ANNALS OF MEDICINE
2025, VOL. 57, NO. 1, 2476728
https://doi.org/10.1080/07853890.2025.2476728

OPHTHALMOLOGY

OPEN ACCESS Check for updates

Development of color learning protocol based on music-color association for people with visual impairment

Hye Young Park

Music Therapy Major, Graduate School of Church Music, Kosin University, Busan, South Korea

ABSTRACT

Background: This research developed and confirmed the feasibility of a color-learning mobile application for people with visual impairment based on the hypothesis that the music-color association may be synaesthetically induced through emotion.

Methods: In total, 120 participants with visual impairment, comprising 60 congenital and 60 adventitious cases, were recruited. They underwent sequential procedures: Procedure 1 involved selecting color-music associations and designing tasks; Procedure 2 focused on application development with accessibility features; and Procedure 3 verified usability and effectiveness.

Results: Significant improvements were observed in hue, luminance, and saturation scores following the use of the music-color association application among participants with both congenital and adventitious visual impairment. The effectiveness of the application in facilitating color learning is evident, suggesting its potential utility in enhancing color perception in this population.

Conclusions: This research introduces a novel framework for color learning among visually impaired individuals using a music-based synesthetic approach. The developed mobile application offers a promising avenue for efficiently improving color perception and learning, thereby addressing the critical need for accessibility and education for this population. Further research should explore the long-term effects and broader applications of synesthetic-induced learning in diverse contexts.

ARTICLE HISTORY
Received 28 February 2024
Revised 16 January 2025
Accepted 19 February 2025

KEYWORDS
Visual impairment; color learning protocol; music-color association; mobile application; music emotions

Introduction

Synesthesia between color and music refers to the transition between auditory and visual senses when music, as an auditory stimulation, stimulates vision, especially the senses of color [1,2]. Early studies on music-color synesthesia reported it as an unusual phenomenon observed only in a few people: synesthetic painters (Kandinsky, Klee, etc.) or musicians (Scriabin, Rimsky-Korsakov, etc.) [3].

Recently, several studies have been conducted on music-color association (MCA) among non-synaesthetes. The correlations between pitch and color, hue, or saturation led to the association of a brighter color with a higher pitch [2]; and a relatively higher pitch was reported to show an association with yellow and green, middle pitch with red and orange, and lower pitch with blue and purple [1]. Audio-visual association in non-synesthetes has been proven by studies on timbre and saturation [4], sound intensity and brightness of color [5], and pitch and luminance [6,7].

How can we understand the MCA in non-synesthetes, that is, the consistent, mutual association between auditory and visual senses? Two hypotheses were proposed to account for this process [1]: one is the 'Direct Connection Hypothesis' claiming that two separate stimuli are directly connected without any medium in the MCA [3,4,8], and the other is the 'Emotional Mediation Hypothesis' claiming that the connection between color and music is formed through the medium, emotion [1,9]. Recent empirical studies have supported the emotional mediation hypothesis, demonstrating that emotions play a key role in the association between color and music (10, 11). However,

CONTACT Hye Young Park legendphy@kosin.ac.kr Music Therapy Major, Graduate School of Church Music, Kosin University, 194 Dongsam-dong, Yeongdo-gu, Busan 49104, Korea

Supplemental data for this article can be accessed online at https://doi.org/10.1080/07853890.2025.2476728.

the cause of the cross-modal pattern remains a topic of ongoing debate.

Studies on cross-modal patterns have been conducted with people with visual impairment (VI) [12–14]. Among the VI synesthetes, some were reported to feel the color from words or specific sounds heard through the ear and texture [15]. Brain imaging studies have proven that the areas in the brain responsible for vision are activated when an individual with VI reads the braille [16]. Notably, the primary visual cortex and V4 (an area specialized for colors) in the extrastriate cortex were used simultaneously in Braille reading [17,18].

While some individuals with VI heavily rely on their reduced visual inputs as primary modality, other individuals with VI may use senses other than vision to conceptualize the surrounding environment. The auditory sense is an efficient medium for them to independently understand and utilize the information gathered from their surroundings, not only rapid and easy access to information, but also in integrated information processing. With a focus on the outstanding auditory performance of individuals with VI, studies have actively investigated an approach of sensory substitution, where information is obtained through the auditory sense in lieu of the visual sense that has either been lost or reduced in function. Ref. [19] made the first attempt to apply a music-based model to a sensory substitution device for VI. This device converts visual information into musical sounds, allowing visually impaired individuals to 'hear' visual information. The device works by first converting the visual image to black and white and then transforming the pixel information into musical elements, with rows of pixels represented by chords and columns by melodies. The vertical position in the image is represented by pitch, and the horizontal position is expressed through time delays. Pixel brightness is represented by sound intensity, with brighter pixels converted to louder sounds and darker pixels to softer sounds.

The 'See ColOr (Seeing Color with an Orchestra),' an innovative interface to express a diversity of colors on the image, use the sounds of musical instruments in an orchestra to enable individuals with VI to determine the color and position of the visual target in an actual setting [20]. In addition, a non-invasive mobility aid was developed based on the auditory circuit for individuals with VI by converting the color and position of daily visual objects into spatialized musical instrument sounds [21].

The conversion of color into sound code is performed through the Hue, Saturation, and Luminance (HSL) system, which represents three traditional attributes of color [20]. H indicates the color of an object, such as red, yellow, or blue; L represents the brightness or darkness of the color, or the intensity of the light energy; and S refers to the vividness of the color, based on its purity rather than light intensity. In this system, H is expressed as the timbre of a musical instrument, S as the pitch, and L as the double bass sound for dark colors and the singing voice for bright colors. These three attributes are also beneficial for developing color-learning protocols for people with visual impairment (VI).

While studies on the HSL system have facilitated color differentiation for individuals with VI based on auditory cues in daily life, the relationship between music and color has often been defined intuitively, without fully accounting for the characteristics of actual users with VI during the process of music-color mapping. This introduces certain limitations, as the color hearing response—which links color to a visual image associated with music—should precede the alignment of sound-color associations and emotional responses from the perspective of the actual listener [22]. Despite the inherent interdependence of these three attributes in perceptually uniform color spaces, this study utilizes them as key parameters, while acknowledging their limitations.

This research developed and confirmed the feasibility of a color-learning mobile application for people with VI, based on the hypothesis that the MCA response may be synesthetically induced with music as a medium despite the neurological injury in VI that limits the vision for color learning. Of significance is the recent report on the positive impact of music classes using a mobile app on learning outcomes, including reinforced self-directedness, enhanced immersion and concentration, reduced time and cost, and real-time application [23]. In line with this approach, an MCA color learning mobile app was developed and is actively used by people with VI in daily life to assist them in achieving color learning with greater initiative and efficiency.

