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Synaesthetic colour associations for Japanese Kanji characters: from the perspective of grapheme learning

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One of the fundamental questions about grapheme–colour synaesthesia is how specific associations between the graphemes and colours are formed. We addressed this question by focusing on the determinants of synaesthetic colours for Japanese Kanji characters (logographic characters) using a psycholinguistic approach. Study 1 explored the influence meaning has on synaesthetic colours for Kanji characters representing abstract meanings by examining synaesthetic colours for antonym pairs (i.e. characters with meanings opposed to each other) in Japanese synaesthetes. Results showed that semantic relations influenced the grapheme–colour associations for characters representing abstract meanings in the early stages of learning abstract Kanji, while the influence was reduced in the grapheme–colour associations for those learned later. Study 2 examined the effect that learning new sounds or meanings of graphemes has on synaesthetic colours for those graphemes. Japanese synaesthetes were taught new sounds or new meanings for familiar Kanji characters. Results indicated that acquiring new information for graphemes slightly but significantly reduced the test–retest grapheme–colour association consistency, suggesting that synaesthetic colours can be modulated to reflect the synaesthete's latest knowledge about graphemes. Implications of these findings are discussed from the perspective of the relationship between synaesthesia and grapheme learning.

This article is part of a discussion meeting issue 'Bridging senses: novel insights from synaesthesia'.

1. Introduction

Despite its long research history, grapheme–colour synaesthesia, a condition in which a visual letter or character (grapheme[1]) induces a specific colour sensation, still remains a complex mystery. It is a multifaceted phenomenon [4,5], and there are several fundamental questions yet to be addressed: for example, why do only some people have grapheme–colour synaesthesia (i.e. genetic and environmental predisposition, e.g. [6,7], cf. [8])? How are the specific associations between the inducer (i.e. graphemes) and the concurrent (i.e. colours) formed (e.g. [9–15])? What kind of perceptual/cognitive processing occurs when experiencing synaesthetic associations (e.g. [16–19])? What is the neural basis of it (i.e. the brain structure and functioning, e.g. [19–22])? How is it related to other perceptual/cognitive abilities and traits (e.g. [23–25])?

This article addresses the second question above, namely, how synaesthetic grapheme–colour associations are formed. Although synaesthesia has been characterized as idiosyncratic (i.e. graphemes do not elicit the same colour in different individuals) [14,26], a number of regularities in the synesthetic experience have also been reported. Such regularities provide important clues for clarifying mechanisms underlying synaesthesia. Previous studies have shown

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that psycholinguistic factors, such as grapheme frequency or familiarity [11,27,28], visual shape [12,15,29], grapheme sound [9–11,30], positions in a grapheme sequence (ordinality, [11,15,28,31]), and meaning or concepts [10,13,32], contribute to forming the synaesthetic colours for graphemes, suggesting that grapheme–colour synaesthesia is a fundamentally psycholinguistic phenomenon.

However, further accumulation of data is needed to fully reveal the relationship between grapheme–colour synaesthesia and psycholinguistic processing. For example, some studies have revealed that synaesthetic grapheme–colour associations are influenced by meaning. Asano & Yokosawa [10] showed that synaesthetic colours elicited by Kanji characters (characters of Japanese logographic script) representing a concrete meaning or an object with typical colours, such as 'red', 'blood' and 'cherry blossoms', are likely to be very consistent with the meaning. Similarly, Mankin & Simner demonstrated that synaesthetic colours for English alphabets can be predicted in part by early-learned letter–word associations—for example, the synaesthetic colour for the letter 'A' tends to be red because A is for apple and apples are typically red ([13]; but also see [31] which suggests that this effect may be language-specific). However, this type of semantic account can be applied only to graphemes that are tied to concrete meanings. Little is known about whether meaning influences synaesthetic colours for graphemes that are tied to abstract meanings.

The relationship between grapheme–colour synaesthesia and grapheme learning also needs to be elaborated. Given that synaesthetic colours are determined by some features of graphemes (e.g. psycholinguistic attributes such as sound, meaning, ordinality, frequency, visual shape and so on), and knowledge about graphemes may be updated by acquiring new knowledge or by learning a new language, does acquiring new knowledge about graphemes modulate the synaesthetic colours for the graphemes? It has been pointed out that grapheme–colour synaesthesia is profoundly connected with grapheme learning [11,15,33]. Synaesthetic colours, which are determined by some features of graphemes, may serve as a memory aid and help grapheme learning, especially in a synaesthete's childhood, in which he/she must learn many graphemes with effort [11,15,33]. Some studies have provided models and empirical data that support this idea. Asano & Yokosawa [11] proposed a model predicting that the feature domain (e.g. sound, visual shape, ordinality) making the largest contribution to discriminating the grapheme from others has the largest impact on synaesthetic grapheme–colour associations. For example, ordinality information (positions in a grapheme sequence) may be useful in discriminating among letters of the English alphabet because there are one-to-one ordinality–grapheme correspondences, while sound may not be useful because the English alphabet is an opaque writing system (i.e. many-to-many grapheme–sound correspondences); in this case, the model predicts that synaesthetic colours for the English letters are strongly affected by ordinality but not sounds. Asano and Yokosawa successfully tested the model through an experiment. The results showed that English letters with similar ordinality, but not those with similar sounds, tended to elicit similar synaesthetic colours, whereas in the case of Japanese Hiragana, which form a strictly transparent writing system (i.e. one-to-one grapheme–sound correspondences), characters representing similar sounds elicited similar synaesthetic colours [11]. Watson *et al*. [33] revealed that the prevalence of synaesthesia tends to be higher in a linguistic environment where people face greater childhood language learning challenges (i.e. the language has an opaque writing system, or many people learn non-native second languages in their childhood). However, it has not been investigated whether synaesthetic colours can be updated when new knowledge about graphemes is acquired; rather, it is usually emphasized that synaesthetes are highly consistent over time in their grapheme–colour associations [34,35]. As noted above, various features of graphemes can affect synesthetic grapheme–colour associations. Changes in the impact of such factors on synaesthesia through language learning (e.g. whether the degree of impact of a factor can be changed along with the maturation of the mental lexicon) can also be of research interest.

