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Automaticity of pitch class-color synesthesia as revealed by a Stroop-like effect

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ABSTRACT

Pitch classes (e.g., *do*, *re*, and *mi*) in music evoke color sensations in pitch class-color synesthesia, which is a recently described form of synesthesia in musicians. The synesthetic color sensations were confirmed to be consistent over an extended time interval, fulfilling a widely-accepted criterion for the authenticity of synesthesia. However, it remains unclear whether the color sensations occurred automatically (i.e., without voluntary effort), which is another defining property of synesthesia. We utilized the Stroop paradigm to investigate this issue in 10 pitch class-color synesthetes. Participants were visually presented with pitch class names in font colors that were either congruent or incongruent with the participants' own color sensations. The speed for reporting the font color was slower when it was incongruent with the synesthetic sensation than when it was congruent. The finding verifies the authenticity of pitch class-color synesthesia by demonstrating that the color sensations occur automatically, even when unnecessary.

1. Introduction

Recently, we discovered a novel form of synesthesia in musicians, termed "pitch class-color synesthesia," where the pitch class (or pitch chroma) of a musical note is associated with color sensations (Itoh, Sakata, Kwee, & Nakada, 2017). According to the helical model of musical pitch perception, the perception of pitches in music consists of two components: pitch height and pitch class (Drobisch, 1855; Shepard, 1964). Pitch height refers to the perceived highness/lowness of the sound that correlates with sound frequency, whereas pitch class (e.g., *do*, *re*, and *mi*) refers to the set of pitches related to each other by octaves, representing the circular component of the helix that is independent of pitch height. Correspondingly, there are two forms of synesthesia induced by pitches: pitch height-color synesthesia and pitch class-color synesthesia (Itoh et al., 2017). Pitch height-color synesthesia is the well-known crossmodal association between pitch height and lightness/brightness (Hubbard, 1996; Marks, 1974, 1975; Simpson, Quinn, & Ausubel, 1956; Ward, Huckstep, & Tsakanikos, 2006). In pitch class-color synesthesia, the higher-order concept of pitch class, rather than the sensory-level highness/lowness of a tone, induces the concurrent sensations of color (Itoh & Nakada, 2018).

Since synesthesia is a subjective experience in nature, it is often difficult to scientifically demonstrate that an individual truly experiences such synesthetic sensations; for example, that the letter "A" is red, or that the pitch class "*do*" is red. Two objective criteria have been used to prove the authenticity of synesthesia. First, the test of consistency has been established as the behavioral "gold standard" for confirming synesthesia (Asher, Aitken, Farooqi, Kurmani, & Baron-Cohen, 2006; Baron-Cohen, Wyke, & Binnie, 1987). In this test, participants describe their synesthetic experiences on one day, and then are given a surprise retest after some time

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to assess the consistency of their descriptions. Second, the automaticity of synesthetic sensations has been considered an important defining feature of synesthesia. Synesthetic sensations occur spontaneously and automatically without requiring intentional effort in many forms of synesthesia. This feature distinguishes synesthesia from mental imagery, which is typically under some amount of intentional control (Nanay, 2018).

With respect to these two criteria, the authenticity of pitch class-color synesthesia has been only partly established. We have previously shown that hues of colors associated with pitch classes were highly consistent between the two tests administered an average of three months apart (Itoh et al., 2017). The mean correlation coefficient across the two tests was 0.91 (95% confidence interval = 0.85–0.97) in 33 synesthetic participants. Regarding automaticity, however, no study has investigated whether these color experiences occurred spontaneously, without requiring voluntary effort.

Therefore, the purpose of the present study was to confirm the automaticity of color sensations in pitch class-color synesthetes using a modified version of the Stroop paradigm (MacLeod, 1991; Stroop, 1935). In a typical Stroop task, a color word is presented in a font color that is either congruent or incongruent with the color word (e.g., the word "red" displayed in a red or green font). When the participant reports the color of the font, response is delayed in the incongruent condition relative to the congruent condition, which is interpreted as reflecting the automaticity of word reading. A less automated task of color naming is impeded by a more automated task of word reading.