Methods

The following three procedures were conducted to develop the music-color association (MCA) color learning protocol. Procedure 1 consisted of two phases. In phase 1, for 80 individuals with VI (40 with congenital visual impairments, CVI and 40 with adventitious visual impairments, AVI), music excerpts suitable for color learning were selected. In phase 2, a set of color-learning tasks was envisaged in an elaborate and systematic manner. In Procedure 2, the mobile app for

MCA color learning was developed and installed on smartphones, and its utility was verified on 12 individuals with VI (five with CVI, seven with AVI) who voluntarily participated in this procedure among the 80 participants in Procedure 1, the result of which led to the modification and complementation of the details of the app. In Procedure 3, pre- and post-tests were performed on 40 individuals with VI (20 with CVI, 20 with AVI) to collect and analyze H, L, and S data. Thus, the MCA color learning protocol was confirmed to be feasible.

The participants of this study were 120 individuals with VI (60 with CVI and 60 with AVI), aged 20–50 years, including 80 in Procedure 1 and 12 in Procedure 2 among 80 participants in Procedure 1 and 40 in Procedure 3. All participants voluntarily agreed to participate and submitted signed consent forms. The researcher identified participants with CVI and AVI through a combination of strategies. During the initial phase of recruitment, participants were asked about their possession of a 'Disabled Person Identification Card' for individuals with VI. Furthermore, only members of the Korea Blind Union were eligible for inclusion in the recruitment process. Additionally, participants were categorized based on the nature of their visual impairment, distinguishing between congenital and adventitious status in accordance with the legal standards established by the Ministry of Health and Welfare of Korea. The details of the inclusion criteria are as follows.

- An adult registered as having VI of the age ≥20 years and ≤50 years
- An individual without auditory impairment (based on a Self-test for Hearing Loss)
- An individual without any impairment other than VI

To select participants, the researcher visited the Korea Blind Union, a representative organization in South Korea supporting the visually impaired, to obtain the contact details of the managers of the top six branches with the largest number of residents with VI. From the six managers, details of the relevant institutions supporting individuals with VI in the respective areas (welfare centers, rehabilitation centers, community centers, etc.) and the educational institutions attended by individuals with VI (schools for the visually impaired, universities, colleges, etc.) were collected. By contacting the respective manager, personal details, including an email address of the 169 individuals with VI who satisfied the criteria and voluntarily agreed to participate, were obtained. Over a direct phone call or on a visit to the place designated by a potential participant, the researcher explained the study purpose and ethical considerations to 169 individuals who agreed to participate, and 120 individuals with VI were selected.

Procedure 1

The purpose of the color-learning protocol developed in this research is to learn the three attributes of color: H (hue), L (luminance), and S (saturation). The colors used in this study are frequently encountered in daily life, and seven chromatic colors (red, yellow, blue, green, purple, pink, and orange) were chosen as the basis for the color system [1,9]. In Procedure 1, color-music excerpts (H/L/S excerpts) were selected, which then formed the foundation for the MCA tasks. These tasks were organized to align with each step of the protocol, ensuring systematic progression through the color learning process.

Phase 1: selection of color-music excerpt

Empirical studies involving the MCA have demonstrated that the MCA response occurs *via* emotional mediation [1,9,22]. For the H excerpt, MCA excerpts based on emotional mediation were selected in two stages. The first selection of H excerpts followed a previous study, in which music stimulation to induce specific emotions was used to define the MCA response in individuals with VI [24]. In this study, the range of music-induced emotions included the four basic emotions (happiness, sadness, anger, and fear), and the effectiveness of emotional inducement and clarity was verified in a previous study [25]. In this study, the scales of 'music-emotion,' 'color-emotion,' and 'music-color' used by [24] were applied to select the H excerpts showing a high level of congruence with MCA responses as the first set of excerpts. In selecting an excerpt, a relatively less known piece was chosen to prevent an association induced by a previous experience; to control the emotional effect of lyrics, songs with lyrics were excluded [26]. Consequently, the first set contained 70 selected H excerpts in total: 10 pieces for each of the seven hues (red, yellow, blue, green, purple, pink, and orange). The second selection of the H excerpts was completed using an online questionnaire to select the final 35 out of 70 initially selected excerpts (seven hues × five excerpts for each) that showed the highest congruence in the MCA responses of the 80 individuals with VI.

The selection of the L and S excerpts was based on the L (high-low) and S (high-low) of the acoustically modified H excerpts selected in the previous section. In a preliminary study on individuals with VI by Park [27], regarding the L and S responses of color to music, H excerpts were used as the reference for L excerpts, and (1) EQ Plug-In was utilized to modify the sound range; (2) Sound Image Plug-In was employed to modify the bandwidth; (3) Reverb Plug-In was applied to modify the spatial feeling. For the S excerpts, as in the L excerpts, the H excerpts were provided first as the reference, and (1) EQ Plug-In was utilized to modify the sound range; (2) Exciter Plug-In was employed to present the sound source of harmonic distortion. An EQ Plug-In, or Equalizer Plug-In, is an audio processing tool that adjusts the balance between frequency components within an audio signal. In the context of Park [27] study on color-to-music conversion for individuals with visual impairments, the EQ Plug-In was employed to modify the sound range of musical excerpts. This adjustment allowed for variations in the luminance (L) and saturation (S) attributes of color when translating them into auditory representations. The EQ Plug-In works by boosting or attenuating specific frequency ranges within the audio spectrum, thereby altering the perceived brightness, warmth, and overall tonal quality of the sound. These manipulations of the frequency content enable the creation of auditory analogues for different levels of luminance and saturation in visual color perception. Likewise, in this study, the L attribute was acoustically applied to differentiate 'L-high excerpt (L-H)' and 'L-low excerpt (L-L)', and the S attribute was also acoustically applied to differentiate 'S-high excerpt (S-H)' and 'S-low excerpt (S-L)'.

Selection of emotional adjective

Emotional adjectives may be used by individuals with VI to express emotions experienced through music in a clear and sophisticated manner [28]. Thus, applying emotional adjectives to express music-induced emotions could be an effective approach for MCA color learning. The same 80 participants with VI in the selection of H excerpts were also involved in the selection of emotional adjectives. Among the final 35 H excerpts, seven excerpts used in the pre- and post-tests were excluded, and the remaining 28 excerpts were used to express the induced emotion using an adjective. The emotional adjective pool provided by the researcher contained 40 words, and the participants were guided to select one adjective from the pool to describe the emotion expressed by a given excerpt. The pool of 40 words was composed with reference to a previous study [28] for a balanced proportion of sensory (visual, auditory, tactile, olfactory, and gustatory), emotional, and behavioral words. The emotional adjectives collected from 80 individuals with VI were analyzed by frequency, and the one ranked the highest was extracted for each excerpt.