In this article, we address these issues using grapheme–colour synaesthesia in the Japanese language. In Study 1, we investigated whether meanings, specifically, the semantic relations between graphemes, influence the synaesthetic colours for graphemes representing abstract meanings. In Study 2, we explored the effect of learning new sounds or meanings for familiar graphemes. A script of the Japanese language, Kanji, is suitable for investigating these issues. The Japanese language has three types of scripts: Hiragana, Katakana and Kanji. Hiragana and Katakana are phonetic scripts, which mean that characters of the scripts represent sounds. Hiragana and Katakana represent the same set of sounds or syllables. Hiragana is mainly used for function words and words in the native Japanese lexicon; by contrast, Katakana is primarily used for words borrowed from another language. Kanji is a logographic script; that is, each character has a meaning. Kanji is used for most of the content words in the Japanese lexicon. Thus, over 2000 characters are used in daily life. These characters are gradually introduced during an individual's development. By the ages of 4–6, most Japanese children can read Hiragana characters. Katakana characters are introduced somewhat later, at around the ages of 6–7. People typically start learning Kanji characters in the first year of primary school, that is, at around the ages of 6–7. Then they master at least 2136 characters by around the age of 15 and continue learning new Kanji characters until adulthood (see [10], for a more detailed introduction to the Japanese scripts). These characteristics of the Japanese language enable a unique examination of the influence of several psycholinguistic factors on grapheme–colour associations within a language. The fact that Hiragana and Katakana characters share sounds but not visual shapes enabled us to isolate the effects of sounds from those of shapes [9]. We also found that visually and semantically different Kanji characters with the same sound are coloured similarly, suggesting that sound is also a determinant of synaesthetic colours for Kanji characters [10]. Character meaning is a strong determinant of synaesthetic colours for Kanji characters, too. The Kanji character representing 'red' (赤) typically elicits the colour red. The Kanji character representing 'cherry blossoms' (桜) is typically associated with light pink, which is just like the colour of cherry blossom petals [10] (see also [2,36] for synaesthetic colour associations in the Chinese language, which also uses a logographic writing system). There are also Kanji characters representing abstract meaning such as 'east' (東) and 'public' (公) in the Japanese language, some of which we used for the investigation of the influence of abstract character meaning on synaesthetic colours in Study 1. In Study 2, we used the fact that Japanese Kanji characters were originally imported from China. We taught Japanese synaesthetes the Chinese sounds or meaning for the Kanji characters, which are different from those in Japanese, and examined whether acquiring such new knowledge affected the synaesthetic colours for the graphemes.

2. Study 1

In Study 1, we explored whether meaning influences synaesthetic colours for Kanji characters with abstract meanings. We hypothesized that synaesthetic colours reflect semantic relations. To test this hypothesis, it would be useful to compare the synaesthetic colours for characters in semantically distant relations and examine whether the synaesthetic colours are also distant from each other. Therefore, we used antonym characters, that is, characters that are opposite in meaning to each other (e.g. 'up' and 'down'), as stimuli. We predicted that antonym character pairs would elicit synaesthetic colours that are dissimilar to each other.

(a) Methods

(i) Participants

Sixteen grapheme–colour synaesthetes (13 female, 3 male, mean age = 25.5 years, range = 20–42 years) and 16 non-synaesthetes (8 female, 8 male, mean age = 21.1 years, range = 20–24 years) participated in this experiment. All were native Japanese speakers.

All the synaesthetes reported experiencing synaesthetic colours when viewing Kanji characters as well as Hiragana and Katakana characters, English alphabets and Arabic numerals. All of the synaesthetes had previously participated in a test in which test–retest consistency of their synaesthetic colour associations for 46 Hiragana characters were measured (mean interval between the first and second synaesthetic colour measurement = 31.4 weeks, s.d. = 26.8 weeks). In the measurements, 138 named W3C (World Wide Web Consortium) colours (see Study 1 Apparatus) were used for the synaesthetic colour selection. The average distance between the colours (e.g. Euclidean distance using CIE $L^*a^*b^*$ coordinates; cf. [35]) selected for a given character in the first and second measurement, averaged over the 46 Hiragana characters, was 21.7 (s.e. = 1.3). This value is strikingly small, given that the analogous value obtained from six non-synaesthetic controls who engaged in the same task using free association or any other strategy of their choice with a two-week interval between the two measurements was 62.3 (s.e. = 7.2) [9], demonstrating that the synaesthetic participants engaged in this study were genuine synaesthetes. Nine of the 16 synaesthetes were 'projectors', who report experiencing synesthetic colours in external space, and the remaining seven were 'associators', who report experiencing synesthetic colours 'in the mind's eye' [37]. All the non-synaesthetic participants in this study reported never experiencing synaesthetic colours for any kind of graphemes.

(ii) Apparatus

Stimulus characters and a colour palette were displayed on a computer screen (Mitsubishi Diamondtron M2 RDF223G). One hundred and thirty-eight named W3C colours were in the palette [9,11]. The locations of the colours in the palette were fixed across trials. See electronic supplementary material, figure S1 for a screenshot of the palette. Synaesthetes were told to select the colour black if a presented character elicited a sensation of the colour black or no synaesthetic colour; no synaesthetes reported having selected the colour black to indicate 'no colour' in an interview after the experiment. Colour coordinates in the CIE $L^*a^*b^*$ systems, used in analyses of the results, were converted from the CIE xyY coordinates of presented colours; all were measured using a Topcon BM-7 luminance colourimeter. We adopted the CIE $L^*a^*b^*$ system because it was designed in such a way that mathematical differences in all colour ranges correspond to perceived colour differences; in other words, it is perceptually uniform [35]. The average colour distance for random colour pairs from the 138 colours on the palette was 67.9. Here, we regard this value as the chance level.

(iii) Stimuli

Thirty-six Kanji antonym pairs were used as stimuli. The pairs were separated, shuffled and presented one by one in a random order; that is, participants were presented with 72 single Kanji characters. The 36 antonym pairs were selected from various semantic categories to increase the diversity of the stimuli: eight related to space (e.g. 右 'right'–左 'left', 高 'high'–低 'low'), six related to physical properties of objects (e.g. 大 'large'–小 'small', 有 'present'–無 'absent'), six related to emotion and values (e.g. 楽 'fun'–苦 'hard', 愛 'love'–憎 'hatred'), six related to human behaviour (e.g. 売 'sell'–買 'buy', 攻 'offence'–守 'defence'), five related to time (e.g. 春 'spring'–秋 'autumn', 新 'new'–旧 'old') and the remaining five related to human-related concepts (e.g. 男 'man'–女 'woman', 公 'public'–私 'private'). The characters varied by the age of grapheme acquisition, namely the school grades in which the characters are taught in Japan, which is regulated by the curriculum guidelines provided by the Ministry of Education, Culture, Sports, Science and Technology in Japan. Children in the first grade are 6–7 years old in Japan. See electronic supplementary material, table S1 for the full list of the stimulus antonym pairs. Selecting characters from various acquisition ages not only increased the diversity of the stimulus characters but also allowed us to examine the relationship between acquisition age and the influence size of semantic relations on synaesthetic colours (see Study 1 Discussion).

(iv) Procedure

Participants selected a colour from the palette corresponding to each of the 72 Kanji characters, presented one by one in random order. Each character was presented only once. Non-synaesthetes were asked to select a colour that 'intuitively goes with' each grapheme.

(b) Results

(i) Comparison with the chance level

Figure 1*a* presents examples of the colours selected by synaesthetes and non-synaesthetes for some of the stimulus antonym pairs. Colour distance for antonym pairs, averaged over the 16 synaesthetes and 16 non-synaesthetes, respectively, is plotted against the school grades in figure 1*b*,*c*.