The Stroop paradigm has been used to demonstrate the automaticity of concurrent sensations in several forms of synesthesia, including grapheme-color (van der Veen, Aben, Smits, & Roder, 2014), sound-color (Ward et al., 2006), and digit-color (Mills, Howell Boteler, and Oliver, 1999). The Stroop paradigm has also successfully been used for the investigation of the neural correlates of pitch-pitch name association in absolute pitch (AP) (Itoh, Suwazono, Arao, Miyazaki, & Nakada, 2005; Schulze, Mueller, & Koelsch, 2013), which is the ability to identify the pitch class of a musical pitch without being given a reference pitch (Takeuchi & Hulse, 1993). In the present study, pitch class names were presented visually in font colors that were either congruent or incongruent with the synesthete's own color sensations. A clear Stroop-like interference was observed as a result; the speed of reporting the font color of a pitch class name was slower when the font color did not match the participant's synesthetic sensation for the pitch class name, as compared to when it matched the sensation.

In addition, we sought to determine the effects of AP on pitch class-color synesthesia. The size of the Stroop effect reflects the strength of color-word association (Klein, 1964). Accordingly, if AP is an essential component of pitch class-color synesthesia, the size of the Stroop-like effect between color and pitch class name should be positively correlated with the synesthetic participants' level of AP. Analyses showed that the size of the Stroop-like interference effect was unaffected by the level of AP, which confirmed our previous finding that AP is not an essential component of pitch class-color synesthesia (Itoh & Nakada, 2018).

2. Material and methods

2.1. Participants

Ten pitch class-color synesthetes participated in the study (19–22 years old, two males). These participants were referred to as case numbers 7, 8, 9, 10, 11, 12, 19, 29, 30, and 33 in our previous report on pitch class-color synesthesia (Itoh & Nakada, 2018), and their profiles and synesthetic sensations are described in detail in Table 1 and Fig. 4.

All participants were undergraduate students at the University of Niigata, Japan, and all were native Japanese speakers. The study was carried out in accordance with the human research guidelines of the Internal Review Board of the University of Niigata, and all participants provided written informed consent before participating in the study.

2.2. AP test

The AP ability of participants was evaluated by a previously described AP test (Itoh et al., 2005), where the participants vocally reported the pitch class name of 60 chromatic scale notes, presented randomly in sequence with a stimulus onset asynchrony (SOA) of 5 s. The sounds were generated by a tone generator (MU100, YAMAHA, Hamamatsu, Japan) using a piano timbre, and the sequence of test tones was digitally recorded and played back through a loud speaker. All notes (both white-key notes and black-key notes) were used for analyses. The answers had to be exactly correct; no semitone errors were permissible.

Critical steps were taken to prevent the use of relative pitch. First, no reference tone was presented at any point of the test, and feedback on the correctness of the participants' responses were not provided. Therefore, the participants had to use their own internal long-term memory for pitch to identify the pitch class names. Second, the sequence of the test tones was randomized, to make the use of relative pitch difficult. Finally, the inter-trial interval was set relatively short. The SOA was 5 s and the duration of the test sounds was approximately 1 s long; therefore, the answers had to be reported within a response time window of approximately 4 s. The procedure was equivalent to that of an established AP test, which has been developed and used extensively by Miyazaki and coworkers (Itoh, Miyazaki, & Nakada, 2003; Itoh & Nakada, 2018; Itoh et al., 2005; Miyazaki, 1990, 2000).

The chance-level performance of the AP test was 8% correct, and the participants' AP test scores were 87%, 98%, 100%, 83%, 100%, 85%, 23%, 38%, 45%, and 42% correct for participant numbers 7, 8, 9, 10, 11, 12, 19, 29, 30, and 33, respectively, as shown in Table 1 in Itoh & Nakada (2018). Thus, the participants displayed varying levels of AP, which was suitable for investigating the effects of AP on pitch class-color synesthesia.

2.3. Procedure

The seven solfège syllables representing the notes of the C major scale (*do*, *re*, *mi*, *fa*, *sol*, *la*, and *si*) were presented visually in the form of Japanese katakana scripts, randomly in sequence and in font colors that were either congruent (50% of trials) or incongruent with the participant's synesthetic color sensations. The colors were customized for each participant based on a color selection test that was obtained prior to this experiment. In the color selection test, participants selected one color for each of the seven pitch classes on a typical color-selection software running on a computer as previously described (Itoh & Nakada, 2018; Itoh et al., 2017). The red, green, and blue values of the selected colors were recorded, and these data were used to specify font colors in the Stroop experiment. The incongruent syllable-color combinations were obtained by randomly shuffling the normal (i.e., congruent) syllable-color pairings for that participant. All colors and pitch classes were equally presented. The order of trials was randomized without any constraint for the number of consecutive congruent (or incongruent) trials.