Selection of situational description

Situational descriptions may assist in more efficient and effective processing of information regarding color through contextual learning of color. A study on the verbal description of responses to music-induced emotions by individuals with VI has indicated that a higher proportion of the understanding of visual information, such as color, size, and shape, by individuals is accounted for by learning through contextual experiences that involve verbal descriptions of a specific scene or situation. Thus, for the intensive color learning in this research, an attempt was made towards color learning based on the stories associated with the final 28 H excerpts. The 80 participants with VI in Procedure 1, after responding to the 28 H excerpts using emotional adjectives, were exposed to the excerpts once more and guided to describe the associated scenes, figures, images, and moods as short stories within two sentences. Hence, the participants provided a description of the episodic memory related to a past event, person, or place, or an imaginary storytelling of the music-induced virtual images, feelings, and moods, based on the presented excerpt.

The situational descriptions provided by the participants for each excerpt were classified into six categories: time, space, event, theme, mood, and expression style, by three doctoral students of music therapy with experience in qualitative study for subsequent content analysis. The relationships between the initial categories were examined, and the categories gradually converged. Through this process, the contents of the situational descriptions in each category were reconstructed according to sentence structure to produce the final 20 descriptions.

Phase 2: music-color association task composition

The MCA color learning tasks in Phase 2 were arranged in the following order: (1) H task, (2) L/S task, and (3) combined task, as depicted in Figure S1. The validity of these tasks was evaluated by experts from three fields: music, fine art, and special education. Specifically, the experts, who held Ph.D. degrees in their respective domains and had substantial experience in research related to visual impairments, participated. A total of 10 experts—professors, teachers, and therapists from each field—were consulted to assess the content validity of the MCA tasks. The content validity ratio (CVR) for each task was calculated using a 5-point Likert scale, and the

results indicated that the CVR for each task exceeded 0.8, confirming the high content validity of the tasks. Based on the expert feedback, the researcher made necessary modifications and enhancements to ensure the tasks were appropriately aligned with the study's objectives.

The H task was a congruent task in which music and hue were connected through emotional mediation. This task consisted of a sub-task of repeated listening to the excerpt matched with the hue and a sub-task of repeated listening to the H excerpt matched with the emotional adjective. The L/S task consists of verbalism-based responses. Verbalism refers to the use of linguistic expressions that have not been acquired but borrowed or copied from those used by individuals without visual impairment, for objects that individuals with VI lack visual experience [29]. In a recent study [28], frequent observations were made of verbalism in individuals with VI's linguistic description of the music played to induce a specific emotion. Based on this method, individuals with CVI in this study, who lack visual experience, were guided to use visually oriented verbalism in the L/S task.

The combined task was structured to allow contextual learning based on descriptions of episodic memory or imaginary storytelling. The episodic memory generated through the color-music excerpt (H/L/S excerpt) is a description of the event, person, and place as experienced by the participant. Imaginary storytelling is the description of storytelling or virtual images induced by music [28]. Here, the tasks were created to enable more specific and efficient color learning through in-depth integrated learning of the H/L/S and emotional adjectives based on the situational descriptions generated for each excerpt.

Procedure 2

An iOS mobile application for MCA color learning (MCA app) was developed in Procedure 2, and color-music excerpts and MCA tasks with the effectiveness verified in Procedure 1 were loaded on the app. A protocol was developed, and a pilot study was conducted in 12 participants with VI (five with CVI and seven with AVI) among the 80 in Procedure 1, who voluntarily agreed to participate. Through the pilot study, detailed methods of presenting the excerpts and quiz results were revised, and new functions were added, whereby the MCA app was optimized.

Phase 1: Music-color association app protocol development

Smartphone-based learning shows a high level of utility, as the learner is not subject to temporal or spatial restrictions. Mobile app-based learning for individuals with VI is an effective means of minimizing mobility limitations and increasing accessibility and convenience. The MCA app employed an iOS operation for both user screen composition and processing logic. Using the Voice Over function of the iPhone, a high-utility app that is easy to use for individuals with VI was created. For example, a user with VI can listen to an item by tapping it through various gestures: double tapping for launching the app, triple-finger swiping for scrolling, and two triple-finger tapping to switch on and off the voice [30]. This study ensured a high level of user accessibility by developing an application that supports the voice command of the touch-pad interface for individuals with VI using iPhones. All three tasks were composed of five steps, as illustrated in Figure S2.

The first to third steps of the MCA app were designed for efficient execution of each step based on the task of 'H excerpt learning.' In Step 1, the participants were given 14 H excerpts (seven 1st rank and seven 2nd rank excerpts) developed in this study to lead them to match and perceive H and the excerpts. In Step 2, which was executed in the same way as in Step 1, the participants were presented with a total of 28 H excerpts, with the addition of 14 H excerpts (seven 3rd rank and seven 4th rank excerpts). In Step 3, through the 28 H excerpts, the participants were guided towards the advanced learning of H excerpts *via* emotional mediation by matching H and the emotional adjectives. In Step 4, based on the task of 'L/S excerpt learning', the participants were guided to categorize the L/S excerpts, the acoustically modified forms of H excerpts; i.e. 'high-low' L excerpts and 'high-low' S excerpts, into contrasting pairs for learning. In Step 5, based on the 'combined task learning,' the participants were guided to match the excerpts of the H/L/S and emotional adjectives with 20 situational descriptions to perform MCA color learning in a more realistic and specific way. The order of the quiz for each item was randomized, and each step was completed in the following step only if the rate of correct responses was 70% or higher. The main screen of the MCA app developed in this research is shown in Figure S3 (see also Figures S1, S2 and S3 in the online supplemental files).

Phase 2: Music-color association app optimization in a pilot study

For the functional validation of the MCA app protocol, a pilot study was conducted on 12 participants with VI (five with CVI, seven with AVI) among 80 Procedure 1 participants to optimize the app. The details of the revisions are as follows.

First, for the presentation of the excerpt, the protocol had an image of speakers tapped by the user to play the excerpt, but as the Voice Over function did not support fluent image-voice relay, the image was replaced with a textual form. In addition, the excerpts loaded on the protocol were designed to first present the relevant data of each item (H/L/S, emotional adjective, and situational description), then allow the user to listen to the excerpt once. However, for more effective color learning, the instructions providing the excerpt data and excerpt play button were made movable regardless of the order, while repeated listening was allowed.

Second, the protocol had scores appearing in a separate window after the quiz in each step, while the next button appeared only if the score was ≥70, and the retry or relearning button appeared if the score was <70. Meanwhile, showing the details of the correct and incorrect quiz items and the score was suggested to be helpful for learning. Thus, the revised app provides details of the quiz results for each item on the result screen.

