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Development of synaesthetic consistency: repeated autonomous engagement with
graphemes and colours leads to consistent associations

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Abstract

Synaesthetic consistency is the hallmark of synaesthesia and plays an important role in the definition and validation of synaesthesia. It has been hypothesised that the acquisition of initially unspecified synaesthetic associations is based on consolidation processes. Thus, we investigated in non-synaesthetes whether repeatedly engaging with grapheme-colour associations mimics the developmental trajectory of synaesthetic consistency in genuine grapheme-colour synaesthesia. This was the case for the two tested experimental groups, irrespective of whether they were instructed to memorize their chosen associations, but not for the passive control group. Moreover, consolidated associations of the experimental groups resembled those frequently found in genuine synaesthesia. Furthermore, the acquisition of consistent grapheme-colour associations resulted in a transfer of benefits to performance in recognition memory for abstract stimuli, as also found in genuine synaesthesia. Our findings suggest that consistent synaesthetic associations are based on consolidation processes due to repeated engagement with graphemes and colours.

Keywords: Synesthesia; Grapheme-color; Association learning; Memory;

Development

1. Introduction

Grapheme-colour synaesthesia describes consistent phenomenological experiences of colour in response to achromatic letters and / or numbers (Ward, 2013). For a synaesthetic individual, the letter A may always trigger a red colour experience (Baron-Cohen, Wyke, & Binnie, 1987). Although synaesthesia tends to run in families, pointing to a genetic basis (Asher et al., 2009), synaesthetic inducers are often cultural artefacts, suggesting a learning component in its development (Simner & Bain, 2013; Simner, Harrold, Creed, Monro, & Foulkes, 2009). For example, synaesthetic associations may reflect environmental contingencies that were consolidated through repeated engagement with grapheme-colour associations during childhood (Witthoft & Winawer, 2006; Witthoft, Winawer, & Eagleman, 2015). Although plausible, it remains to be investigated if repeated engagement with unspecified grapheme-colour associations is sufficient to result in consistent grapheme-colour associations (i.e., the hallmark of grapheme-colour synaesthesia). Thus, we tested in non-synaesthetes whether repeatedly engaging with grapheme-colour associations promotes synaesthetic consistency.

There is general agreement that synaesthetic associations are consistent over time and tests of consistency have become the gold standard to confirm the genuineness of any type of synaesthesia (Baron-Cohen et al., 1987; Carmichael, Down, Shillcock, Eagleman, & Simner, 2015; Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007; Rothen, Seth, Witzel, & Ward, 2013). During a consistency test, participants are repeatedly asked to indicate their synaesthetic experiences for potential synaesthetic inducers. While synaesthetes can rely on their synaesthesia when performing such a test, non-synaesthetes are dependent on their memory.

Therefore, synaesthetes generally outperform non-synaesthetes in consistency tests (e.g., Rothen et al., 2013).

To investigate the development of grapheme-colour synaesthesia, Simner et al. (2009) conducted a consistency test with more than 600 children at the age of 6 - 7 years, including a re-test 12 months later. Moreover, a subsample of 80 children (synaesthetes and non-synaesthetes) was tested again at the age of 10 - 11 years (Simner & Bain, 2013). The consistency test was based on a palette of 13 distinct colours and consistency was measured as percentage of identical grapheme-colour associations between different runs or sessions. Five of eight synaesthetes identified in the original study were still classified as synaesthetes at the age of 10 - 11 years. Crucially for the purpose of our study, these studies showed an increase in the percentage of consistent synaesthetic associations (henceforth synaesthetic consistency) from an average of 34% at age 6 - 7 years to 48% at 7 - 8 years and to 71% at 10 - 11 years. The data suggest that synaesthetic consistency, at least for grapheme-colour synaesthesia, seems to gradually develop in childhood during the first school years when children learn to read and write.