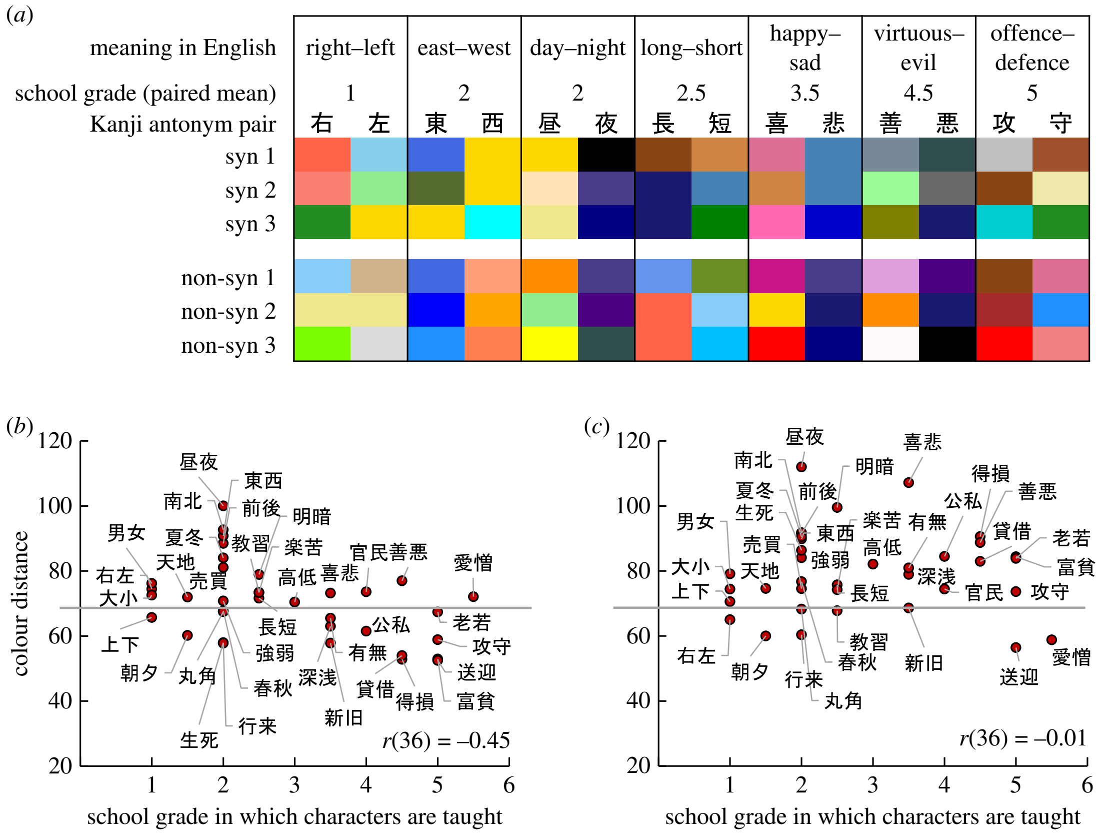

Figure 1. Results of Study 1. (*a*) Examples of colours associated with Kanji antonym pairs by three synaesthete (syn) and three non-synaesthete (non-syn) participants. (*b*,*c*) Colour distance for antonym pairs, averaged over the 16 synaesthetes (*b*) and 16 non-synaesthetes (*c*), is plotted against the school grades (paired mean). The horizontal line in (*b*,*c*) indicates the chance level of 67.9.

To assess whether antonym character pairs elicited colours that were dissimilar to each other, we calculated the mean Euclidean distance in the CIE $L^*a^*b^*$ colour space between colours selected for a given pair of antonym characters and compared it to the chance level (67.9) using a one-sample *t*-test (two-tailed). The statistical effects of multiple comparisons were controlled by using false discovery rate [38]. The results for synaesthetes revealed that only one pair was significantly more distant than the chance level (昼 'day'–夜 'night': $t_{15} = 4.11$, $p < 0.01$, $d = 1.03$). The same analysis for non-synaesthetes revealed that five pairs were significantly more distant than the chance level (南 'south'–北 'north': $t_{15} = 3.51$, $p < 0.01$, $d = 0.88$; 昼 'day'–夜 'night': $t_{15} = 5.42$, $p < 0.01$, $d = 1.36$; 生 'alive'–死 'dead': $t_{15} = 3.39$, $p < 0.01$, $d = 0.85$; 明 'bright'–暗 'dark': $t_{15} = 4.88$, $p < 0.01$, $d = 1.22$; 喜 'happy'–悲 'sad': $t_{15} = 4.54$, $p < 0.01$, $d = 1.13$).

To summarize, synaesthetes associated significantly dissimilar synaesthetic colours only for one out of the 36 antonym character pairs. Non-synaesthetes tended more to associate distant colours to antonym pairs. A *t*-test comparing the mean colour distances (averaged over the 32 antonym pairs) for synaesthetes and non-synaesthetes revealed that non-synaesthetes selected more distant colours for antonym pairs in general than synaesthetes ($t_{30} = 3.10$, $p < 0.01$, $d = 0.13$). Non-synaesthetes, who do not experience colours for graphemes, may have relied more on conventional images of the contrastive character meanings when they were asked to associate a colour to each Kanji character.

(ii) Effects of the school grades in which characters are taught

By plotting the colour distances for antonym pairs against the paired means of the school grades in which the characters are taught (figure 1*b*,*c*), we found an interesting trend: a negative correlation between colour distances for antonym character pairs and the school grades in the case of synaesthetes ($r_{36} = -0.45$, $t_{34} = 2.94$, $p < 0.01$). Negative correlations between colour distances and school grades mean that antonym character pairs learned earlier in life elicited synaesthetic colours that were more dissimilar. This result suggests that semantic relations influenced the grapheme–colour associations for characters representing abstract meanings in the early stages of learning abstract Kanji, while the influence was reduced in the grapheme–colour associations for those learned later. Interestingly, we did not observe a negative correlation in the case of non-synaesthetes ($r_{36} = -0.01$, $t_{34} = 0.03$, $p = 0.97$).

The apparent effects of school grades, however, could have resulted from various factors other than the age of grapheme acquisition, such as sound, shape and the concreteness of the meaning represented by the characters (cf. [9–11,15]). Data were therefore entered into a hierarchical regression analysis to test the relative contribution of school grade to the colour distances for antonymous Kanji character pairs, while controlling for sound similarity between the first syllable of the most typical reading of the characters (identified using [39]) comprising each antonym pair, subjective visual similarity between the antonym character pairs (rated by six Japanese-speaking adults on a five-point scale) and the paired mean of the subjective concreteness of the character meaning (based on [40]). See electronic supplementary material, table S2 for the details of these variables. Participant group (synaesthete = 1; non-synaesthete = 0), school grade (paired mean), sound similarity, visual similarity and concreteness were entered into Step 1 of the regression model, and the interaction of participant group and grade in Step 2. The VIF (variance inflation factor) values were all below 1.3, indicating that multi-collinearity was not an issue. All variables were centred to the mean by subtracting the group mean value from individual values. The Step 1 model was significant ($R^2 = 0.18$, adjusted $R^2 = 0.12$, $F_{5,66} = 2.87$, $p < 0.05$). Participant group was the only significant predictor of the colour distances for antonym character pairs ($\beta = -0.36$, $t_{66} = 3.23$, $p < 0.01$). The addition of the interaction of participant group and grade marginally significantly improved the model ($\Delta R^2 = 0.04$, $\Delta F_{1,65} = 3.20$, $p = 0.08$). The interaction marginally significantly predicted the colour distances for antonym pairs ($\beta = -0.20$, $t_{65} = 1.79$, $p = 0.08$), suggesting that school grade differentially affected colour distances between synaesthetes and non-synaesthetes even when controlling for the effects of sound, visual shape and concreteness. A simple slope analysis to examine the marginally significant interaction showed no effect of group in lower school grades (−1 s.d. grade; $\beta = -0.16$, $t_{65} = 1.04$, $p = 0.30$), but did show a significant negative relationship between group and colour distance for antonym pairs (i.e. smaller distances in synaesthetes) in higher school grades (+1 s.d. grade; $\beta = -0.56$, $t_{65} = 3.58$, $p < 0.01$). The overall results indicate that synaesthetes and non-synaesthetes associated equally dissimilar colours with antonym pairs learned in lower school grades, while synaesthetes associated less dissimilar colours than did non-synaesthetes with those learned in higher school grades.