Third, before starting the three tasks (H, L/S, and combined) loaded on the protocol, a screen was added to measure the current emotional valence and emotional arousal in a self-reported questionnaire. This step was based on a previous study that reported a direct effect of emotional valence and arousal on music-emotion perception in individuals with VI [25]. Color learning in this study is based on the claim that color and music can be associated through a shared emotion as a medium. Thus, considering the potential influence of emotional valence and emotional arousal in MCA color learning by individuals with VI, a new screen was added to the relevant content.

Procedure 3

The feasibility of the MCA app was to be performed on 40 participants with VI (20 with CVI, 20 with AVI), but two participants who did not complete all five steps were excluded, and the data of the final 38 participants with VI (20 with CVI, 18 with AVI) were analyzed.

Study tool: the colour learning assessment tool (CLAT)

As a tool for the confirmation of the feasibility of the MCA app for individuals with VI, the 'color learning assessment tool' (CLAT) was developed, and the changes in color learning based on pre- and post-tests were measured. For this, among the 35 color-music excerpts selected in Procedure 1, seven 5th rank excerpts were used. The CLAT consisted of 15 excerpts: 5 H excerpts, 5 L excerpts, and 5 S excerpts to determine the learning performance of the three attributes of color: H, L, and S. The time taken for CLAT was within 20 min.

Process in detail

Procedure 3 was performed as follows: First, the researcher explained the entire study process to the participants. Second, understanding of the process was checked verbally, and the pre-test *via* the CLAT was conducted on small groups of three to four participants with VI. Third, immediately after the pre-test, an hour of orientation was provided regarding the MCA app installation and the method of use and rules to increase the understanding and familiarity of the participants in each group with the MCA color learning tasks. Fourth, the researcher guided the participants to start the MCA app within three days of orientation. The app is accessible at any time, without temporal or spatial restrictions, to allow learning.

Data analysis

The data collected in this research were analyzed using the Statistical Package for Social Sciences (SPSS version 24.0). Frequency analysis and descriptive statistics, including mean and standard deviation, were conducted to assess the CLAT performance of participants' MCA responses. Both tests yielded results greater than .05, indicating normality for the Kolmogorov-Smirnov test and confirming equal variances across groups for Levene's test. This justified the use of parametric tests (t-tests, ANOVA) due to meeting assumptions of normality and homogeneity of variances. However, the Shapiro-Wilk test in Procedure 3 showed non-normality ($p < .05$), leading to the use of non-parametric tests. The Wilcoxon Signed Rank Test analyzed within-group differences, and the Mann-Whitney U test assessed between-group differences. To determine the correlations among the CLAT scores regarding emotional valence and emotional arousal, a correlation analysis was carried out for pre- and post-test variance. For all statistical analyses, the level of significance was set at .05.

Results

The demographic characteristics of the participants were as follows: A total of 120 adults (55 women, 65 men, M age = 36.26 years, age range 20–50 years) were recruited (Table 1).

Table 1. Demographic characteristics of participants ($N = 120$).

Characteristic	Category	CVI ($n = 60$) n (%) or M ± SD	AVI ($n = 60$) n (%) or M ± SD	χ^2 or t	p
Gender	Male	36	29	1.645	.272
	Female	24	31		
Age	–	37.23 (8.593)	35.28 (8.283)	1.266	.208
Music education	None	17	15	0.709	.871
	<1 year	20	19		
	1–3 years	14	18		
	>3 years	9	8		
Degree of vision	Blindness	60	11	–	
	Low vision	0	49		
Level of disability	Severe	60	27	–	
	Moderate	0	33		

CVI: people with congenital visual impairment; AVI: people with adventitious visual impairment; 'Severe' and 'moderate' level of disability were classified according to the Ministry of Health and Welfare of Korea criteria.

Study tool development

Selection of color-music excerpt

To select the color music excerpts, the level of congruence for each H excerpt in the research participants was numerically coded based on a 4-point Likert scale, and the results are presented in Table 2. The difference in congruence for each H excerpt between the congenital visual impairments (CVI) and adventitious visual impairments (AVI) groups was statistically analyzed using a t-test, where no significant difference was found.

Selection of emotional adjective

To apply emotional adjectives to color learning by individuals with VI in this research, the adjectives with the highest frequency were extracted for each excerpt, as shown in Table 3. The association between emotional adjectives, colors, and the corresponding musical excerpts is presented in Table 4. To test the significance of the differences in emotional adjectives according to the group and H excerpt, a two-way ANOVA was performed. The difference according to group was not significant, nor was the interaction between the group and H excerpt. However, there was a significant difference in the frequency of emotional adjectives according to the H excerpt ($F = 2.379$, $p < .05$), for which the LSD post-hoc test was conducted. The results indicated that compared to orange or green, yellow, purple, and pink showed significantly higher levels of frequency ($p < .05$). The degrees of freedom for the group effect was 1, for the color effect was 6, and for the group*color interaction effect was 6.

Selection of situational description

The results were comparatively analyzed through a series of content analyses by three experts to extract common themes. The 20 final situational descriptions with verified reliability are listed in Table 5.

Music-color association app development

The app consisted of five steps: Steps 1–3 for the learning of H excerpts, Step 4 for the learning of L and S excerpts, and Step 5 for the combined task, with advanced learning of the three-color attributes (hue, luminance, and saturation) based on the combination of the associated emotional adjectives and situational descriptions. A quiz is presented to complete each step, and the following step appears only when the quiz score is 70% or higher.

Music-color association app feasibility

The variation in the CLAT scores was analyzed to determine the feasibility of the MCA app, as detailed in Table 6. The independent variable was the application of the MCA color learning protocol, while the dependent variable was the color learning outcomes assessed through task achievement, including hue, saturation, and luminance, measured using CLAT. For the pre- and post-test differences in CLAT scores of the app users, the Wilcoxon signed-rank test was performed, and a significant effect was found across all variables, H, S, and L, based on the pre- and post-test comparison (p=.000). In addition, the Mann-Whitney U test was performed for the difference in CLAT scores between the CVI and AVI groups, and no significant between-group difference was found for H, S, or L. Furthermore, correlation analysis was performed for the pre- and post-test variance to analyze the correlation between emotional valence and emotional arousal in the MCA app, and no significant correlation was found for either valence or arousal with the pre- and post-test variance in CLAT scores.

Discussion

This study aimed to develop a mobile app based on a systematic analysis of the music-color association (MCA) responses of individuals with VI for color learning and to verify the effectiveness of the app. The main findings are as follows:

Table 2. Selection of color-music excerpts for CVI and AVI ($n = 80$).