Related to the notion that synaesthesia develops during the first school years, Watson et al. (2014, 2017) proposed that grapheme-colour synaesthesia develops as a consequence of learning strategies, which are adopted when learning to deal with the meaning of abstract information of complex systems of cultural artefacts (e.g., reading and writing). Recently, Watson et al. (2017) provided empirical evidence that learning challenges in childhood may promote the development of grapheme-colour synaesthesia. They tested whether growing up with an orthographically more difficult language (English) leads to an enhanced prevalence of synaesthesia in contrast to growing up with an orthographically easier language (Czech). Although the main

hypothesis was not confirmed, further analyses revealed the expected relation between orthographic difficulty and prevalence of synaesthesia when children growing up with only one language (apart from Czech) in the first two years of life were compared. The authors speculated that children growing up with a more difficult language build synaesthetic associations to support learning their mother tongue. Crucially, such a strategy would entail repeated engagement with unspecified grapheme-colour associations which become gradually consolidated over time.

Others have suggested that synaesthetic associations are shaped by environmental contingencies (Hancock, 2006; Rich, Bradshaw, & Mattingley, 2005; Witthoft & Winawer, 2006, 2013; Witthoft et al., 2015). For instance, a relation between coloured letter-toys and synaesthetic associations has been found not only in case studies (Hancock, 2006; Witthoft & Winawer, 2006) but also in larger samples (Rich et al., 2005; Witthoft & Winawer, 2013; Witthoft et al., 2015). More recently, Witthoft et al. (2015) showed that for 400 out of 6588 grapheme-colour synaesthetes, their synaesthetic associations could be traced back to one specific coloured magnetic-letter set. Witthoft and Winawer (2013) proposed that grapheme-colour synaesthesia can develop as a consequence of conditioned mental imagery. That aside, the data suggest at least that repeated engagement with coloured letters may result in consistent grapheme-colour associations which may further develop into synaesthetic phenomenology.¹

Furthermore, non-random patterns of grapheme-colour associations in large samples of grapheme-colour synaesthetes and non-synaesthetes (Simner et al., 2005) may be interpreted as indirect evidence for an influence of environmental contingencies during the development of synaesthesia (cf. also Mankin & Simner, 2017, Root et al., 2018) and cross-modal correspondences in non-synaesthetes, which

have previously been interpreted as a weak form of synaesthesia (Martino & Marks, 2001). Simner et al. (2005) compared grapheme-colour associations in consistency tests from over 300 non-synaesthetes with the associations of synaesthetes. The results showed that both groups tended to associate some graphemes with certain colours more often than would be expected by chance (e.g., A-red). Moreover, there was also substantial overlap between the specific grapheme-colour associations of the two groups, suggesting a common mechanism behind the development of synaesthetic consistency and cross-modal correspondences. Specifically, synaesthetic associations might at least be partly determined by consolidated cross-modal correspondences (cf. also Newell & Mitchell, 2016).

Based on our brief literature review, it seems plausible to assume that the acquisition of *initially unspecified* grapheme-colour associations is based on a consolidation process of environmental contingencies, possibly due to self-employed learning strategies when mastering the skills of reading and writing. The assumption of a consolidation process finds further support in frequent anecdotal reports of synaesthetic siblings who discussed with each other during childhood whose grapheme-colour associations are “correct” (i.e., consolidation due to repeated engagement with grapheme-colour associations). Since also non-synaesthetes are subjected to the same environmental contingencies as synaesthetes (Mankin & Simner, 2017), one can reasonably expect them to exhibit the hypothesized consolidation mechanism when they are required to repeatedly engage in *autonomously* associating colours to letters and to develop consistent grapheme-colour associations (henceforth, grapheme-colour consistency).

To test this hypothesis, we had two groups of non-synaesthetes engage in a daily grapheme-colour association task (i.e., a simplified version of a categorical

synaesthetic consistency test) over a period of ten days, without any reference to synaesthesia (henceforth grapheme-colour engagement phase). Participants of both groups were instructed to select colours for each letter of the alphabet and the digits 0 - 9, based on their gut feeling. One group was further instructed to memorize the selected colour for each of the graphemes. The other group received no further instructions. Crucially, grapheme-colour associations were not specified, by contrast to synaesthesia training studies with predefined grapheme-colour associations (e.g., Bor, Rothen, Schwartzman, Clayton, & Seth, 2014; Colizoli, Murre, & Rouw, 2014; Rothen, Schwartzman, Bor, & Seth, 2018). Both groups completed a continuous consistency test in a session before (henceforth pre-session) and after (henceforth post-session) the engagement phase. A third group completed only the pre- and post-session, with an unfilled interval of ten days in between. We expected an asymptotic increase in grapheme-colour consistency in both experimental groups over the course of the engagement phase. Moreover, we expected a faster increase in grapheme-colour consistency in the group that was required to memorize the self-selected grapheme-colour associations in comparison to the group without this requirement. We expected little to no increase in grapheme-colour consistency for the group that completed the consistency test before and after an unfilled interval.