To analyse the factors influencing colour distances for antonym pairs in synaesthetes in detail, we further conducted a two-step hierarchical regression analysis of the colour distances for antonym pairs for synaesthetes. The predictors were school grade, sound similarity, visual similarity and concreteness (Step 1) and all two-way interactions (Step 2). Only the Step 2 model was significant ($R^2 = 0.48$, adjusted $R^2 = 0.27$, $F_{10,25} = 2.30$, $p < 0.05$). The results showed that school grade ($\beta = -0.67$, $t_{25} = 3.32$, $p < 0.01$), interaction of grade and sound similarity ($\beta = -0.82$, $t_{25} = 2.85$, $p < 0.01$), and interaction of sound similarity and concreteness ($\beta = -0.88$, $t_{25} = 2.70$, $p < 0.05$) were significant predictors of the colour distances for antonym character pairs. A simple slope analysis to examine the interaction of grade and sound similarity showed a significant negative relationship between grade and colour distance for antonym pairs with similar initial sounds (+1 s.d. sound similarity; $\beta = -1.45$, $t_{25} = 3.57$, $p < 0.01$), but no effect of grade for those with dissimilar initial sounds (−1 s.d. sound similarity; $\beta = 0.11$, $t_{25} = 0.43$, $p = 0.67$). These results suggest that the effects of sound similarity were greater (i.e. antonym character pairs with similar sounds tended to elicit more similar colours) in higher school grades. A simple slope analysis to examine the interaction between sound similarity and concreteness showed a significant negative relationship between concreteness and colour distance for antonym pairs with similar initial sounds (+1 s.d. sound similarity; $\beta = -0.73$, $t_{25} = 2.30$, $p < 0.05$), and a significant positive relationship between the two for those with dissimilar initial sounds (−1 s.d. sound similarity; $\beta = 0.69$, $t_{25} = 2.14$, $p < 0.05$). This interaction was unexpected and difficult to interpret. Our initial question of Study 1 was whether synaesthetic colours reflect semantic relations, therefore, the experiment was not designed to examine complex interactions between various grapheme properties. Future research is needed to clarify the interactions of concreteness and sound properties in synesthetic grapheme–colour associations.

(c) Discussion

Our initial simple prediction that dissimilar colours would be associated (in comparison with chance level) with antonym character pairs was not supported, as colours associated with only 1 out of 36 antonym pairs was significantly more distant than chance level in the synaesthete group. Indeed, the way semantic relations affect grapheme–colour associations was more complex. Further analyses revealed that antonym character pairs that were learned in lower grades elicited synaesthetic colours that were more dissimilar to each other. That is, semantic relations affect synesthetic colours in the early stages of learning abstract Kanji, and the impact of semantic relations decreases later. This tendency was unique to synaesthetes; non-synaesthetes generally associated contrastive colours to antonyms, and the school grades at which the characters were learned did not affect the colour choices. Non-synaesthetes, who do not experience colours for graphemes, may have relied on conventional images of the contrastive character meanings when they were asked to associate a colour with each Kanji character (e.g. associating a bright colour with 善 'virtuous' and a dark colour with 悪 'evil'). The overall pattern of results remained after controlling for the effects of sound similarity and visual similarity of the characters comprising antonym pairs, and the concreteness of the character meaning.

We interpret the reduced effects of semantic relations on the antonym pairs that were learned in higher grades as follows: the results from previous studies indicate that synaesthetic colours for Japanese early-acquired characters (e.g. Hiragana) generalize to late-acquired graphemes via phonology and/or meaning (i.e. Kanji); for example, Kanji characters pronounced /shi/ (e.g. 視, 詩, 師) tend to elicit colours that are similar to those elicited by the Hiragana character representing the /shi/ syllable (i.e. し) [10,11]. This generalization suggests that synaesthetic colours for Kanji characters that are learned in higher grades are more likely to be affected by a variety of factors, and this may attenuate the influence of semantic relations. This possibility may be partly supported by the results of the hierarchical regression model with the data from synaesthetes, which suggest that the effects of sound similarity were greater in higher school grades.

One may wonder if the negative correlation between the school grades and the synaesthetic colour distance in synaesthetes could be attributed to possible qualitative differences between antonyms that are taught in lower and higher school grades, where those taught in lower grades are subjectively more contrastive in meaning. In order to address this concern, a measure of the subjective meaning distances between different antonym pairs (e.g. whether 'east–west' is subjectively more distant than 'offence–defence') is required. One possible method to obtain such a measure is latent semantic analysis (LSA), which is used in natural language processing to analyse relationships between words based on the assumption that semantically similar words should occur in similar contexts [41]. This intriguing method is, however, not suitable (at least in its current form) for measuring meaning distances between antonyms; it has long been a challenge to LSA to recognize antonyms since antonymous words tend to occur in similar contexts (cf. [42]). Thus, a direct test of this concern awaits future study. However, the results of the hierarchical regression model showing a greater impact of sound similarity in higher school grades in synaesthetes suggest that the effects of school grades could be attributed to developmental changes in how various factors affect synaesthetic colours, rather than to qualitative differences between antonyms that are taught in lower and higher school grades.

Previous studies on grapheme–colour synaesthesia have revealed the effect of meaning on synaesthetic colour selections [10,13,32]. For example, in the case of Japanese grapheme–colour synaesthetes, the synaesthetic colours elicited by Kanji characters representing colour names or names of objects with typical colours are usually very consistent with their meaning (e.g. the Kanji character meaning 'red' typically elicits red, and the character meaning 'cherry blossoms' typically elicits light pink). These findings made it difficult to determine whether synaesthetes merely associate general, conventional colour images of the character meanings (when possible) in the same way as non-synaesthetes do when they were asked to associate a colour to a character, or whether the meaning effects on grapheme–colour association in synaesthetes is qualitatively different from those in non-synaesthetes. The results of the current study support the latter possibility, as school grades differentially affected grapheme–colour associations between the two groups. Although meanings do affect grapheme–colour associations, for synaesthetes meaning is only one of a variety of psycholinguistic factors that affect synaesthetic colours.