Category	Composer	Title	Time	CVI M (SD)	AVI M (SD)	t	p
Red	Dmitri Shostakovich	Violin Concerto No. 1 in A minor, Op. 99, 4th mov.	00:00–00:20	101 (0.54)	106 (0.48)	−0.517	.607
	Bela Bartok	The Miraculous Mandarin Op. 19, Sz. 73	21:23–21:40	94 (0.73)	98 (0.67)		
	Lee Morgan	The Sidewinder (1963)	00:37–00:55	85 (0.68)	89 (0.76)		
	Edward Elgar	Enigma Variation Op. 36: XIII. BGN	00:18–00:38	79 (0.61)	80 (0.75)		
	Gustav Mahler	Symphony No. 9 in D major, 1st mov.	10:27–10:45	71 (0.69)	71 (0.73)		
Yellow	Dmitri Shostakovich	Ballet Suite No. 3, Part 2	00:01–00:20	100 (0.50)	106 (0.48)	−0.145	.885
	Franz von Suppe	Poet and Peasant Overture	07:05–07:21	89 (0.81)	92 (0.70)		
	Johannes Brahms	Violin Sonata No. 3 in D Minor, Op. 108: II. Adagio	00:00–00:18	85 (0.73)	87 (0.67)		
	Wolfgang Amadeus Mozart	Symphony No. 38 in D Major, K. 504, 2nd mov.	00:00–00:21	77 (0.79)	77 (0.65)		
	Ludwig van Beethoven	String Quartet No. 16 in F major, Op. 135, 3rd mov.	00:22–00:45	74 (0.66)	71 (0.76)		
Blue	Rimsky-Korsakov	Capriccio Espagnol, Op. 34 – Alborada	00:00–00:21	94 (0.73)	98 (0.59)	−0.309	.758
	Johannes Brahms	Hungarian Dances WoO.1 – No. 20 in E minor/Arr. for Orchestra	00:00–00:18	87 (0.81)	91 (0.75)		
	Edvard Grieg	Piano Concerto in A minor, Op. 16, 2nd mov.	00:00–00:17	83 (0.85)	84 (0.77)		
	Antonin Dvorak	Piano Trio No. 4 in E minor, Op. 90, 'Dumky': III Andante - Vivace non troppo	00:00–00:22	74 (0.76)	76 (0.87)		
	Robert Schumann	Kinderszenen Op. 15: XII. Kind im Einschlummern	00:00–00:21	73 (0.95)	72 (0.60)		
Green	Ennio Morricone	'Once upon a Time in America' Soundtrack – Prohibition Dirge	00:13–00:34	93 (0.65)	99 (0.64)	−0.515	.608
	Frederic Chopin	Etude Op. 10, No. 11 in E Flat Major	00:00–00:19	87 (0.67)	91 (0.75)		
	Antonin Dvorak	Slavonic Dance No. 1, Op. 46 in C Major	00:03–00:20	84 (0.84)	84 (0.54)		
	Jacques Offenbach	Gaite Parisienne	00:00–00:20	76 (0.74)	79 (0.86)		
	Felix Mendelssohn	Songs Without Word, Op. 62, No. 2	00:00–00:15	65 (0.70)	67 (0.69)		
Purple	George Crumb	Black Angels Image 4 Devil Music	00:00–00:20	110 (0.49)	104 (0.54)	0.312	.756
	Richard Strauss	Eine Alpensinfonie Op.64, Auf dem Gletscher	00:06–00:25	107 (0.47)	102 (0.63)		
	Bela Bartok	Concerto for Orchestra, Sz. 116, BB123, 3rd mov.	00:00–00:18	99 (0.71)	101 (0.67)		
	John Cage	Seventy-Four	00:10–00:25	88 (0.60)	84 (0.77)		
	Olivier Messiaen	Vingt Regards de l'Enfant Jesus n 12 La Parole Toute Puissante Miguel Henriques	01:33–01:53	77 (0.82)	82 (0.63)		
Pink	Frederic Chopin	Preludes, Op. 28, No. 7 in A Major	00:00–00:23	108 (0.60)	103 (0.54)	0.251	.802
	Wolfgang Amadeus Mozart	Violin Sonata No. 26 in B Flat Major, 1st mov., K. 378	00:00–00:21	99 (0.64)	98 (0.67)		
	Robert Schumann	Symphony No. 2 in C Major, Op. 61, 3rd mov.	00:00–00:23	87 (0.71)	93 (0.52)		
	Alexander Scriabin	Etude in C Sharp Minor, Op. 2, No. 1	00:00–00:15	84 (1.01)	78 (0.63)		
	Rimsky-Korsakov	Symphonic Suite 'Scheherazade,' Op.35, 3rd mov.	00:00–00:20	68 (0.79)	67 (0.80)		
Orange	Johannes Brahms	String Sextet No. 1 in B Flat Major, 3rd mov.	00:00–00:23	97 (0.55)	100 (0.59)	0.153	.879
	Wolfgang Amadeus Mozart	Piano Sonata No. 9 in D Major, K. 311, 3rd mov.	00:00–00:20	94 (0.57)	93 (0.85)		
	Hugo Wolf	Italian Serenade in G Major	00:00–00:22	87 (0.81)	84 (0.77)		
	Dmitri Shostakovich	Ballet Suite No. 3, I. Waltz	00:00–00:19	81 (0.65)	79 (0.83)		
	Felix Mendelssohn	Symphony No. 3 in A Minor, Op. 56, 3rd mov.	00:50–01:13	67 (0.76)	70 (0.70)		

First, for the MCA response to excerpt H among the color-music excerpts for individuals with VI, the colors purple and pink showed high congruence. The highest frequency was observed for purple among the seven colors associated with happiness, sadness, anger, and fear by Park [27], who explored the color association response to each emotional category in individuals with VI. The color purple is the darkest and heaviest color among the seven chromatic colors used in this research. The purple symbol represents uncertainty, a neutral state without a certain direction, and neither warm nor cold. Thus, the high congruence exhibited by the purple color in this study might be indicative of an association between music and the color image of uncertainty, vagueness, or anxiety induced by the excerpt used in the experiment. The music excerpts for purple included musical devices such as abrupt and unexpected changes in harmonic progression, sharp dissonances, dark timbre, and non-traditional instrumentation. This

Table 3. Color-dependent difference in emotional adjective based on the group and hue ($n = 80$).

