation could be the fact that the timbres produced by strings and panpipes are heavily characterized by salient noise components, causing a fair amount of roughness. The noise components of flute and piano are less pronounced but gain dominance with ascending pitch as the harmonic partials are pushed out of the audible spectrum, while the noise remains. On the other hand, the trumpet remains an outlier. The panpipe has a soft, hollow, breathy character, whereas strings are bright and would presumably bear a greater resemblance to the trumpet than the panpipe. The glockenspiel, as the only other percussive instrument, should not differ that greatly from the piano, despite sounding brighter and showing a more distinct attack.

Altogether, the results do not suggest any underlying perceptual systematics in terms of instrument-color mappings. The auditory stimuli might be a possible explanation. Spreading an instrument over a wider range of pitches offers the opportunity to experience a wider range of its multiplicity of timbres but also levels the distinctiveness of the compound sound character of the instrument. But more importantly, especially the younger children might have been distracted by the music as such from the instrument's sound itself. Moreover, the often predominant matching of high pitches with bright colors and low pitches with dark colors (see below) is impossible for two reasons. First, the auditory stimuli consist of the same musical piece and thus the same notes. Second, the visual stimuli, the very limited color palette basically consists only of primary colors which are hard to rank in terms of brightness. Furthermore, the irrelevance of the color red seems odd. Also, Emmett did not elaborate on the possible confounding influence of the children's favorite colors.

Ward and colleagues (2006) published a study comparing the mapping behavior of ten sound-color synesthetes. Three experiments were conducted, the first of which compared the synesthetes with a group of ten non-synesthetes. For this review's sake we only focus on how the non-synesthetes fared in this first experiment.

The participants were asked to freely pick a color from the RGB-space and to match it with each of 70 sound stimuli. The sounds consisted of ten piano tones, each at a different pitch, ten pure tones, and ten string tones matched in pitch to the piano tones. The other 40 auditory stimuli were ten single tones of several other instruments as well as ten dyads each of the piano, strings and pure tones respectively. The test was repeated after ten minutes and after two to three months (ibid, pp. 266–267).

The results showed a low internal consistency for non-synesthetes in terms of hue matching but found the increase of brightness with ascending pitch as a common underlying mechanism for both, synesthetes and non-synesthetes (ibid, pp. 268–269). The only effect of timbre, if the absence of partials is considered a 'different timbre', is that 'musical notes from the piano and strings are, literally, more colourful than pure tones' (ibid, p. 270).

In 2014, Adeli and colleagues published a study investigating the crossmodal correspondences between musical instruments and colored shapes. A total of 119 participants were asked to match eight musical instruments (electric piano, marimba, guitar, cello, tenor saxophone, triangle, crash cymbals, gong) with one of three shapes (angled, mixed, curved variations of an irregular star- or splash-like shape) in four colors (red, green, blue, yellow) as well as four grayscales (black, dark, middle, and light gray).

It is worth noting how the auditory stimuli were prepared. The first five of the eight instruments were presented at four different pitches each (100, 150, 200, 250 Hz), resulting in 20 sounds. These sounds were filtered to share the same normalized temporal envelope. The authors acknowledge the detriment in timbral integrity as 'listeners [...] could not use the full range of musical timbre, making the decision more difficult'. The last three instruments were only represented by one sound each, making that a total of 23 auditory stimuli. The 'sounds of percussive instruments i.e., Triangle, Crash Cymbals and Gong were not windowed' (Adeli et al., 2014, p. 2). A potential problem is that at least guitar, marimba and electric piano (if analogous) are percussive instruments as well, since a string, plate, or contact is 'percussed' (struck or plucked), i.e., the energy is only exerted momentarily (see, e.g., Fletcher & Rossing, 1998).

The results reveal the tendency to match rounder shapes with softer timbres (Adeli et al., 2014, p. 4). With regard to color, the results show a matching of predominantly blue and green with the artificially shaped pitched sounds, whereas the unaltered sounds of triangle, crash cymbals, and gong were matched with yellow and red. Grayscale matchings were similar. The 'soft' artificially shaped sounds were generally matched with lighter grayscales, while the unaltered sounds were matched with black. The triangle, however, was matched with brighter grayscales. Moreover, a correlation of higher pitches and brighter grayscales was reported (ibid, pp. 6–8). Due to the manipulation of the pitched sound stimuli, the significance of the results with regard to the sound characters of musical instruments is questionable. Thus, the main takeaway, again, is the concurrence of increasing brightness and ascending pitch.

Recently, Cuskley and colleagues (2019) compared the mapping of color to auditory stimuli (vowels) and to visual stimuli (graphemes) in synesthetes and non-synesthetes. Although the human voice is not per se a musical instrument, it still produces timbres. Moreover, this study bears some significance with respect to the comparison of synesthetes and non-synesthetes.

Here, we focus on the vowel-color mapping. A large group of 1,164 participants was asked to intuitively match 16 vowels with a color picked by means of a regular continuous RGB color picker. Sound intensities were adjusted but fundamental frequencies (i.e., voice pitches, 120–124 Hz) were not. Each sound was presented three times, resulting in 48 trials (ibid, p. 1654).

Based on the mean Euclidean distances in the color space, a consistency rating for each participant was calculated. Vowels were evaluated based on the vowel formants F1 and F2 which are known to be significant predictors of color selection (ibid, p. 1652–1655). The structure of

Figure 2
The combined results of the three studies conducted at the Prometheus Institute in Kazan'

	author(s)	most frequently matched colors no. 1	no. 2	no. 3	color legend
flute	Trofimova	38.0	11.3	10.6	red
	Ovsjannikov	25.2	22.5	13.9	golden
	Vanečkina *et al.*	33.3	26.6	26.6	orange
trumpet	Trofimova	13.0	11.6	11.6	yellow
	Ovsjannikov	18.1	11.6	10.9	green
	Vanečkina *et al.*	26.6	21.3	20.0	light blue
violin	Trofimova	17.3	17.3	14.7	blue
	Ovsjannikov	17.6	12.2	10.8	violet
	Vanečkina *et al.*	17.3	14.6	12.0	purple
cello	Trofimova	17.5	12.1	11.2	brown
	Ovsjannikov	24.3	12.8	10.8	white
	Vanečkina *et al.*	12.0	6.6	6.6	bright
double bass	Trofimova	35.7	18.9	6.1	silver
	Ovsjannikov	25.2	23.0	15.1	grey
	Vanečkina *et al.*	33.3	24.0	21.3	dark
piano	Trofimova	15.1	12.7	12.0	black
	Ovsjannikov	16.9	11.3	10.6	
	Vanečkina *et al.*	32.0	10.6	8.0	

The six most exemplifying instruments are shown. Studies are indicated by the author's names in the second column. 1–3: the three most frequently selected colors, with the absolute number of selections given in the color swatch. Split swatches indicate identical selections numbers consecutively. 'Color legend': Names of the combined color palette for all three studies.

the mappings was evaluated by comparing the vowel mappings within an F1–F2 space and the color mappings within the color space. The mapping was considered structured when a pair of similar vowels in the F1–F2 space was mapped onto a pair of similar colors in the color space (the same with dissimilar pairs). The correlation of the distances in both spaces resulted in a structure-score that was higher for highly structured mappings (ibid, pp. 1661–1662).