3. Study 2

In Study 2, we explored the effect of learning new sounds or meanings for familiar graphemes. It is widely known that synaesthetes show remarkably high test–retest consistency in grapheme–colour associations [34,35]. However, knowledge about graphemes may be updated by acquiring new knowledge or by learning a new language. Does acquiring new knowledge about graphemes modulate the synaesthetic colours for the graphemes? To answer this question, we used the fact that Japanese Kanji characters were originally imported from China more than 1500 years ago. Although most of the modern Japanese Kanji characters are also used in the modern Chinese language as Chinese characters, many of them differ in sounds and meaning. We taught Japanese synaesthetes the Chinese sounds or meaning for the Kanji characters, which are different from those in Japanese.

For example, for the Kanji character 祖, which is pronounced as /so/ in Japanese, we taught the participants that in Chinese, this character is pronounced as /zǔ/. The character 坊 means 'monk' in Japanese, and we taught the participants that in Chinese, this character means 'town'. We predicted that acquiring new information about graphemes would affect their synaesthetic colours and lower the test–retest consistency.

(a) Methods

(i) Participants

Eleven grapheme–colour synaesthetes (9 female, 2 male, mean age = 21.3 years, range = 20–23 years) and 11 gender-matched non-synaesthetes (9 female, 2 male, mean age = 21.4 years, range = 20–23 years) participated in this experiment. All were native Japanese speakers, and none spoke or read Chinese.

All the synaesthetes reported experiencing synaesthetic colours when viewing Kanji characters as well as Hiragana and Katakana characters, English alphabets and Arabic numerals. We confirmed that synaesthetic participants engaged in this study were genuine synaesthetes based on test–retest consistency criteria in the same way as in Study 1. Five of the synaesthetic participants were projectors and the remaining six were associators [37]. All the non-synaesthetic participants in this study reported never experiencing synaesthetic colours for any kind of graphemes.

(ii) Apparatus

Stimulus characters and a colour palette were displayed on a computer screen (Mitsubishi Diamondtron M2 RDF223G). The palette included 256^3 colours (i.e. each of the RGB components ranged from 0 to 255). See electronic supplementary material, figure S1 for a screenshot of the palette. Colour coordinates in the CIE $L^*a^*b^*$ systems, used in analyses of the results, were converted from the CIE xyY coordinates of presented colours; all were measured using a Topcon BM-7 luminance colourimeter. We used a finer-grained colour palette in this experiment, when compared with those used in Study 1 (i.e. a 138-colour palette) to detect the possible modulation of synaesthetic colours, which could be subtle.

(iii) Stimuli

This experiment consisted of two task blocks: a new sound learning block and a new meaning learning block. In each block, participants were presented with six test Kanji characters for which new (i.e. Chinese) sounds/meanings were taught and six control Kanji characters for which no new information was taught. The full list of the stimulus characters is available as electronic supplementary material, table S3.

Test and control stimulus characters for sound learning task block. We prepared a set of 46 Kanji characters that are also used in the Chinese language as Chinese characters, but whose pronunciations are different between the two languages. The selection of the characters was supervised by a Chinese–Japanese bilingual, whose native language is Chinese and who speaks Japanese fluently. All of the 46 characters represent a single mora sound in the Japanese language. Based on the Japanese vocabulary database 'Nihongo-no Goi Tokusei' [39], characters that have only one highly typical reading were included in the stimulus set (i.e. these are characters with a one-to-one relationship between graphemes and phonemes in the Japanese language). All characters had moderate to high word familiarity ratings, 5.69 on average (range: 3.79–6.54), and low to moderate visual complexity ratings, 3.50 on average (range: 2.42–3.96), both on a scale that ranged from 1 to 7 (where higher values mean higher familiarity/visual complexity), in the Japanese vocabulary database [39]. Six of the 46 Kanji characters (可, 規, 個, 佐, 智, 斗) were used as control stimuli.

For each synaesthete, a different set of six test stimulus characters was selected from the remaining 40 characters. Asano & Yokosawa [10] revealed that, at least in some cases, character sound influences synesthetic colours for Kanji characters. Based on this, we hypothesized that learning a new sound for a Kanji character would modulate the synaesthetic colour for the character. A prerequisite for testing this hypothesis was that the synaesthetic colours for the test stimulus Kanji characters were influenced by their Japanese sounds before the learning session. To satisfy this prerequisite as much as possible, six test stimulus characters were selected using the following procedure: synaesthetic participants were individually asked to participate in a web-based pre-test by the day before they participated in the laboratory experiment. In the pre-test, they were asked to select a colour corresponding to each of the 40 characters, presented one by one in a randomized order, from a 138 named W3C colour palette. They were asked to select 'no colour' when they did not experience any synaesthetic colour for the given character. We used the 138-colour palette in the pre-test to reduce the requisite effort in selecting colours. Experimenters (authors T.T. and M.A.) then compared the synaesthetic colour (if any) for each of the 40 Kanji characters with that for the Hiragana character corresponding to the Japanese sound of the Kanji character (e.g. the synaesthetic colour for the Kanji character 祖, which is pronounced as /so/ in the Japanese language, was compared with the synaesthetic colour for the Hiragana character そ, which represents the sound /so/). If the two elicited similar synaesthetic colours, the two authors regarded that the synaesthetic colour for the Kanji character was largely determined by its sound and included the character as a test stimulus with high priority (note that synaesthetic colours for Hiragana characters are elicited by sound quality, [9]). If there were more than six such characters, characters with Chinese sounds that were more dissimilar to the corresponding Japanese sounds were given priority (e.g. 卯 [Japanese: /u/, Chinese: /mǎo/] had priority over 亜 [Japanese: /a/, Chinese: /yà/]). Characters with higher familiarity in the Japanese language also had higher priority.

Each non-synaesthetic participant was matched with one of the synaesthetic participants, and he/she was presented with the same set of stimulus characters as the paired synaesthete.

Test and control stimulus characters for meaning learning task block. Based on the Japanese vocabulary database [39], we first extracted Kanji characters with high (greater than or equal to 5) subjective familiarity ratings and middle to low (less than 4) visual complexity. From those, with the Chinese–Japanese bilingual's help, we sought characters with meanings in Japanese that are different from those in Chinese. We finally selected 12 such characters. Six of them had concrete meanings in both languages (e.g. 坊, Japanese meaning: 'monk', Chinese meaning: 'town'), and the remaining six had abstract meanings in both languages (e.g. 念, Japanese meaning: 'to wish', Chinese meaning: 'to read aloud'). Half of the characters (three with concrete and three with abstract meaning) were used as test stimuli and the other half were used as control stimuli. The same set of test and control characters were presented to all synaesthete and non-synaesthete participants.

(iv) Procedure

Each task block consisted of one learning session and two colour measurements: pre-learning and post-learning. The order of the two blocks were counter-balanced among synaesthete participants. Non-synaesthete participants were tested in the same block order as the paired synaesthetic participants.