Category	Emotional Adjective n (%)								Group effect (F, p)	Color effect (F, p)	Group* Color (F, p)	Post-hoc
	CVI	AVI	CVI	AVI	CVI	AVI	CVI	AVI				
Red	Glamorous		Hot		Passionate		Threatening		0.025, .876	2.379, .045*	0.705, .647	Green, Orange < Red, Blue < Purple, Yellow, Orange
	8 (20)	12 (30)	9 (22.5)	8 (20)	14 (35)	18 (45)	13 (32.5)	15 (37.5)				
Yellow	Glittering		Warm		Happy		Lovely					
	15 (37.5)	23 (37.5)	10 (25)	8 (20)	16 (40)	22 (55)	12 (30)	13 (32.5)				
Blue	Hopeful		Cold		Depressive		Calm					
	18 (45)	15 (37.5)	6 (15)	5 (12.5)	18 (45)	14 (35)	11 (27.5)	12 (30)				
Green	Blooming		Fragrant		Refreshing		Lively					
	6 (15)	7 (17.5)	8 (20)	10 (25)	7 (17.5)	8 (20)	14 (35)	16 (40)				
Purple	Mysterious		Lofty		Anxious		Sad					
	17 (42.5)	14 (35)	15 (37.5)	13 (32.5)	22 (55)	16 (40)	13 (32.5)	11 (27.5)				
Pink	Clean		Cute		Pure		Soft					
	17 (42.5)	14 (35)	24 (60)	16 (40)	11 (27.5)	9 (22.5)	12 (30)	15 (37.5)				
Orange	Lively		Joyful		Sweet		Fresh					
	8 (20)	8 (20)	9 (22.5)	7 (17.5)	15 (37.5)	13 (32.5)	10 (25)	11 (27.5)				

*$p < .05$.

Table 4. Emotional adjectives associated with colors and musical excerpts.

Adjective	Color	Music
Glamorous	Red	D. Shostakovich, Violin Concerto No. 1, Op.99, 4th mov. (00:00–20)
Hot		B. Bartok, The Miraculous Mandarin Op. 19, Sz. 73 (21:23–40)
Passionate		Lee Morgan, The Sidewinder (00:37–55)
Threatening		E. Elgar, Enigma Variation Op. 36: XIII. BGN (00:18–38)
		G. Mahler, Symphony No. 9 in D major, 1st mov. (10:27–45)
Glittering	Yellow	D. Shostakovich, Ballet Suite No. 3, Part 2 (00:01–20)
Warm		F. Suppe, Poet and Peasant Overture (07:05–21)
Happy		J. Brahms, Violin Sonata No. 3, Op. 108, 2nd mov. (00:00–18)
Lovely		W. A. Mozart, Symphony No. 38, K. 504, 2nd mov. (00:00–21)
		L. Beethoven, String Quartet No. 16, Op. 135, 3rd mov. (00:22–45)
Hopeful	Blue	Rimsky-Korsakov, Capriccio Espagnol, Op. 34 – Alborada (00:00-21)
Cold		J. Brahms, Hungarian Dances No. 20/Arr. Orchestra (00:00–18)
Depressive		E. Grieg, Piano Concerto Op. 16, 2nd mov. (00:00-17)
Calm		A. Dvorak, Piano Trio No. 4, Op. 90, 3rd mov. (00:00–22)
		R. Schumann, Kinderszenen Op. 15: 12. Kind im Einschlummern (00:00–21)
Blooming	Green	Ennio Morricone, 'Once upon a Time in America' Prohibition Dirge (00:13–34)
Fragrant		F. Chopin, Etude Op. 10, No. 11 (00:00–19)
Refreshing		A. Dvorak, Slavonic Dance No. 1, Op. 46 (00:03–20)
Lively		J. Offenbach, Gaite Parisienne (00:00–20)
		F. Mendelssohn, Songs Without Word, Op. 62, No. 2 (00:00–15)
Mysterious	Purple	G. Crumb, Black Angels Image 4 Devil Music (00:00–20)
Lofty		R. Strauss, Eine Alpensinfonie Op.64, Auf dem Gletscher (00:06-25)
Anxious		B. Bartok, Concerto for Orchestra, Sz. 116, BB123, 3rd mov. (00:00–18)
Sad		J. Cage, Seventy-Four (00:10–25)
		O. Messiaen, Vingt Regards de l'Enfant Jesus n 12 La Parole Toute Puissante Miguel Henriques (01:33–53)
Clean	Pink	F. Chopin, Preludes, Op. 28, No. 7 (00:00–23)
Cute		W. A. Mozart, Violin Sonata No. 26, K. 378, 1st mov., (00:00–21)
Pure		R. Schumann, Symphony No. 2, Op. 61, 3rd mov. (00:00–23)
Soft		A. Scriabin, Etude in C Sharp Minor, Op. 2, No. 1 (00:00–15)
		Rimsky-Korsakov, 'Scheherazade,' Op.35, 3rd mov. (00:00–20)
Lively	Orange	J. Brahms, String Sextet No. 1, 3rd mov. (00:00–23)
Joyful		W. A. Mozart, Piano Sonata No. 9, K. 311, 3rd mov. (00:00–20)
Sweet		H. Wolf, Italian Serenade in G Major (00:00–22)
Fresh		D. Shostakovich, Ballet Suite No. 3, I. Waltz (00:00–19)
		F. Mendelssohn, Symphony No. 3, Op. 56, 3rd mov. (00:50–73)

result supports the hypothesis that the emotion induced by the music excerpt elicits an association with the hue.

Second, in addition to the purple color, the pink color also showed a high level of congruence. The pink color is brighter and lighter than the others tested in this research, except for yellow. With regard to color images in both music and emotion, one of the characteristics of purple was negative; however, the positivity of pink was unanimous among the emotional adjectives selected by participants. This strong tendency towards a positive color image seemed to be externalized by certain musical factors such as fluent melodic lines, traditional harmonic progressions as commonly observed in classical and romantic music, brighter timbre, thin and transparent musical texture, and gradual dynamic changes. Individuals with VI, especially

Table 5. List of situational descriptions for color-music excerpts.

Color	Context	Emotional adjective	Luminance /Saturation
Red	An exciting mood of festivity in a parade of an amusement park	Glamorous	bright
	An imminent threat felt before a war in a historical novel	Threatening	vivid
Yellow	An enjoyable and peaceful meal time with family	Happy	bright
	A group of people laughing in a big party	Glittering	vivid
	A mother gazing down at a baby in her embrace	Lovely	bright
Blue	A lonely walk on one's way to work in the early morning	Depressive	dim
	An excitement felt before the ship launches	Hopeful	bright
	A feeling of gazing at the calm sea from the deck of a cruise ship	Calm	dim
Green	A feeling of sprouting green leaves on a spring day	Fragrant	vivid
	An exciting, noisy mood at a barbeque party	Lively	bright
Purple	A situation of encountering an intruder while being alone at night	Anxious	dark
	A feeling of warning right before a scary event	Mysterious	dim
	A heroic death in a war movie	Lofty	vivid
Pink	A mother singing a lullaby to her baby	Cute	dark
	A feeling of morning dew on a leaf	Clean	bright
	A memory of free time with morning sunshine at a restaurant	Soft	vivid
Orange	A small party in a college dorm lounge	Joyful	bright
	The experienced of biting a sweet and juicy orange	Sweet	bright
	A scene of kids playing hide-and-seek	Lively	vivid
	A bustling scene of students on the beach at a summer camp	Fresh	bright

Table 6. The pre- and post-test variance in CLAT scores for color-learning ($n = 38$).