There were two tasks, the Syllable and Color tasks, and their order was randomized across participants. In the Syllable task, participants simply read aloud the solfège syllable that was presented on a computer screen, while ignoring the font color. In the Color task, participants reported the font color of the stimulus, while ignoring the pitch class name information. The specific color word (i.e., red, blue, green, etc.) to be used for each font color was determined by each participant prior to performing the tasks. The number of trials was 10 for each pitch class, five congruent and five incongruent. There were 70 trials in each task as there were seven pitch classes.

The experiments were conducted using Presentation software (Neurobehavioral Systems, Berkeley, CA) running on a computer that was connected to a cathode ray tube monitor (SONY G520, Tokyo, Japan).

In both tasks, participants were asked to respond as fast as possible by voice, and reaction times (RTs) were measured using voice onsets. The voice onset was measured using the "Sound Response Device" function of Presentation software, in which a voice input was registered as a response when its magnitude exceeded the preset threshold that was adjusted before the experiment for each participant. For each participant and task, the median RT was obtained separately for congruent and incongruent conditions, using only correctly responded trials. Accuracy was measured in terms of the percentage of correct responses. In the Color task, a response was considered correct when the reported color matched the participant's earlier report of synesthetic color sensation that was obtained in the color selection task.

2.4. Statistical analyses

The RT and accuracy data were analyzed using an analysis of variance (ANOVA) as described below, using SPSS Statistics version 25 (IBM, Armonk, NY, USA). The effect sizes are shown in terms of partial eta squared (η_p^2) or Cohen's *d*.

3. Results

3.1. RT

The RT data for all individual subjects and all conditions are shown in Fig. 1A. In the Color task, the mean (± standard error of mean, s.e.m.) RT for the congruent and incongruent trials was 632 (± 28) ms and 688 (± 24) ms, respectively. In the Syllable task, the mean (± s.e.m.) RT was 392 (± 13) ms in the congruent condition and 387 (± 11) ms in the incongruent condition.

These data were analyzed with a two-way repeated-measures ANOVA using the factors "Task" (Syllable task versus Color task) and "Congruency" (congruent versus incongruent). The Task × Congruency interaction was significant, $F(1, 9) = 11.1$, $p = 0.009$, $\eta_p^2 = 0.55$, indicating that congruency of the stimulus affected the RT differently between the two tasks. In the Color task, the main effect of Congruency was significant, $F(1, 9) = 8.7$, $p = 0.016$, $\eta_p^2 = 0.49$, indicating a Stroop-like interference effect. In the Syllable task, the main effect of Congruency was not significant, $F(1, 9) = 2.0$, $p = 0.191$, $\eta_p^2 = 0.18$, indicating that there was no "reverse" effect. The effect size of the interference in terms of Cohen's *d* was 0.67 in the Color task and 0.15 in the Syllable task.

In terms of the preconditions for performing an ANOVA, the RT data in all four conditions were found to be consistent with a normal distribution (one sample Kolmogorov-Smirnov test, $p > 0.05$), but the variances were greater in the Color task than in the Syllable task, as depicted in Fig. 1A. Therefore, the above statistical results should be interpreted with caution.

Nevertheless, similar findings were obtained using a nonparametric approach. The Wilcoxon signed-rank test revealed that the effect of congruency was significant in the Color task ($Z = 2.7$, $p = 0.007$), but not in the Syllable task ($Z = 1.1$, $p = 0.24$). The effect size of the interference in terms of *r*, which was calculated from the *Z* statistic by the method by Rosenthal (1991), was 0.60 for the Color task and 0.25 for the Syllable task.

3.2. Accuracy

The accuracy data are shown in Fig. 1B. In the Color task, the mean (± s.e.m.) percentage of correct responses for the congruent and incongruent trials were 99.0% (± 0.2) and 98.1% (± 0.6), respectively. In the Syllable task, the mean (± s.e.m.) was 100.0% (± 0.0) in the congruent condition and 99.9% (± 0.1) in the incongruent condition.

The ANOVA revealed that the main effect of Task was significant, $F(1, 9) = 19.6$, $p = 0.003$, $\eta_p^2 = 0.64$, indicating that there were more errors in the Color task (98.4% correct) than in the Syllable task (99.9% correct). The effect of Congruency was not significant, $F(1, 9) = 3.8$, $p = 0.085$, $\eta_p^2 = 0.29$, and the Task × Congruency interaction was also not significant, $F(1, 9) = 1.8$,