Regarding the vowels-colors mapping, the findings are in line with earlier studies. Participants matched higher F1 values (i.e., lower vowels) with darker, redder and bluer colors. Moreover, they matched higher F2 values (i.e., front vowels, e.g., /e/, /i/) with brighter, greener and yellower colors and low F2 values (i.e., back vowels, e.g., /o/, /u/) with darker colors, such as red, brown, and blue. Low and front vowels (e.g., /a/) are matched with redder colors (ibid, pp. 1660, 1664). Please note the counterintuitive terminology. The low–high axis of a formant or vowel does *not* refer to frequency but to the tongue position in the mouth. If a vowel is low, the tongue is also low in the mouth (i.e., caudally, towards the floor of the mouth). If a vowel is 'back', the tongue is as well (i.e., posterior, towards the uvula). However, if the value of F1 is low, the tongue is high in the mouth (superior, towards the palate) and if F2 is low, the tongue is back in the mouth (ibid, p. 1652). The interesting take-away is the influence of F2. Cuskley and colleagues suggest that the 'association of front vowels with high F2 to lighter colors could be related to more widespread cross-modal phenomena such as pitch-lightness associations' (ibid, p. 1664). However, pitch is not a possible factor in this case. But since the oral cavity space is smaller for higher and more front vowels (ibid, p. 1664), a smaller cavity leads to higher resonance frequencies (i.e., formants) which, in turn, results in brighter timbre.

Regarding the comparisons of synesthetes and non-synesthetes, the findings summarize as follows: Both groups shared the same tendencies but synesthetes achieved more structured mappings (ibid, p. 1662), showed higher consistency (ibid, p. 1652), and used wider color and brightness ranges, i.e., making more 'extreme' selections, especially matching brighter and yellower colors to high vowels (ibid, p. 1663) and front vowels (ibid, p. 1661).

Completely unrelated to the research reported above, three empirical studies were conducted at the Prometheus Institute in Kazan, Tatarstan, a multisensory research institute. For a bibliographic review on the multisensory research at the Prometheus Institute, see Jewanski and colleagues (2019).

These studies are based on each other. Trofimova (1977) tested twelfe colors (red, orange, yellow, green, light blue, blue, violet, purple, brown, white, gray, black) and 13 musical instruments (cello, clarinet, double bass, drum, flute, guitar, harp, piano, saxophone, small bell, timpani, trumpet, violin). Ovsjannikov (2000) and Vanečkina and colleagues (2002) subsequently added cymbals to the instruments list and extended the color palette with bright and dark gray, silver and golden. In these studies, the instruments were only referred to by name and not presented via auditory stimuli. Neither author disclosed specifics regarding the color space or color values.

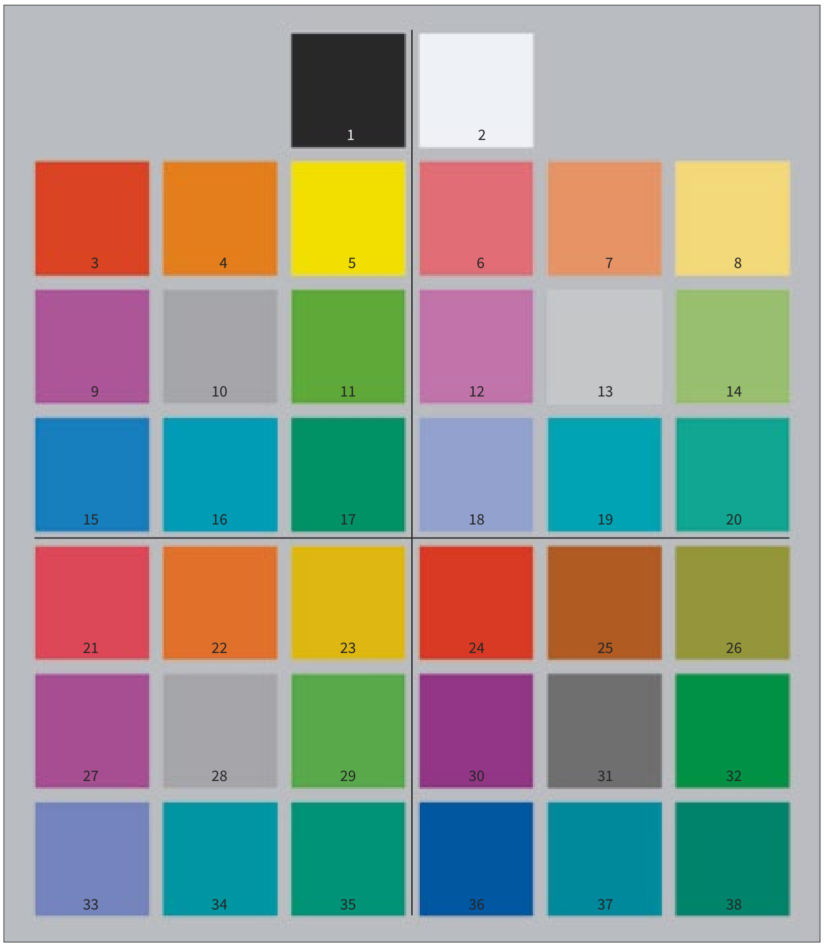
For the sake of comparison and simplicity, we created an overview, collapsing the results of all three studies into a joint graph and reducing them to the most exemplifying instruments: a woodwind (flute), a brass (trumpet), three bowed strings (violin, cello, double bass, as timbral continuum throughout a wide pitch range), and one percussive string instrument (piano). Figure 2 shows the three most frequently selected colors for each of the above named instruments in each study.

Trofimova's general take, that associations were based on underlying emotions and high pitches are more frequently matched with bright colors, is in line with Wundt and the more recent studies reviewed above. Some of Trofimova's specific explanations are quite reasonable. E.g., the piano is blue, black and white, with the latter ones referring to the piano keys. The bell (not in Figure 2) is light blue due to the similarity of light blue bellflowers and purple (in Russian, purple is a metaphor for a little bell). The trumpet is, among other colors, yellow because of its brassy appearance. Other explanations seem a bit far-fetched. E.g., the violin is blue due to its lyrical sound. However, Trofimova offered new ideas such as explanations based language (bell) or the actual color of an instrument (trumpet). Alas, the two subsequent studies did not offer any interpretations or explanations.