In the pre-learning measurement, synaesthetes selected a synaesthetic colour from a 256^3 colour palette on a computer screen for each test and control stimulus Kanji character. Non-synaesthete participants were asked to select a colour that 'intuitively goes with' each character. The six test and six control characters were mixed and presented in random order. Each character was presented only once. Participants were also allowed to select a 'no colour' button if they felt it was appropriate to do so.

A learning session followed. In the beginning of this session, participants were told that they were going to learn Chinese sounds (in the new sound learning block) or meaning (in the new meaning learning block) for six Kanji characters (i.e. test stimulus characters). Participants were asked to learn the new information through writing and computer-based training and were tested on whether they had acquired the new knowledge about the graphemes with a paper and pencil assessment.

Specifically, in the new sound learning block, participants first listened to the sound of each test stimulus character, which was recorded by the native Chinese–Japanese bilingual, and were asked to write down on paper the sound as they heard it using Japanese phonetic Hiragana characters. In each trial of the following computer-based training, a fixation dot was presented in the centre of a computer screen for 1000 ms, followed by the visual presentation of a test stimulus character. Then, Chinese sounds of two characters, one of which was the correct sound of the visually displayed character, and the other was incorrect, were successively presented in random order 1000 ms after the onset of the character. Participants indicated which one (first/second) was correct by a key press. Feedback on the accuracy of the response was given. In order to lower the learning burden, the six test stimulus characters were split into two groups (three characters each) and computer-based trainings were conducted separately for the two character groups. At least 81 trials (at least 27 trials for each of the three characters) were conducted in each computer-based training session, and the training continued until 12 successive correct responses were made. After each computer session, participants were asked to write down again on paper the sounds of all three test stimulus characters from memory using Hiragana characters. After the second computer session, right after the paper test for the three characters in the session, participants were also tested on the sounds of all six stimulus characters. These paper tests served as confirmation of their newly acquired Chinese character sounds. No new information was taught for the six control stimulus characters during the learning session.

The learning session procedure in the new meaning learning block was the same as that in the new sound learning block, except that the new meanings were presented to participants as written words. Participants wrote down the new meanings (words) on paper in the first part of the learning session and in the last confirmation tests. In the computer-based training, a test stimulus character was presented above the centre of the screen, and the correct and an incorrect meaning were simultaneously added to the left or right bottom (randomly determined) of the screen 1000 ms after the onset of the character. Participants indicated which one (left/right) was correct by a key press.

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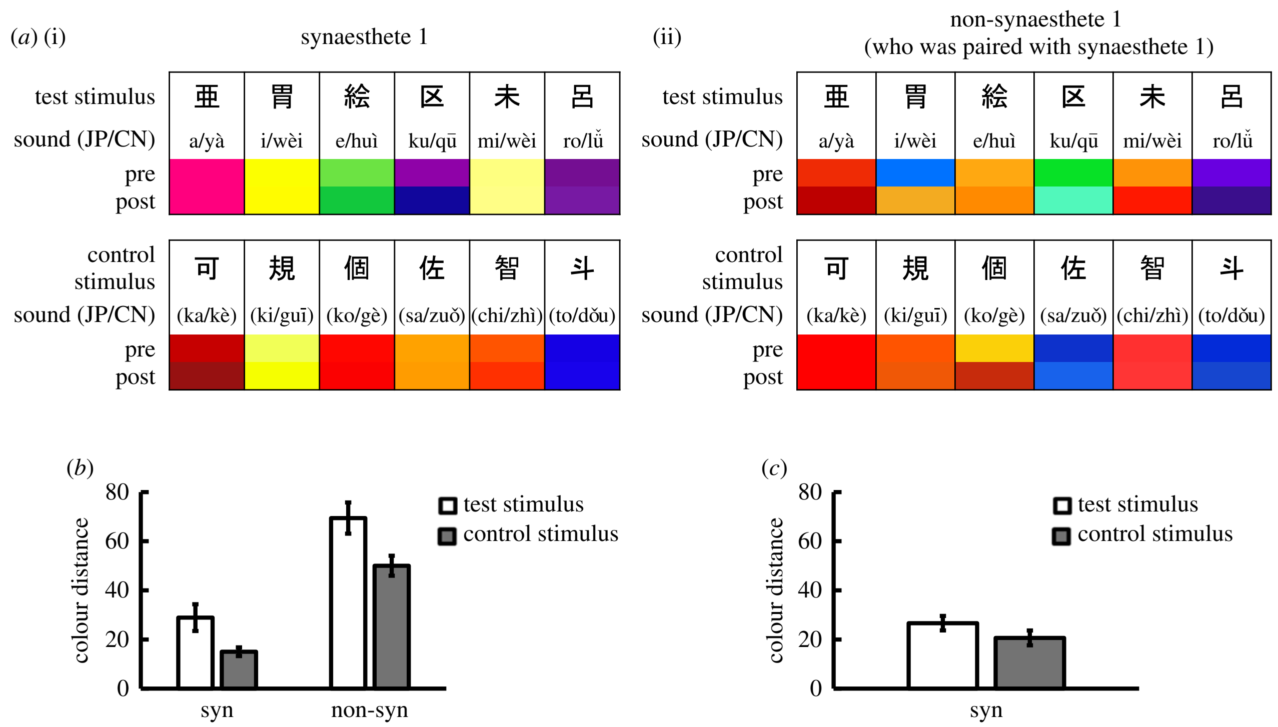

Figure 2. Results of Study 2. (*a*) Examples of colours associated with test and control stimulus characters in the new sound learning task by a synaesthete (i) and a paired non-synaesthete (ii) (JP, Japanese sound; CN, Chinese sound). Note that the new sounds of the control stimuli were not taught in the experiment. (*b*) Mean colour distance in the CIE $L^*a^*b^*$ colour space between the pre- and post-learning sessions in the main experiment (the data from new sound learning and new meaning learning tasks were combined). (*c*) Mean colour distance in the CIE $L^*a^*b^*$ colour space between the pre- and post-learning sessions in the control experiment. Error bars represent standard errors.

Incorrect sounds/meanings in the learning tasks were chosen as follows: in half of the trials, the incorrect meaning for the displayed character was chosen from the correct meanings for the other two characters that should be learned in the same learning task block. For example, in a task block in which Chinese meanings for 床 (Japanese meaning: 'floor', Chinese meaning: 'bed'), 机 (Japanese: 'table', Chinese: 'machine') and 坊 (Japanese: 'monk', Chinese: 'town'), the incorrect meaning in a trial with 床 was randomly chosen from either the Japanese word representing 'machine' (i.e. 機械) or 'town' (i.e. 街). In the other half of the trials, the incorrect meaning was randomly chosen from three Japanese words, each of which was semantically related to one of the three to-be-learned Chinese meanings. For example, when the to-be-learned Chinese meanings were 'bed', 'machine' and 'town', the incorrect meanings for this half of the trials were chosen from the three Japanese words representing 'sofa', 'parts (of a machine)' and 'country', respectively.

The training session was followed by the post-learning measurement, in which participants selected colours from a 256^3 colour palette on a computer screen for each of the six test and the six control stimulus Kanji characters. The procedures were exactly the same as those of the pre-learning measurement.