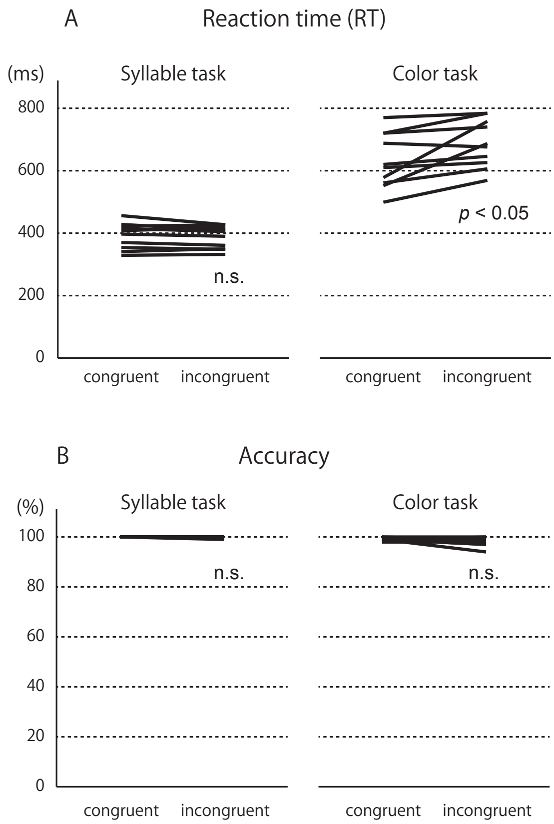

Fig. 1. Behavioral results. Reaction time (RT) data reveal a significant Stroop effect in the Color task, but no reverse Stroop effect in the Syllable task (A). There was no evidence for a Stroop interference in the accuracy measure, likely due to a ceiling effect (B). Each line represents a single participant.

$p = 0.120$, $\eta_p^2 = 0.17$. Thus, a Stroop-like interference was not statistically significant in the accuracy measure, likely due to a ceiling effect.

Regarding the preconditions for performing an ANOVA, the one sample Kolmogorov-Smirnov test indicated that the accuracy data for the incongruent condition in the Color task were consistent with a normal distribution, $p > 0.05$, but not in the other three conditions. The variances were also not homogeneous, as illustrated in Fig. 1B. Therefore, the ANOVA findings should be interpreted with caution.

Similar findings were obtained with a nonparametric approach. The Wilcoxon signed-rank test revealed that the effect of congruency was not significant in the Color task ($Z = 1.6$, $p = 0.102$) or in the Syllable task ($Z = 1.0$, $p = 0.317$). Thus, a Stroop-like effect was not statistically significant in the accuracy measure, even when a nonparametric approach was taken.

3.3. Effects of AP

To examine the effects of AP on the automaticity of pitch class-color association, the size of Stroop-like interference, expressed as the difference in RT between incongruent and congruent trials, denoted ΔRT, was plotted against the level of AP of the participants (Fig. 2). The Pearson correlation coefficient between ΔRT and AP was -0.092, $p = 0.401$, indicating a marginal correlation.

4. Discussion

The present study employed the Stroop paradigm to demonstrate the automaticity of pitch class-color association in pitch class-color synesthetes. A clear Stroop-like effect was demonstrated, in that the speed of reporting the font color of a pitch name syllable was delayed when the font color was incongruent with the synesthetic sensation. According to the automaticity account of Stroop interference, the result is interpreted as indicating that the less automated process of naming the color of a font was interfered by the more automated process of pitch name-to-color association (MacLeod, 1991). This finding is consistent with our previous conclusion that colors are associated with verbal labels of pitch classes, rather than pitch, in pitch class-color synesthesia (Itoh et al., 2017). The "reverse" Stroop effect was absent, as the speed of reading the pitch name syllables was not significantly affected by font color. Thus, the synesthetic association between pitch class names and colors was asymmetric or unidirectional, with the pitch class-to-color association being more automated than the color-to-pitch name association.

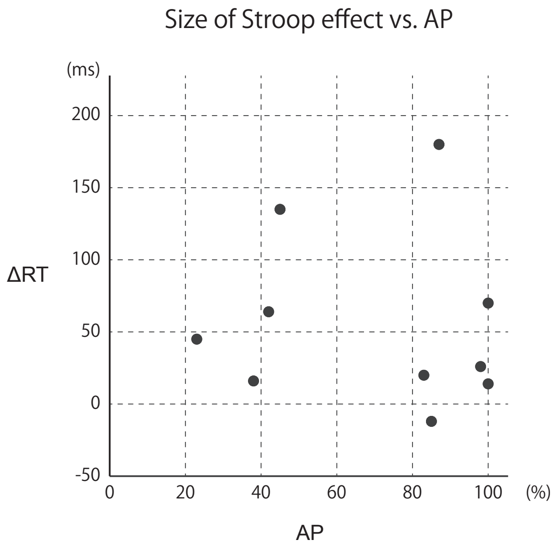

Fig. 2. The size of the Stroop effect, as measured by the difference in RT between incongruent and congruent trials (ΔRT), was not correlated with the level of AP.