The present study was replicated in a study conducted in Madagascar (Ambros et al., 2021) to clarify the extent to which audiovisual crossmodal correspondences are culturally learned. Sixty-three participants from Toliara (a city in southwestern Madagascar) took part (10–60 years old, ∅: 27.3, female = 30, male = 33). The interrater reliability turned out to be low (Cohen's $\kappa = 0.012$), possibly this can be attributed to the too broad color selection of 38 colors. Also, the individual agreement in tone-color-assignments of the subjects was consistently low. It was found that the color black was associated several times – the sounds of the flute, the trombone, the horn as well as the bassoon were most frequently matched with black at all pitches (ibid, pp. 1077). This was probably confounded by the center-top position of the color swatch on the questionnaire. The results suggest that this type of crossmodal correspondences is not an innate, universal trait, but refers to learned factors that are shaped by experiences with the environment or culture and language. However, further research on non-Western populations is necessary (ibid, pp. 1078).

Preliminary conclusions

All told, these studies could not convey any overarching systematics for timbre-color mapping. A broad variety of instruments was matched with the same color and vice versa. Interestingly, participants did not reliably match visual brightness and auditory pitch, which is thought to be a common principle of crossmodal correspondences (Hubbard, 1996). This, however, is easily explained with the visual stimuli, i.e., the often very limited color palettes. If only primary colors (red, green, blue, yellow) are provided, it is very hard to consistently rank them in terms of brightness. In addition, many studies did not provide critical information regarding color spaces and values. Hence, the word 'red' might refer to very different chromatic perceptions. Another likely source of inconsistency is the fact that musical instruments sometimes are presented visually through their names rather than as auditory stimulus. Unfortunately, forgoing the auditory presentation effectively converts the audiovisual crossmodal correspondence into a purely visual word-color or name-color correspondence. Furthermore, the name inadvertently leads participants to associate the color with their own impression of the given instrument – including its appearance, its use in (classical) music, the mood it conveys or any other association to its name. E.g., the trumpet appears brassy, hence a yellow color might be selected. The trumpet is used in heroic baroque music so it might be associated with red, since red could be considered a heroic (or royal) color.



The BCP palette based on Griscom (2014, p. 29). It comprises of eight color hues (red, orange, yellow, purple, green, blue, cyan, bluegreen) arranged around a grayscale in a 3 × 3 matrix. These colors are repeated for times in four different shades. Row-wise from the top left (3 × 3) quadrant: saturated, light, muted, dark. The grayscale swatches in the center of each 'block' provide an easy guide to comprehend the systematics. Adding black and white atop the arrangement makes it a total of 38 swatches. The colors are numbered strictly row-wise. Color names in the quadrant-order described above, with the number in parentheses, are: black (1), white (2); saturated: bright red (3), orange (4), yellow (5), purple (9), gray (10), bright green (11), grayblue (15), bright cyan (16), bright bluegreen (17); light: light pink (6), light orange (7), light yellow (8), light purple (12), light gray (13), light green (14), light lilac (18), light cyan (19), torquoise green (20); muted: pinkred (21), muted orange (22), ochre (23), muted purple (27), middle gray (28), muted lightgreen (29), bluepurple (33), muted cyan (34), muted bluegreen (35); dark: bloodred (24), brown (25), olivegreen (26), dark purple (30), dark gray (31), applegreen (32), dark blue (36), dark greenblue (37), dark green (38).

Figure 3
The *Berkeley Color Project* (BCP) palette

Aims

The goal of this study is to gain insight into underlying patterns of mapping sounds of musical instruments' with colors. Based on the conclusions above, we decided to use auditory stimuli without further non-auditory information (e.g., instrument names) and we put emphasis on providing a more extensive color palette.

The main goal may be broken down into the following questions:

1) Are there consistent and systematic assignments of colors or brightness values to timbres of musical instruments?
2) Are these assignments consistent with previously described color-timbre mappings?
3) Is it possible to find correlations between colors or brightness values and specific timbre features?
4) Do participants prefer specific colors (i.e., hue values) or rather certain brightness values with indifference to the respective color hue?

Methods

Visual stimuli: Color map

Previous studies often restricted the available colors to about six to twelve. Therefore, participants were limited to very basic selections, e.g., between red and blue, lacking the opportunity to select different shades (especially different brightness and saturation levels) of the same color. Few studies included darker and brighter shades but not necessarily of the same hue (e.g., dark and bright red), again rendering participants unable to select different shades of the same color.

The visual stimuli used in this study consist of the 37 colors from the Berkeley Color Project (BCP). The BCP palette consists of four primary colors (red, yellow, green, blue) and four intermediate colors (orange, chartreuse, cyan, purple), equidistant to the adjacent primary colors, in four shades (saturated, light, muted, dark) each (Palmer & Schloss, 2010, p. 8878). These colors were complemented with five achromatic colors (black, white, and three intermediate grays; Schloss et al., 2011, p. 499), resulting in 37 colors, arranged in 38 swatches. Since the muted and saturated swatches share the same average brightness, their respective grays were the same (Palmer et al., 2013, p. 8837). For the sake of simplicity, we maintained the arrangement of 38 'colors' during our analysis. For the actual values of the BCP colors in the CIE 1931 xyY space see Palmer and colleagues (2013, Table S1, p. 5 of the supporting information) and Griscom (2014, p. 20). In our analysis, we used CIELuv values which offer a more perceptually uniform space than CIE 1931 xyY. All colors were simultaneously presented on a single map as arranged squares of 100 × 100 pixels against a neutral gray background (Figure 3).

Auditory stimuli: instrument sounds

For this study, recordings of ten different musical instruments (bassoon, cello, clarinet, flute, French horn, oboe, trombone, trumpet, tuba, violin) from the *Vienna Symphonic Library* (VSL) were used. In agreement with previous empirical studies, we excluded the human voice and focused on traditional symphonic orchestral instruments instead.

The intent was to present each instrument at three different pitches (low, middle, high) and in two different variations of articulation (staccato, legato), resulting in a total of 60 sounds. Because the bassoon, staccato, E2 sound was missing in the actual listening task, the study ended up having 59 sounds. The pitch chroma for every stimulus was 'E', effectively setting up a grid of octaves (E2–E6). The three pitches for a given instrument fell into three adjacent octaves according to its natural pitch range, e.g., E2–E4 for bass, E3–E5 for mid, and E4–E6 for treble instruments. However, the clarinet jumped one octave (E3, E4, E6).

Different pitches and articulation styles were included to account for the well known fact that a musical instrument's timbre changes according to these factors (e.g., Stumpf, 1890; Houtsma, 1997; Marozeau et al., 2003; Reymore et al., 2023). All auditory stimuli were equalized in loudness. Prior to the actual testing, participants could adjust the volume according to their comfort.

Participants and procedure

A total of 40 participants (17–74 years old, ∅: 34.68, SD: 15.46, female = 17, male = 22, diverse = 1) took part in the task. With the exception of three people (USA, Russia, not specified), all participants were from German-speaking countries (Austria or Germany). Thirty-three of them had experience with playing a musical instrument, seven did not.