	CVI			AVI			
Category	Pre	Post	Z	Pre	Post	Z	z
H	15.66 ± 4.96	24.33 ± 4.47	−3.794***	18.14 ± 3.83	28.14 ± 3.65	−3.784***	−0.532
L	17.66 ± 6.58	24.33 ± 4.47	−3.512**	16.66 ± 6.56	24.44 ± 5.11	−3.128**	−0.557
S	11.99 ± 6.34	20.33 ± 5.06	−3.801***	13.32 ± 4.57	19.25 ± 5.05	−2.966*	−1.400

H: hue; L: luminance; S: saturation; CLAT: color learning assessment tool.
*$p < .05$; **$p < .01$; ***$p < .001$.

congenital visual impairments (CVI), may acquire color information and images through text and verbal descriptions. Basically, color learning of individuals with VI could be done through verbalism in education-based, media-based, and contextual verbalism. Thus, the negativity associated with the color purple and the positivity for the color pink observed in this study should be understood as internalized and modified characteristics triggered by verbalism-based knowledge during a long life as an individual with VI.

Third, for the response of individuals with VI to emotional adjectives based on color-music excerpts, the colors yellow, purple, and pink showed relatively higher frequencies with significance compared to the other colors. Specifically, the bright, light, and most positive emotional valence of the corresponding excerpt is presumed to have led to a high level of MCA responses in association with emotional adjectives. This implies that auditory stimulation of music with clear valence may be associated with the response to H in the visual dimension. The result of the highest frequency of emotional adjectives for the yellow excerpt coincided with a previous study [31], which reported that the response induced by music was relatively clearer for happiness among the four investigated emotions: happiness, sadness, anger, and fear.

Fourth, the L/S task applied visually oriented verbalism in the design for more effective and advanced learning of colors. Visually oriented verbalism refers to the daily use of words closely associated with visual information, including H, L, and S, by individuals with CVI without any direct experience [29]. Thus, the use of visually oriented verbalism in this study is presumed to have contributed to color learning by individuals with VI based on the complementary acquisition of sensory information.

The MCA combined task consisted of episodic memory, a specific experience elicited by music, and situational description focused on imaginary or creative storytelling induced by music [28]. The task thus converted the visual images of H, L, and S into the content described by other senses in individuals with VI for reconstruction into an experienced or imagined event that enhanced their color learning to be more realistic and specific. This process implied that music as a sound unit of meaning and a non-linguistic means of communication was interpreted as comprehensive and sophisticated information in the MCA combined task and in individuals with VI and limited vision.

Fifth, color learning by individuals with VI using the MCA app in this research resulted in a significant improvement in the learning of all three

attributes: H, L, and S. This finding suggests that individuals with VI can acquire color information in daily life through their association with music and emotional mediation. This research confirmed that color learning with the MCA app enables a more interactive and realistic learning experience. Individuals with VI can actively reconstruct color information using the app, leveraging their auditory sense to compensate for limited vision. Previous studies have highlighted the effectiveness of auditory sense in art activities, showing that it can serve as a valuable tool for individuals with VI to engage with visual dimensions [32,33].

Lastly, color learning by individuals with VI using the MCA app showed no significant difference in the scores of H, L, and S based on the time of onset of CVI or AVI. The response to color belongs to the unique dimension of visual perception; it is difficult to acquire it through other cognitive functions. While individuals with VI are often able to discern colors, those with CVI are unable to directly perceive any colors, so that it is easy to assume that they do not have the same concepts of color as people without VI. However, individuals with CVI are able to acquire the concepts related to color based on linguistic, sensory, and emotional associations [28]. This research has shown a lack of difference in the emotions associated with color between individuals with CVI and AVI, which indicates that the color concepts acquired by individuals with CVI through the senses other than visual perception could resemble the color concepts in those with AVI. A study regarding color preference in individuals with VI also reported a lack of difference in the color concepts compared to others with different degrees of VI (CVI vs. low vision) [34]. In line with earlier study, the MCA responses in this research were indicative of a lack of differences according to the onset of the impairment. Hence, the MCA responses are influenced not by the variables related to the onset of VI but by the emotional variables induced by music.

In conclusion, this research has introduced a novel approach to color learning for individuals with VI through MCA. The research has highlighted the intricate interplay between auditory stimuli, emotional mediation, and color perception in both congenital and adventitious VI. The findings emphasized the important role of music-induced emotions in driving MCA responses. Three attributes of color (hue, luminance, and saturation) have emerged as useful factors for color learning for VI, illustrating the profound connection between musical salient and subjective emotional responses. Moreover, the development and validation of a color-learning mobile application based on MCA presented a new approach for expanding the educational experiences of VI. By leveraging music as a medium for sensory substitution, the app empowers users to actively engage in color learning despite visual impairments.

Based on the discussion, the following suggestions are made for further studies.

Although cluster sampling would have been ideal for the generalization of the results, this research used convenience sampling for practical reasons. Further studies should thus target an adequately large sample size to conduct an extensive investigation and learning regarding music-color responses. While only the onset of VI was treated as a VI-related variable in this study, further studies should conduct an in-depth analysis involving the degree, cause, and progression of the impairment. In this study, a self-report questionnaire was used to investigate MCA responses through emotional mediation. Further studies should thus apply a complementary, psychophysiological method, such as electroencephalography or electromyography, for precise and scientific analysis of MCA responses.

Acknowledgements

I thank Prof. Hyun Ju Chong for helpful discussions and Dr. Miran Cho and Jaesuk Ye for assisting with the experiments.

Ethical approval

This study was conducted in accordance with the ethical principles of the Declaration of Helsinki. Informed consent was obtained from all participants prior to their participation in the study. Ethical approval was granted by the Kosin University Institutional Review Board [IRB No. 2020-0028].

Disclosure statement

The author declares that the research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

Funding

This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-2020S1A5A8042482).

ORCID

Hye Young Park http://orcid.org/0000-0003-4414-7672

Data availability statement

The data that support the findings of this study are available from the corresponding author, H.Y.P., upon reasonable request.

References

[1] Palmer SE, Schloss KB, Xu Z, et al. Music–color associations are mediated by emotion. Proc Natl Acad Sci U S A. 2013;110(22):8836–8841. doi: 10.1073/pnas.1212562110.

[2] Ward J, Huckstep B, Tsakanikos E. Sound-colour synaesthesia: to what extent does it use cross-modal mechanisms common to us all? Cortex. 2006;42(2):264–280. doi: 10.1016/s0010-9452(08)70352-6.