(b) Results

(i) Number of trials required to complete sound/meaning learning tasks

The mean number of trials required to complete a session in the sound and meaning learning tasks (averaged over the two sessions in each task) were 82.6 (s.d. = 4.4, range = 81.0–96.5) and 82.1 (s.d. = 3.4, range = 81.0–93.0), respectively, for synaesthetes, and 83.1 (s.d. = 4.0, range = 81.0–93.0) and 81.4 (s.d. = 1.3, range = 81.0–85.5), respectively, for non-synaesthetes.

(ii) Pre–post-learning colour consistency

No synaesthete selected the 'no colour' option. Two non-synaesthetes selected this option: one selected it 11 times (out of 48 responses in total) and the other selected once. These responses were regarded as missing data and removed from the following analyses. Examples of colours selected for test and control stimulus characters by a synaesthete and a non-synaesthete, respectively, are shown in figure 2*a*. To assess whether learning new information modulated colours associated with stimulus graphemes, we compared the colours selected for the test and control stimulus characters between the pre- and post-learning sessions and analysed pre–post-learning consistencies (i.e. pre–post-colour distances in the CIE $L^*a^*b^*$ colour space) of the colours.

Figure 2*b* illustrates the mean colour distances in the CIE $L^*a^*b^*$ colour space between the pre- and post-learning sessions, in which the data from the two tasks were combined (see electronic supplementary material, figure S2 for the separate plot). Larger colour distance indicates lower pre–post-colour consistency. A three-way ANOVA with participant group (synaesthetes/non-synaesthetes), task (sound learning/meaning learning) and stimulus type (test/control) as factors revealed that, compared to non-synaesthetes, synaesthetes' grapheme–colour associations were highly consistent between the pre- and post-learning sessions ($F_{1,20} = 46.69$, $p < 0.01$, $\eta^2 = 0.70$). Importantly, pre- and post-learning consistencies were slightly but significantly lower (i.e. the distances were larger) for test stimuli than control stimuli ($F_{1,20} = 14.86$, $p < 0.01$, $\eta^2 = 0.42$), suggesting that there was modulation of grapheme–colour association by learning the new sound or meaning. There was no main effect of the task ($F_{1,20} = 0.642$, $p = 0.43$, $\eta^2 = 0.03$) nor were there any statistically significant interactions (participant group and task: $F_{1,20} = 1.85$, $p = 0.19$, $\eta^2 = 0.08$; participant group and stimulus type: $F_{1,20} = 0.41$, $p = 0.53$, $\eta^2 = 0.01$; task and stimulus type: $F_{1,20} = 0.24$, $p = 0.63$, $\eta^2 = 0.01$; the three-way interaction: $F_{1,20} = 2.17$, $p = 0.16$, $\eta^2 = 0.10$). See electronic supplementary material, Results and figure S1 for the analyses of pre–post-learning luminance and saturation consistency.

(c) Control experiment for Study 2

In the experiment above (the 'main experiment' of Study 2), consistent with our hypothesis, pre- and post-learning consistencies were significantly lower for the test stimuli than the control stimuli. This result suggests that acquiring new information about graphemes affects grapheme–colour associations. However, there is one concern that should be addressed: in the main experiment, each control stimulus character was seen a total of only 2 times, while each test stimulus character was seen at least 27 times. It is possible that the greater colour changes for test stimuli between pre- and post-learning sessions than for the control stimuli were caused by the increased exposure to the test stimuli during the learning session.

To address this concern, we conducted a control experiment in which participants were exposed to both test and control stimulus characters the same number of times in a meaning learning task. This time, one-half of the learning task trials were 'Chinese meaning' trials, in which, just as in the trials in the main experiment, a test stimulus character (e.g. 坊) was presented above the centre of the screen, followed by the presentation of the correct (e.g. a Japanese word representing 'town') and an incorrect meaning (e.g. a Japanese word representing 'machine'), and participants were asked to select the correct Chinese meaning of the displayed character by a key press. The rest were 'Japanese meaning' trials, in which a control stimulus character was presented and participants were asked to select the 'correct Japanese meaning'. For example, when the presented character was 花 (flower), the options consisted of 花 (i.e. the correct Japanese meaning) and another character (e.g. 豆 'bean', i.e. the incorrect Japanese meaning). Thus, in a Japanese meaning trial, the task was virtually to select the same character as the stimulus character from the given two options. Importantly, in this control experiment, participants were exposed to both test and control stimulus characters the same number of times, during which a new meaning was learned for the former but not for the latter. The Chinese and Japanese meaning trials were mixed within a session, and trial orders were randomized for each subject. The trial type was cued at the beginning of each trial; instead of a fixation dot, the character 中, which is the initial character of the Japanese word for 'China' (中国), was displayed in white on a black circle for the Chinese meaning trials, and the character 日, which is the initial character of the Japanese word for 'Japan' (日本), was displayed in the same way for the Japanese meaning trials.

(i) Methods

Twelve grapheme–colour synaesthetes (all female, mean age = 27.0 years, range = 19–43 years) participated in this experiment. This time, only synaesthetes were tested. None of them participated in the main experiment. All were native Japanese speakers, and only one spoke or read Chinese. One synaesthete was a novice learner of the Chinese language. All the synaesthetes reported experiencing synaesthetic colours when viewing Kanji characters as well as Hiragana and Katakana characters, English letters and Arabic numerals. We confirmed that the synaesthetic participants engaged in this study were genuine synaesthetes based on test–retest consistency criteria in the same way as in Study 1 and in the main experiment of Study 2.

Exactly the same apparatus and set of test and control stimulus characters as in the main experiment were used in this control experiment. The procedures were also the same as in the main experiment, except that the Japanese meaning trials, in which control stimulus characters were presented, were added and a trial-type cue was presented at the beginning of each trial (see above). At least 162 trials (at least 27 trials for each of the three test and three control stimulus characters) were conducted in each computer-based training session, and the training continued until 24 successive correct responses were made. The incorrect options for the test stimulus characters (i.e. Chinese meaning trials) were exactly the same as in the main experiment. The incorrect options for the control stimulus characters (i.e. Japanese meaning trials) were selected based on the same criteria as those for the test stimulus characters.

(ii) Results

Three synaesthetes selected the 'no colour' option once (out of 24 responses in total) for each: one selected it for a test stimulus character and the other two selected it for a control stimulus character. These responses were regarded as missing data and removed from the following analysis. In addition to this, two synaesthetes already knew the meanings of two test stimulus characters before they were taught the meaning in this experiment; one of the synaesthetes learned them in a novice Chinese language class, and the other learned it through a trip to a Chinese-speaking country. These responses were also removed from the analysis. The mean number of trials required to complete a session in the meaning learning task (averaged over the two sessions in each task) was 163.3 (s.d. = 3.17, range = 162.0–173.5).