The participants were asked to select those three colors they considered the best match for each of the 59 sounds. The task was conducted in a quiet environment under normal daylight conditions. The visual stimuli were presented on a Hanns.G HT231HPB touchscreen with a resolution of 1,920 × 1,080 pixels. The auditory stimuli were presented via Steinberg UR22 sound card and Superlux HD681 over-ear-headphones. The color map was shown throughout the entire task. One trial consisted of playing one sound and the immediate selection of the three colors by tapping the respective swatches on the screen. The sounds were presented once each in random succession, resulting in a total of 59 trials within one session. Since long term consistency is reportedly low (Ward et al., 2006; see above) and intrapersonal consistency was of no particular importance for this study, repeated trials or a retest were forgone.

Evaluation

To assess the overall inter-rater agreement, Fleiss' kappa (κ) was calculated. The absolute numbers of matchings of timbres and colors were aggregated, resulting in a full 59 × 38 (sounds × colors) matrix. It was subsequently collapsed into a 10 × 38 (instruments × colors) matrix by adding up the numbers of all sounds of the same instrument. The significance of each instrument-color combination was assessed by means of Fisher's exact test. Moreover, the influence of articulation (staccato, legato) on the color assignment as well as the co-occurrence of color classes (i.e., dark, bright, muted, saturated, etc.) and octave registers is visualized via heatmaps.

To investigate the influence of timbre on the sound-color mappings, a collection of acoustic signal properties ('descriptors'), characterizing spectral and temporal aspects of the timbre were extracted computationally by means of the MIRtoolbox (Lartillot & Toiviainen, 2007) and LibROSA (McFee et al., 2015). The 'spectral centroid' (SC) numerically pinpoints the center of gravity of the frequency spectrum of a given sound and thus is closely related to perceptual auditory brightness concepts (e.g., Schubert & Wolfe, 2006). As another descriptor for timbral brightness, the 'high-frequency ratio' (HFR, i.e., the amount of spectral energy above 1.5 kHz) was extracted. 'Roughness' is a perceptual sound quality that might be described as the amount of 'buzz' a sound has to it. It is usually defined as the frequency modulation two simultaneous tones mutually engage in (e.g., Fastl & Zwicker, 2007, p. 257). It was calculated using the implementation of the Vassilakis roughness model included in the AudioCommons timbral models (Font et al., 2016; Vassilakis & Fitz, 2007). The 'percussive-harmonic ratio' (PHR) is a numeric expression of the balance between percussive signal components (e.g., attack noises) and harmonic signal components (partials). It was extracted via LibROSA using the median filtering approach of Fitzgerald (2010). The descriptors 'attack time' and 'release time' estimate the duration of the onset and release phase respectively. Additional to the timbral characteristics, the octave of the auditory stimuli was included in order to account for pitch differences. The color selections were recorded in RGB space and then converted to CIELuv values using the standard illuminant D65 as in Cuskley and colleagues (2019). CIE spaces are based on human perception of color whereas the RGB space is based on image rendering for computer monitors. For each auditory stimulus, the mean CIELuv color values were calculated across all colors assigned to it by all participants. The correlation coefficients (Pearson's r) between the extracted timbre features and these mean color selections were calculated to identify the features with the potentially biggest impact on matching decisions.

Results

The overall agreement between individual raters concerning specific color selections was low (Fleiss' κ = 0.07), which might not be very surprising given the high number of possible color options (38) per stimulus. When collating the colors according to the eleven color hues as defined in the BCP palette, there is still only

Figure 4
Heatmap of color selections

Heatmap comparing the color selections relative to playing styles legato (leg) and staccato (sta). Numbers are percentages. As can be seen easily: there is little to no difference between legato and staccato in terms of color selections. There is, however, a small preference to match darker or muted blueish colors with legato sounds and brighter, warmer colors with staccato sounds.

slight agreement (Fleiss' $\kappa = 0.10$). Also, as Figure 4 shows, almost no differences could be found for the distribution of color selections depending on articulation (legato vs. staccato). However, there was a small tendency towards darker, muted colors (e.g., dark blue, dark purple) to be matched with legato sounds, while colors from yellow/orange hues (e.g., orange, light orange, muted orange, ochre) were slightly more often matched with staccato sounds. The reason for this could be the faintly shorter attack time for staccato sounds which is caused by a faster build up of higher partials. Perceptively, this might be interpreted as 'brightness' or 'presence'.

The columns of Figure 5 display those colors that were significantly more often matched to the sounds of the respective instrument than to all the other instruments (according to Fisher's exact test, $p < .01$, the black line in Figure 5 indicates the Bonferroni-adjusted $\alpha = .00013$ for multiple testing).

When only the adjusted results are taken into account, the trombone and French horn were not significantly more often matched with certain colors. The bassoon, cello, and tuba, all three instruments with lower pitch ranges, were primarily matched with brown. The trumpet was predominantly matched with red and yellow which is consistent with previously reported mappings. The clarinet was matched with white. For the violin, only yellow hues were significantly overrepresented, while the oboe was