Pitches evoke color sensations in two steps in listeners with pitch class-color synesthesia. The pitch class of the musical sound is first identified by its name, and then the pitch class name is associated with its color (Itoh & Nakada, 2018; Itoh et al., 2017). In the context of this "two-step hypothesis," the second step of pitch class name-to-color association represents the defining feature of pitch class-color synesthesia, whereas the first step of pitch class identification represents a general musical ability (Itoh & Nakada, 2018). This experiment presented pitch class names in the form of scripts, to focus on the second step of pitch class name-to-color conversion without being confounded by the effects of pitch information. A clear Stroop-like effect was observed, providing convince evidence for automaticity of the second step.

Notably, AP did not affect the size of the Stroop-like interference, corroborating the two-step hypothesis that two separable brain functions underlie the pitch-to-color conversion: a musical function of pitch class identification and pitch class-color association (Itoh & Nakada, 2018). We have previously shown that although AP facilitates the first step of pitch class identification, it does not influence the second step of associating colors with pitch class names (Itoh & Nakada, 2018). Hence, the small effect size ($r = -0.092$) of the influence of AP on the Stroop-like effect was reasonable; however, due to the small sample size of this study, we would not consider the lack of statistically significant correlation in the present study a definitive finding.

Given the observed automaticity of pitch class-to-color conversion in the second step, whether a musical sound automatically evokes color sensations in pitch class-color synesthetes depends on whether the first step of pitch-to-pitch name conversion is automatic. There are two brain strategies for identifying the pitch class of a musical sound: the use of either AP or relative pitch (Itoh et al., 2005). Relative pitch is the musical ability to identify the pitch class of a note by identifying the interval between that note and a given reference note. Pitch naming using AP is fast and automatic, whereas that using relative pitch is slow and requires intentional effort (Itoh et al., 2005; Miyazaki, 2000; Takeuchi & Hulse, 1993). Therefore, it is likely that pitches evoke automatic color sensations in possessors of AP but not in non-possessors, although future experiments are needed to confirm this prediction.

Due to the rarity of synesthesia, the number of participants in this experiment was small, which was a limitation of this study. However, the effect size of the Stroop-like interference was large (Cohen's $d = 0.67$), which enabled us to detect a statistically significant effect with a limited sample size. Alternatively, the conclusion that there was no reverse Stroop-like effect, which had a Cohen's d of 0.15, remains tentative. It is possible that future studies using larger sample sizes reveal a small, but significant, reverse Stroop-like effect. Nevertheless, the relative size of the Stroop-like effect and the reverse Stroop-like effect differed, suggesting that the pitch class-to-color association was more automated than the color-to-pitch class association.

Finally, we note that the term "automaticity" may have alternative meanings in various literature (Pashler, 1999; Price & Mattingley, 2013). For example, the automaticity of synesthesia is linked to the presence of a neural circuit that is specialized for that (arguably lower level) sensation, similar to the way in which we perceive the color of light (Hubbard, Arman, Ramachandran, & Boynton, 2005; Nunn et al., 2002; Sperling, Prvulovic, Linden, Singer, & Stirn, 2006). However, behavioral experiments have indicated that the color sensation in grapheme-color synesthesia is "automatic" in a more limited sense, in that it is only an involuntary feeling of experiencing a color that occurs as a part of a controlled process, under the influence of selective attention (Mattingley, 2009; Price & Mattingley, 2013; Treisman, 2005). In the present study, the role of controlled processes on pitch class-color synesthesia remain uncertain as attentional demands were not explicitly controlled. As another source of potential confound, the participants likely noticed that they were being tested for their synesthesia. Nevertheless, this study provided the first convincing evidence that in a standard Stroop paradigm setting, pitch name is involuntarily converted to colors in pitch class-color synesthesia, even when such conversion is unnecessary and disadvantageous.

5. Conclusion

This experiment used a Stroop task to demonstrate that pitch class names are automatically associated with color sensations in pitch class-color synesthesia. Combined with our previous finding that confirmed the consistency of color sensations over time, multiple objective criteria establish pitch class-color synesthesia as a novel form of genuine synesthesia.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.concog.2019.04.001.

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