[3] Marks LE. On colored-hearing synesthesia: cross-modal translations of sensory dimensions. Psychol Bull. 1975;82(3):303–331. doi: 10.1037/0033-2909.82.3.303.

[4] Caivano JL. Color and sound: physical and psychophysical relations. Color Res Appl. 1994;19(2):126–133. doi: 10.1111/j.1520-6378.1994.tb00072.x.

[5] Spence C. Crossmodal correspondences: a tutorial review. Atten Percept Psychophys. 2011;73(4):971–995. doi: 10.3758/s13414-010-0073-7.

[6] Evans KK, Treisman A. Natural cross-modal mappings between visual and auditory features. J Vis. 2010;10(1):6.1–612. doi: 10.1167/10.1.6.

[7] Parise CV, Spence C. Audiovisual crossmodal correspondences and sound symbolism: a study using the implicit association test. Exp Brain Res. 2012;220(3-4):319–333. doi: 10.1007/s00221-012-3140-6.

[8] Pridmore RW. Music and color: relations in the psychophysical perspective. Color Res Appl. 1992;17(1):57–61. doi: 10.1002/col.5080170110.

[9] Barbiere JM, Vidal A, Zellner DA. The color of music: correspondence through emotion. Empir Stud Arts. 2007;25(2):193–208. doi: 10.2190/A704-5647-5245-R47P.

[10] Hauck PIA, Von Castell C, Hecht H. Crossmodal Correspondence between Music and Ambient Color Is Mediated by Emotion. Multisens Res. 2022;35(5):407–446. doi: 10.1163/22134808-bja10077 35985652.

[11] Valdés-Alemán P, Zamudio-Gurrola A, Téllez-Alanís B. The emotional link between color and music: What happens with atonal music?. Psychomusicology: Music, Mind, and Brain. 2022;32(1-2):46–57. doi: 10.1037/pmu0000288.

[12] Bartolome JI, Cho G, Cho JD. Multi-sensory color expression with sound and temperature in visual arts appreciation for people with visual impairment. Electronics. 2021;10(11):1336. doi: 10.3390/electronics10111336.

[13] Iranzo Bartolomé J, Cho JD, Cavazos Quero L, et al. Thermal interaction for improving tactile artwork depth and color-depth appreciation for visually impaired people. Electronics. 2020;9(11):1939. doi: 10.3390/electronics9111939.

[14] Jabbar MS, Lee CH, Cho JD. ColorWatch: color perceptual spatial tactile interface for people with visual impairments. Electronics. 2021;10(5):596. doi: 10.3390/electronics10050596.

[15] Steven MS, Blakemore C. Visual synaesthesia in the blind. Perception. 2004;33(7):855–868. doi: 10.1068/p5160.

[16] Sadato N, Pascual-Leone A, Grafman J, et al. Activation of the primary visual cortex by braille reading in blind subjects. Nature. 1996;380(6574):526–528. doi: 10.1038/380526a0.

[17] Burton H, Snyder AZ, Diamond JB, et al. Adaptive changes in early and late blind: a FMRI study of verb generation to heard nouns. J Neurophysiol. 2002;88(6):3359–3371. doi: 10.1152/jn.00129.2002.

[18] Burton H. Visual cortex activity in early and late blind people. J Neurosci. 2003;23(10):4005–4011. doi: 10.1523/JNEUROSCI.23-10-04005.2003.

[19] Cronly-Dillon J, Persaud K, Gregory R. The perception of visual images encoded in musical form: a study in cross-modality information. Proc Biol Sci. 1999;266(1436):2427–2433. doi: 10.1098/rspb.1999.0942.

[20] Deville B, Bologna G, Vinckenbosch M, et al. See color: seeing colours with an orchestra. In: Lalanne D, Kohlas J, editors. Human machine interaction. London: Springer; 2009. p. 251–279.

[21] Bologna G, Deville B, Pun T. Blind navigation along a sinuous path by means of the see color interface. In: Mira J, Ferrández JM, Álvarez JR, et al., editors. Lecture notes in computer science: bioinspired applications in artificial and natural computation. Vol. 5602. London: Springer; 2009. p. 235–243. doi: 10.1007/978-3-642-02267-8_26.

[22] Whiteford KL, Schloss KB, Helwig NE, et al. Color, music, and emotion: bach to the blues. Iperception. 2018;9(6):2041669518808535. doi: 10.1177/2041669518808535.

[23] Chong EK. Teaching and learning music theory in the age of AI and mobile technologies. IJDS. 2019;10(3):1505–1509. doi: 10.20533/ijds.2040.2570.2019.0186.

[24] Park HY. A convergence study on music-color association responses of people with visual impairment mediated by emotion. J Korea Converg Soc. 2019;10(5):313–321. doi: 10.15207/JKCS.2019.10.5.313.

[25] Park HY, Chong HJ. A comparative study of the perception of music emotion between adults with and without visual impairment. Psychol Music. 2019;47(2):225–240. doi: 10.1177/0305735617745148.

[26] Scherer KR, Zentner MR. Emotional effects of music: production rules. In: Juslin PN, Sloboda JA, editors. Music and emotion: theory and research. Oxford: Oxford University Press; 2001. p. 361–392.

[27] Park HY. Music-color association responses based on emotion to three attributes of color by people with visual impairments. Korean J Visual Impairment. 2020;36(4):169–186. doi: 10.35154/kjvi.2020.36.4.169.

[28] Park HY, Lee SJ, Chong HJ. A comparative study of verbal descriptions of emotions induced by music between adults with and without visual impairments. J New Music Res. 2020;49(2):151–161. doi: 10.1080/09298215.2020.1717544.

[29] Vinter A, Fernandes V, Orlandi O, et al. Verbal definitions of familiar objects in blind children reflect

their peculiar perceptual experience. Child Care Health Dev. 2013;39(6):856–863. doi: 10.1111/cch.12002.

[30] Duarte C, Desart S, Costa D, et al. Designing multimodal mobile interaction for a text messaging application for visually impaired users. Front ICT. 2017;4:26. doi: 10.3389/fict.2017.00026.

[31] Juslin PN, Laukka P. Communication of emotions in vocal expression and music performance: different channels, same code? Psychol Bull. 2003;129(5):770–814. doi: 10.1037/0033-2909.129.5.770.

[32] Cavazos Quero L, Lee CH, Cho JD. Multi-sensory color code based on sound and scent for visual art appreciation. Electronics. 2021;10(14):1696. doi: 10.3390/electronics10141696.

[33] Cho JD, Jeong J, Kim JH, et al. Sound coding color to improve artwork appreciation by people with visual impairments. Electronics. 2020;9(11):1981. doi: 10.3390/electronics9111981.

[34] Park J. A study on color preference and associative language of visually impaired children. Korean J Visual Impairment. 1994;10(1):93–118.