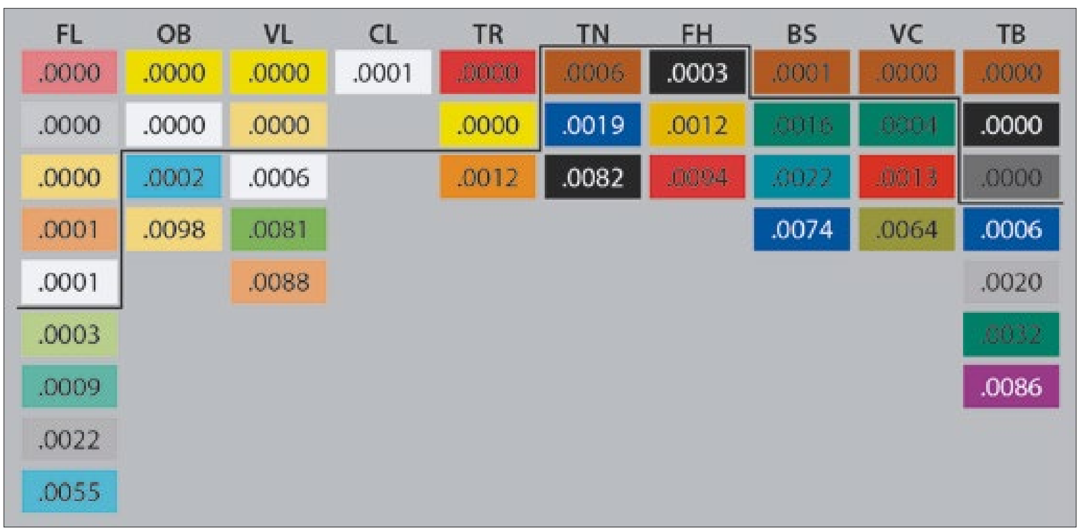
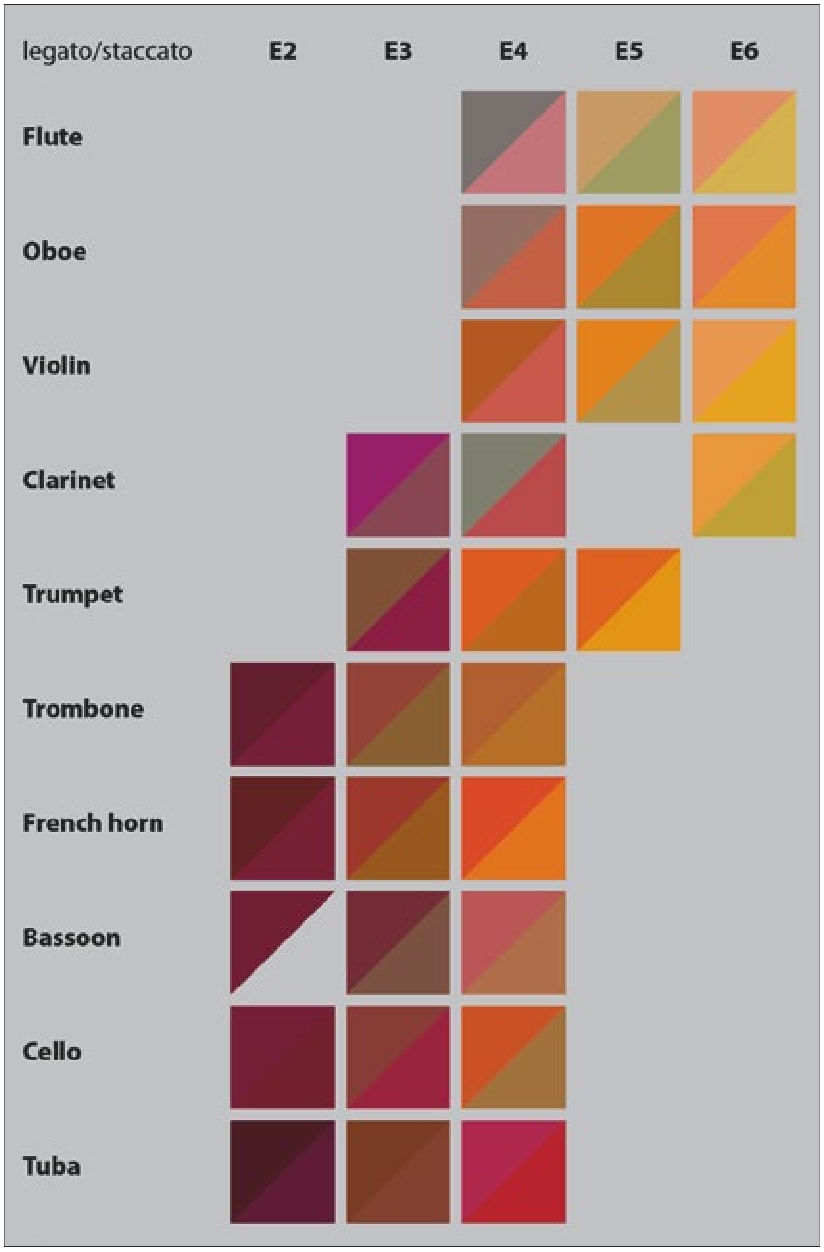


Figure 5
The significantly more frequently chosen colors for every instrument

FL = flute, OB = oboe, VL = violin, CL = clarinet, TR = trumpet, TN = trombone, FH = French horn, BS = bassoon, VC = cello, TB = tuba. The *p* values ($< .01$) are given in the respective color swatches. The black line indicates the Bonferroni-adjustment for multiple testing ($p < .00013$)



Columns are octaves, tiled swatches show legato/staccato (in that order). It is obvious that lower sounds (towards the bottom left corner) are matched with darker, more saturated colors with red/brown/purple hues, while higher sounds (towards top right corner) are matched with brighter, less saturated colors with yellow/orange hues

Figure 6
Average colors for every stimulus

matched with both, white and yellow. The flute was matched with reddish, orange, generally bright pastel shades.

When all significant overrepresentations are considered, the findings become less specific in terms of hue, except for the clarinet and the trumpet. Two general observations stand out:

1) Regarding brightness: instruments with lower pitch ranges (right hand side in Figure 5) were generally matched with darker colors, while instruments with higher pitch ranges were matched with brighter colors.
2) The same holds true for saturation: Instruments with lower pitch ranges were preferably matched with saturated colors while instruments with higher pitch ranges were matched with less saturated, pastel-like shades.

A way to find consistent underlying tendencies in color selections is, to generate average colors. Figure 6 displays a palette with averaged colors for every sound. The CIELuv values of every color matched to one sound were separately merged into mean values for L*, u*, and v* respectively and then combined to a new color. It represents the mean position of all colors matched with the respective sound within the CIELuv-space. If red and green (u*) as well as yellow and blue (v*) colors were equally frequently matched to a sound they would offset each other, resulting in a neutral or grayish average. Likewise, equally frequent selections of darker and brighter colors would offset and lead to a medium brightness value (L*). Hence, if, e.g., reddish colors would be selected more frequently, the average color would be tinged red. As can be seen, with a few weak exceptions, red, yellow, orange, ochre, olive tones prevail. The chart offers the following takeaways:

1) Blue was obviously not a preferred color in this task.
2) Over the full range, the tendency to match brighter colors with higher pitches becomes very obvious.
3) There seems to be the opposite tendency for saturation, i.e., lower pitches were matched with more saturated colors. This is especially true for the lowest octave (E2 mean saturation: 87.4%, E3–E6 mean: 61.7%).
4) The often moderate saturation of the average colors (65.6%) and the tendency towards 'muddy' colors, especially for staccato sounds, hint at discord among participants (i.e., visualizing the weak inter-rater agreement).
5) Additionally, the colors matched with higher pitches show a tendency toward yellowish hues while the colors matched to lower pitches show a tendency towards dark reddish and brownish hues.

Incidentally, it stands out that primary colors were mostly not among the favorites. The most popular colors comprised a spectrum of mostly yellow, brown and orange colors, with a little bit of blue/gray/black sprinkled in. In total numbers, the five most frequently selected colors are 'yellow' (471 selections), 'brown' (422), 'orange' (417), 'bright red' (312), and 'muted orange' (308). Out of the four primary colors red, green, blue, and yellow, only yellow and red ('bright red') were among the most frequently selected colors. Maybe, the BCP palette bears a possible explanation. Although it theoretically contains red, green, blue, and yellow even in four different shades, it only contains an obvious pure primary yellow ('yellow'), two arguable options for red ('bright red', 'bloodred'), but no clear-cut primary target for pure green or blue. The most frequently selected green and blue tones are 'dark blue' (271, maybe a possible option for a primary blue) and 'bright green' (188). However, the fact remains: Mixed colors such as orange or brown in different shades and saturations were preferred over primary colors, except for yellow, of course. The palette of the most frequently selected colors for each instrument by octave registers illustrates this. It (almost exclusively) comprises of yellow, brown and orange tones. It actually seems to be more a scale of unspecific brightness values rather than a list of specific colors. From dark to bright the scale would be: brown → orange → muted orange → light orange → yellow → light yellow.