Figure 2*c* illustrates the mean colour distances in the CIE $L^*a^*b^*$ colour space between the pre- and post-learning sessions. We successfully replicated the results of the main experiment, even after controlling for the amount of exposure to stimulus characters: a *t*-test revealed that pre- and post-learning consistencies were slightly but significantly lower (i.e. the distances were larger) for the test stimuli than the control stimuli ($t_{11} = 2.58$, $p < 0.05$, $d = 0.75$). Interestingly, all 12 synaesthetes introspectively reported after the experiment that they thought that learning a new meaning for a grapheme did not affect the synaesthetic colours; however, there was a significant modulation of grapheme–colour association by learning the new meaning.

(d) Discussion

Although the effects of learning new sounds or meaning were seemingly small (figure 2*a*,*c*), consistent with our hypothesis, acquiring new information about graphemes affected grapheme–colour associations and lowered the test–retest consistency by a statistically significant amount. The finding of the main experiment was successfully replicated in the control experiment. The results suggest that synaesthetic colours are slightly but significantly modulated to reflect the synaesthete's latest knowledge about the graphemes.

Learning new information about graphemes lowered the test–retest grapheme–colour association consistency not only in synaesthetes but also in non-synaesthete participants in the main experiment (i.e. there was no interaction between the participant group and stimulus type). We interpret this result as follows: it would be quite natural for non-synaesthetes to use a strategy of associating characters to colours depending, when possible, on sounds or meanings. If this holds true, acquiring new sounds/meanings of characters would lower the test–retest consistency even in non-synaesthetes. For example, a non-synaesthete may spontaneously associate the character 基, which is pronounced as /ki/ in the Japanese language, with the colour yellow because the word representing the colour in Japanese is pronounced as /ki-iro/. When a new sound for the character (i.e. the Chinese sound, /jī/) is taught, however, the updated knowledge about the character sounds may offer another strategy, leading to an inconsistency between the colours associated with the character in pre- and post-learning colour measurements. A difference between synaesthetes and non-synaesthetes emerged in the general test–retest consistency: synaesthetes were much more consistent in grapheme–colour associations. Nevertheless, the newly acquired knowledge modulated the synaesthetic colours.

4. General discussion

Through two studies, we elaborated the influence of meaning and new knowledge acquisition about graphemes on synaesthetic grapheme–colour associations. We have demonstrated that semantic relations influenced the grapheme–colour associations for characters representing abstract meanings in the early stages of learning abstract Kanji, while the influence was reduced on the grapheme–colour associations for those learned later (Study 1), and synaesthetic colours are modulated to reflect the synaesthete's latest knowledge about the graphemes (Study 2).

Some previous studies have shown that grapheme attributes such as ordinality, frequency/familiarity, sound and visual shape can induce a second-order effect (i.e. graphemes with similar attributes are associated with similar colours) on grapheme–colour associations [11,15,28,31]. However, the results of Study 1 are the first to show that the idea of second-order mapping can be extended to the semantic domain, and the synaesthetic colour associations for graphemes (logographic characters) with abstract meaning can be at least in part explained in this way. The results of Study 2 are the first empirical and systematic evidence of updating synaesthetic colour for graphemes.

The results of the two studies indicate that synaesthetic colours for graphemes reflect the dynamics of the status of the mental lexicon. The results of Study 1 showed that the influence of semantic relations is attenuated in the synaesthetic colour associations for Kanji characters with abstract meanings that are learned in the higher school grades. This may be attributed to the maturation of the mental lexicon. Children in higher grades have a more mature lexicon. Given that synaesthetic colours for Japanese early-acquired characters (e.g. Hiragana) generalize to late-acquired graphemes via phonology and/or meaning (i.e. Kanji) [9–11], synaesthetic colours for Kanji characters that are learned in higher grades are more likely to be affected by various factors. This may attenuate the influence of semantic relations on synaesthetic colours. The results of Study 2 revealed that acquiring new information about graphemes affected their synaesthetic colours and lowered the test–retest consistency. This suggests that although it is widely known that synaesthetes are highly consistent over time in grapheme–colour associations [34,35], synaesthetic colours can be (slightly) modulated to reflect the latest status of the lexical knowledge about the graphemes. These results underscore the importance of having developmental/learning perspectives in achieving a full understanding of grapheme–colour association processes in grapheme–colour synaesthesia. It has been reported that synaesthetic associations in child synaesthetes are less consistent over time than in adult synaesthetes [43,44]. The results of Study 2 are consistent with such findings: school-age children continuously learn new lexical knowledge, dramatically updating their mental lexicon, and this may lower the test–retest consistency of grapheme–colour associations in children. Although we observed a statistically significant modulation of synaesthetic colours by new information acquisition about graphemes in Study 2, the effects were seemingly small (figure 2*a*,*c*). This might suggest that lexical representations (and the synaesthetic colours associated with them) are basically consolidated in the adult brain, although they can be slightly modulated even in adults. One remaining question is when and how such consolidation of synaesthetic associations occurs. It would require a cross-disciplinary collaboration among psycholinguistics, developmental science, neuroscience, genetics and other areas to address this question.

The findings of the current studies strengthen the view that grapheme–colour synaesthesia is a psycholinguistic phenomenon—the view that grapheme–colour synaesthesia builds on normal language processing [9–11,13–15,45]. Synaesthetic colours are elicited by grapheme attributes such as meaning (including semantic relations among abstract concepts) and sounds, and the development of lexicon and changes in lexical representation of graphemes may affect the synaesthetic colours. The influence occurs possibly because maturation of the lexicon or knowledge acquisition modulates the relative impact of several grapheme attributes on synaesthetic colours or adds some noise to grapheme-attribute mappings. Mental lexicon updating can occur in several ways: language development in childhood is one form of such updating, and foreign language learning in adulthood is another. The two studies in this article, one of which focused on semantic processing in early school-age children and another focused on new linguistic knowledge acquisition in adults, are the first steps to explore the relationship between such updating of the lexicon and synaesthetic grapheme–colour associations. Further research in this area is needed to connect the dots and see the big picture of the nature of grapheme–colour synaesthesia.

Ethics. In both Study 1 and Study 2, informed consent was obtained from all participants of this study after the nature and possible consequences of the studies were explained. The rights of the participants were protected. All the experimental procedures had been approved by the Ethical Committee of the Department of Psychology, Graduate School of Humanities and Sociology, The University of Tokyo in Japan (no. 201305).

Data accessibility. The full stimulus lists and the datasets supporting this article have been uploaded as part of the electronic supplementary material.

Authors' contributions. M.A., S.T. and K.Y. contributed to conception, design, analysis and interpretation of data of Study 1. M.A., T.T. and K.Y. contributed to conception, design, analysis and interpretation of data of Study 2. S.T. and M.A. collected the data of Study 1. T.T. and M.A. collected the data of Study 2. M.A. drafted the article and K.Y. commented on it. All authors approved the final version.

Competing interests. We have no competing interests.

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Endnotes

[1]Following Henderson [1], we employ the term 'grapheme' to denote the functional distinctive unit of any writing system, rather than restricting the definition to the written representation of phonemes (see also [2]). Therefore, in this article, the term 'grapheme' refers to not only letters of phonetic scripts, but also Japanese Kanji and Chinese characters, which represent both meaning and sounds (cf. [3]).

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