When grouping the most frequent color selections for each instrument by octave registers, the correspondence of this brightness scale to an ascending pitch scale becomes evident (Figure 7). It is well in line with the palette of mean colors for every stimulus (Figure 6). However, the correspondence is not flawless, as some instruments skip steps (bassoon: brown to bright orange), reverse direction at some point (flute: lighter yellow is matched with lower octave than pure yellow), or match with colors not in the theoretical scale mentioned above (clarinet: dark purple). A reason for the irregularities could potentially be the rather small sample of 40 participants since irregularities should smooth out when testing a larger sample, provided the findings otherwise indeed represent an underlying pattern.

As became evident in Figures 5, 6, and 7, the influence of pitch seems to exceed any potential influence of timbre. While some instruments were significantly matched with certain colors (e.g., violin with yellow, bassoon/cello/tuba with brown), the concurrence of ascending pitch and increasing brightness seems to be the dominating underlying mechanism. The following matrix (Figure 8), giving the different BCP shades as well as black and white against stimulus octaves, illustrates the systematic correlation of higher pitches with brighter colors or white and lower pitches with darker colors or black. This trend is consistent with previous findings (see above). Interestingly, the correlation of octaves with saturation contradicts the findings stated above of decreasing saturation along ascending pitch.

To more closely examine the influence of specific timbral aspects on the matching of sounds and colors, a collection of timbre descriptors were extracted. As Figure 9 shows, the observed correlations support the concurrence of increasing brightness with ascending pitch. Most prominently, the octave of the auditory stimuli correlates strongly with the brightness of the selected colors (r = .92, p < .001). Naturally, a similarly strong correlation is found between the octaves and the L* values of the colors (r = .96, p < .001). Additionally, descriptors such as SC and HFR, both related to the fundamental frequency, correlate positively with visual brightness as well as the L* values. The normalized v values show the same general trend as the visual brightness and L* values, especially with strong correlations with octave (r = .81, p < .001) and HFR (r = .81, p < .001). The normalized u* values do not correlate significantly with octave or SC and only weakly with HFR (r = .29, p < .05). In other words, since higher v* values imply a shift towards yellow, the amount of yellow increases with ascending pitch. Higher u* values imply a shift towards red, so the amount of red increases moderately with auditory brightness but, apparently, not with pitch.

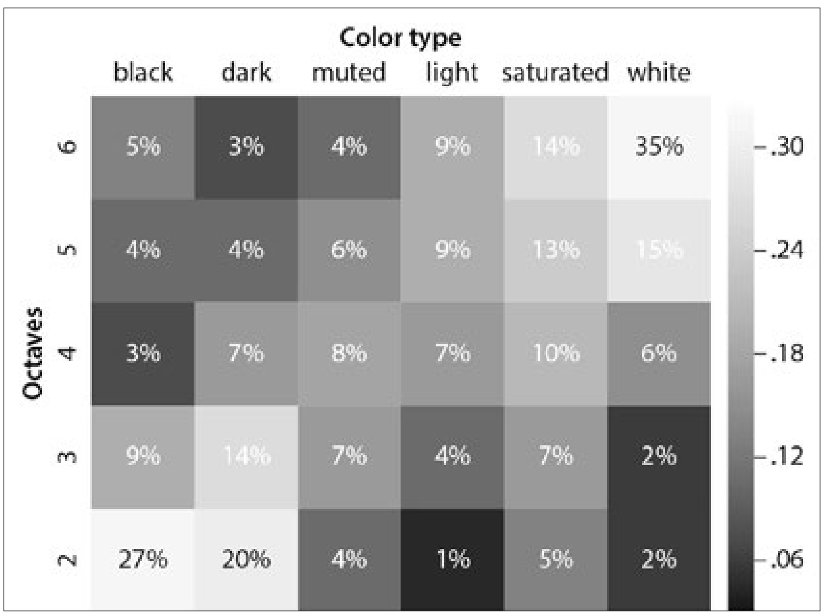
These findings not only support the notion that color brightness increases along with pitch

	E2	E3	E4	E5	E6
flute			lt. orange	lt. yellow	yellow
oboe			mtd. orange	orange	yellow
violin			mtd. orange	yellow	yellow
clarinet		drk. purple	brown		yellow
trumpet		brown	yellow	yellow	
trombone	brown	brown	yellow		
French horn	brown	orange	yellow		
bassoon	brown	brown	lt. orange		
cello	brown	brown	orange		
tuba	brown	brown	brown		

As in Figure 6, the preference for yellow/orange/red/brown is as striking as is the overall tendency to match lower sounds (again, towards bottom left corner) with darker, saturated colors and higher sounds (towards top right corner) with brighter, desaturated colors. Occasional exceptions from the rule clearly do not break the trend.

Figure 7
The most frequently selected color for each instrument and octave

Figure 8
Correlation matrix of octaves and color types



This graph clearly shows that low pitches were more frequently matched with black or dark colors as high pitches were more frequently matched with brighter colors and white.

Optic features in rows, acoustic features in columns. Sat. = saturation, bright. = visual brightness; SC = spectral centroid, HFR = high frequency ratio, PHR = percussive/harmonic ratio. Given values = Pearson's *r* ($p < .05$). The concurrence of visual brightness with octave and SC and HFR as auditory brightness-related features is striking, as is the redundance of that tendency for the green values. Blue values reverse the trend (decreasing with rising pitch) and red, interestingly, does not correlate with octave but still does so with SC and HFR.

Figure 9
Correlation matrix of timbre features and color values

but also that hue shifts towards more yellow tones at higher pitches, as is reflected in Figures 6 and 7. Roughness and PHR are negatively correlated with visual brightness, i.e., brighter colors are preferably matched with less rough sounds and vice versa. Also, rough sounds are more likely to be matched with more saturated colors. Longer attack times tend to be matched with higher u* values.

This might reflect the trend that legato sounds tend to be matched with slightly more reddish colors than staccato sounds (see Figure 6).

Comparing non-synesthetes with one synesthete

It's an ongoing debate (Brang & Ramachandran, 2020) whether crossmodal correspondences and synesthesia combine into a continuum from weak synesthesia (i.e., crossmodal correspondences) to strong synesthesia (Martino & Marks, 2001; Marks, 2013) or if both really are separate phenomena (Spence, 2011; Deroy & Spence, 2013; Parise & Spence, 2013). Be that as it may, synesthetes and non-synesthetes show the same overall tendencies (Ward et al., 2006; Cuskley et al., 2019), most prominently accordantly preferring to match higher pitches with brighter colors and lower pitches with darker colors (Ward et al., 2006). Ward and colleagues generally explored 'how different aspects of an auditory stimulus are mapped on to the visual domain in both synesthetes and controls' (ibid, p. 266; see review above). Menouti and colleagues (2015, p. 2) investigated the consistency of timbre-color mappings of synesthetes compared to non-synesthetes. They reported that, depending on the color space, two of the three tested synesthetes (RGB space) or all three synesthetes (CIELuv space) showed a significantly higher timbre-color mapping consistency than the control group comprising non-synesthetes. Cuskley and colleagues (2019; see review above) compared synesthetes and non-synesthetes in a vowel-color mapping task. Besides that, we are not aware of an existing in-depth comparison of synesthetes and non-synesthetes specifically focusing on timbre-color mappings.

To provide further insight, we asked one tone-color synesthete (SD), who happens to be a musician as well, to freely describe his synesthesia to our auditory stimuli. Some other recent studies on colored hearing as well have asked only one (Bergfeld Mills et al., 2003) or two participants (Farina et al., 2017; Zdzinski et al., 2019) for detailed descriptions.

The results are a mixture of similarities and differences to the results of our empirical study. For SD, the cello is a dark reddish brown and the violin is tan (a pale brown tone) which roughly agrees with the colors most often chosen for the respective instruments in our listening experiment. In contrast to our findings, SD's color sensations have a much weaker tendency to brighten when the instrument shifts to higher registers (Figure 10).

Beyond that, SD's color selections are much more nuanced and specific. But of course, he was free to pick any color he'd like, whereas our participants were restricted to the provided color palette. But this very precise picking is in line with other synesthetes (e.g., Emrich et al., 2002, pp. 89–152). Instead of plain yellow it's 'many different shades of yellowish orange, like a flame from a match or a candle' or instead of plain silver it's 'silver, reflecting back wisps of light blue sky'. Such specific descriptions, with or without references in nature or extended with textures, are typical for synesthetes and practically impossible to account for with (manageable) color palettes as the BCP palette (Menouti et al., 2015, pp. 2–3; Gruß, 2017, p. 325).

Discussion and outlook

With respect to our first question (Are there consistent and systematic assignments of colors or brightness values to timbres of musical instruments?), the results were somewhat ambiguous. The cello, tuba, and bassoon were (preferably) matched with brown (Figure 5) which is clearly (cello and tuba) reflected in the most frequently selected colors for each instrument and octave register (Figure 7) and hinted at in the average colors (Figure 6), indicating some degree of reliability. The violin was matched with yellow colors, the oboe with yellow and white, and the flute with bright (reddish) pastel shades. These latter

	low register		middle register		high register	
	SD	results	SD	results	SD	results
flute	silver, reflecting back wisps of light blue sky	light orange	bright, whitish silver, reflecting back a small bit of pale sky blue	light orange	almost white, with just a tinge of silver	yellow
oboe	dark olive green	muted orange	olive green	orange	olive green	yellow
clarinet	a bit darker than "focal" blue (about RGB 0, 0, 225)	dark purple	"focal" blue (like with a blue crayon; RGB 0, 0, 255)	brown	a slight bit lighter than "focal" blue (about RGB 100, 100, 255)	yellow
bassoon	dark, reddish brown colors, maroon or burgundy	brown	dark, reddish brown colors, maroon or burgundy	brown	you have to go comically high to lighten the color(s) from those of medium pitch; if done, this pales things to a pinkish tan color, and adds tinges of green	light orange
French horn	only slightly darker than for medium pitch	brown	"School bus" yellow (RGB 255, 216, 0)	orange	only slightly paler than for medium pitch	yellow
trumpet	the same as medium pitch, but with more orange tinges	brown	many different shades of yellowish orange, like a flame from a match or a candle	yellow	the same as medium pitch, but with more yellow tinges	yellow
trombone	same as medium pitch, but with more and darker red tinges	brown	many different shades of dark orangish red, like embers glowing in a fireplace	brown	same as medium pitch, but with more orange tinges	yellow
tuba	even darker purple (RGB 75, 0, 75)	brown	very dark purple, almost black (RGB 95, 0, 95)	brown	you have to go comically high on a tuba to make the color lighter than that which I see for medium pitches	brown
violin	a very light tan color (about RGB 237, 201, 175)	muted orange	a very light tan color (about RGB 237, 201, 175)	yellow	a very light tan color (about RGB 237, 201, 175)	yellow
cello	a dark, reddish brown color, "burnt umber" (RGB 138, 51, 36)	brown	a dark, reddish brown color, "burnt umber" (RGB 138, 51, 36)	brown	a dark, reddish brown color, "burnt umber" (RGB 138, 51, 36)	orange

Figure 10
Comparison of our results with one synesthete (SD)

Odd columns ('SD') show SD's descriptions for each instrument at the respective register (i.e. its low, middle or high stimulus), even columns ('results') show the most frequently selected color from our study (see Figure 7). Basic takeaways are: (1) In contrast to our participants, SD seems to 'see' most of the instrument in a consistent color. (2) The underlying mechanism of high pitches eliciting brighter color sensations is present but apparently not as blatant. (3) For the most part, SD also does not 'see' primary colors.

matchings do not prevail in the average colors, although the violin swatches, in comparison, show a stronger touch of yellow. The average colors in Figure 6 illustrate the weak agreement among raters with regard to instrument-color mappings but, at the same time, reveal a salient underlying pattern: low pitches are more often matched with dark and more saturated colors while high pitches are more often matched with lighter and more desaturated colors. This is well illustrated by the correlation of the octave registers with the BCP shades (Figure 8). All in all, these mappings seem to be more dependent on pitch than timbre. These findings are in accordance to Ward and colleagues (2006), who report inconsistent mappings of sounds to colors in non-synesthetes who still showed a 'central tendency to map certain pitches to certain lightnesses' (ibid, pp. 277–278). However, the mapping of vowels to colors independent from pitch (Cuskley et al., 2019) showed the same tendency of matching vowels like /e/ or /i/ with brighter colors and vowels like /o/ or /u/ with darker colors. Moreover, the preferred color matchings (/e/, /i/ with yellower, greener; /o/, /u/ with red, brown, blue; ibid, p. 1664) share some similarities with our brightness-color mappings (i.e., the x-axes in Figures 6 and 7). So, a systematic influence of timbre on color selections might still factor in, although it is clearly overruled by the influence of pitch.

With respect to our third question (Is it possible to find correlations between colors or brightness values and specific timbre features?), it is safe to say that correlations between auditory and visual stimuli properties could be found (Figure 9). These correlations essentially support the aforementioned concurrence of increasing brightness with ascending pitch. Also, the hue shifts from larger shares of red at lower pitches to more yellow at higher pitches or brighter timbres. If the eye follows the ascending diagonal from the bottom left swatch (tuba, E2) to the top right swatch (flute, E6) in Figure 6, this development becomes easily observable. Moreover, brighter colors are preferably matched with less rough sounds and vice versa.

With respect to our second question (Are these assignments consistent with previously described color-timbre mappings?), some of our results are in agreement with previous findings. The trumpet was matched with red and yellow, which corroborates previous mappings, albeit probably not based on auditory cues but other associations. The combination of cello and brown was reported by Trofimova (1977) and Ovsjannikov (2000), the combination of violin and yellow was reported by Ovsjannikov (2000) and Vanečkina and colleagues (2002). However, in both cases the agreement only holds true for the most frequently selected color. When looking further down the color list, a true concept of a color-instrument association cannot be found (compare Figures 2 and 5). Aside from instrument-color mappings, our results obviously agree with and reconfirm the well established concurrence of ascending pitch and increasing brightness as firm underlying mechanism of crossmodal correspondences (Figures 5–8). However, some observations were incompatible with earlier findings. E.g., orange colors matched to the low registers of the flute and the violin were not reported before.

Finally, with respect to our fourth question (Do participants prefer specific colors (i.e., hue values) or rather certain brightness values with indifference to the respective color hue?), our results suggest a tendency towards a red/brown–yellow/orange axis, which probably is more a manifestation of the tendency to match timbres with certain brightness values rather than specific colors. This, of course, does not mean nobody ever has a specific color in mind when asked to make a selection based on timbre. It is just that these selections generally do not seem to be reliably related to auditory characteristics of a musical instrument beyond brightness which is, probably more often than not, overruled by pitch.

Pitch being the more crucial factor seems plausible, since the general conception of pitch as a one-dimensional high-low (i.e., frequency) axis is easily digestible. As such, it is also easily quantified and aligned with one-dimensional color properties, e.g., hue (i.e., frequency) or brightness (intensity). Of course, a strong argument can be made that hue, as 'the name of the color' (Munsell, 1905, p. 20), is a circular dimension, just as the 'chroma' or 'quality' of musical pitch (Shepard, 1964, p. 2346; first proposed by Révész, 1913, p. 17). However, as correlates of frequency (i.e., the audible/visible ranges of the sound spectrum or the electromagnetic spectrum respectively), hue and pitch indeed unfold along a one-dimensional low–high (infra–ultra) axis.

Timbre, as described above, due to its intrinsic multidimensionality, is not a quantifiable conception. Also, a musical instrument not only produces 'one' timbre, just as it does not only produce one pitch and/or one loudness. A timbre produced by a musical instrument sometimes drastically changes when the instrument shifts into another register. A consistent acoustic explanation of this behavior for almost all wind instruments as well as a treatise of the vast implicit historic knowledge thereof among musicians and composers is offered by Reuter (2002).

Consequently, Raff, as stated above, matched each instrument with several colors, e.g., the 'flute from bright and colorless to blue air [and] the oboe from bright yellow to sap green' (Raff, 1854, p. 169). Taking all this into account, it is not surprising that participants repeatedly fail to reliably match one singled out color to a bunch of varying timbres that is meant to constitute the 'singular' sound character of an instrument. This, however, does not rule out any effect of timbre, as 'timbre' still applies to the level of single sounds. Brightness is generally reported as the most salient dimension of timbre (Saitis & Siedenburg, 2020; for an extensive review on timbre dimensions, see Reuter & Siddiq, 2017). The problem is, brightness not only changes with timbre (shifting the relative energy distribution of spectral components along the frequency axis) but also with pitch (moving the entire spectrum up or down the frequency axis). This dependence of timbre on pitch is well known (e.g., Krumhansl & Iverson, 1992; Marozeau & de Cheveigné, 2007). In fact, pitch seems to dominate timbre in shared perceptual environments (Siddiq et al., 2018). Thus, it is difficult to discern the effects of timbre and pitch.

Comparisons with earlier studies hardly help in that regard, because color selections were often based on inconsistent and/or blurry circumstances. As things are, instrument-color mappings were often confounded by non-stimulus-related associations such as the visual appearance and/or cultural character of the instrument. This might apply to the trumpet, which, in accordance with earlier findings, was matched with red and yellow. In general, if the participants' conceptions of the instruments in question are only triggered by auditory stimuli instead of the instruments being explicitly introduced, i.e., given by name, the color selections show little agreement.

In order to understand the influence of associations, the implications of the following conditions on timbre-color mappings should be investigated in the future: instrument presented
1) by name
2) via image,
3) via sound and by name,
4) via sound and without additional information.
Another important aspect are the visual stimuli. The color palette in past studies was often too limited. It is crucial to provide enough options in terms of hue, brightness, and saturation. If the palette is limited to saturated colors, participants will pick saturated colors even if studies with more extensive palettes show a preference for muted colors.

Although the color palette remained static throughout the entire task, no position bias was discernible in the color selections. One could argue that the mapping of brighter colors to higher pitches was biased by the fact that brighter colors were arranged towards the top of the screen (i.e., higher) and darker colors towards the bottom. But looking into specific colors disproves this argument. E.g., black is the first color at the very top of the palette while brown and dark grey are located towards the bottom. All three colors were frequently matched with low pitches and almost never with high pitches. Still, it should be considered to alter at least the positions of the colors in future studies, e.g., rotating the entire palette orthogonally as did Palmer and colleagues (2013, p. 8841), although no effects of the rotation were reported.

Furthermore, it is unclear if favorite colors and/or age confounds with color selections. For adults, Eysenck (1941) reported blue, red, green, violet, orange, yellow (this order for men, for women swap orange and yellow) as the most frequent favorite colors. A more recent publication reports the order blue, green, black, red (Holm et al., 2009). No matter which list, these colors rarely appear among the top choices for timbre-color mappings. Neither Hall (1883; see above) nor Emmett (1994; see above), working with underaged participants, elaborated on the potential influence of favorite colors. In terms of age, no existing study (including this one) differentiated between children and adults to find out if changing favorite colors have any noticeable impact on color selection.

In retrospect, our results agree with principles of crossmodal correspondences described by Athanasius Kircher nearly 400 years ago and endorsed in later studies. The instrument-color mappings show some isolated findings (e.g., cello/bassoon/tuba matched with brown, violin matched with yellow). The timbre-color mappings show consistency especially with regard to the relation of auditory and visual brightness. The latter one, however, was probably more a pitch-color mapping, as pitch turned out to be the more salient factor for color selections.

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Saleh Siddiq
Universität Wien
Institut für Musikwissenschaft
Spitalgasse 2, Hof 9 (Campus)
A-1090 Wien
saleh.siddiq@univie.ac.at