Furthermore, all three groups completed two recognition memory tests (i.e., words and fractals) in the pre- and post-session: first, to confirm the groups did not differ with regards to memory performance before the engagement phase; second, we did not want to miss the opportunity to explore if the potential acquisition of synaesthetic associations enhances memory performance, as is the case in genuine synaesthesia (cf. Rothen, Meier, & Ward, 2012). However, we suspected that the engagement phase might be too short to affect memory performance.

2. Method

2.1. Participants

We tested a total of 74 participants, who were randomly assigned to one of three groups: a group that had to select colours for letters on basis of their gut feeling (i.e., implicit group), a group that was additionally instructed to memorize the selected colours (i.e., explicit group), and a group with an unfilled interval (i.e., control group). Inclusion criteria were normal (or corrected to normal) vision and absence of synaesthesia (based on phenomenological self-reports). Three participants did not complete the study, and data of two datasets included multiple missing data points due to technical errors. Further, we excluded four participants who did not seem to have followed the instructions. Their average performance in the daily engagement phase (i.e., categorical consistency test) was lower than 2.5 *SD* from the average performance of the respective group (i.e., explicit and implicit). The remaining 65 participants entered the analysis: $N_{\text{explicit}} = 21$ (average age = 22 years, $SD = 2.31$, range = 12.91, 20 women, 3 left-handed), $N_{\text{implicit}} = 21$ participants (average age = 22 years, $SD = 1.83$, range = 5.79, 21 women, 2 left-handed), and $N_{\text{control}} = 23$ (average age = 22 years, $SD = 2.46$, range = 10.43; 23 women, 3 left-handed). All participants were undergraduate psychology students who participated in return for course credits and all participants were fluent in German. The study was approved by the local ethics committee of the University of Bern. Participants were informed that they could withdraw at any time during the experiment before they consented to participate.

Sample size determination was based on an a-priori power analysis with G*Power 3 (Faul, Erdfelder, Lang, & Buchner, 2007). Effect sizes for power calculations were based on comparisons between synaesthetes and controls for consistency (i.e., Cohen's $d = 1.8$; Rothen et al., 2013) and recognition memory for

words (i.e., Cohen's $d = 0.6$; Ward, Hovard, Jones, & Rothen, 2013). Notably, the recognition memory advantage in synaesthesia is smaller for words than fractals (Ward et al., 2013). For reasons of simplicity, the calculations included the between subject factor *Group* (experimental vs. control) and the within subject factor *Session* (pre- vs. post). For both tasks (consistency and memory), a medium average correlation between the repeated measures of the factor *Session* was assumed ($r = .50$) and a power level of 0.95 was chosen. The power analyses revealed that four participants per group were required for the consistency task and 20 participants per group for the memory tasks in order to achieve a 95% probability of detecting a true interaction between the factors *Group* and *Session*. Due to the multi-session design, we decided to test 24 - 25 participants per group to account for potential dropouts.

2.2. Apparatus and materials

The apparatus differed depending on the specific testing session. The pre- and post-sessions were conducted in a laboratory setting. The remaining sessions were conducted autonomously by the participants at their homes. The stimuli of the laboratory-based tasks were presented on a flat 21-inch Sony Trinitron cathode ray tube monitor (85 Hz refresh rate) driven by a NVIDIA GeForce GTX970 graphics card (NVIDIA Corporation, Santa Clara, California) with a spatial resolution of 1280×1024 pixels and a colour resolution of 8 bits per channel. The CIE1931 chromaticity coordinates and luminance of the monitor primaries were $R = (0.625; 0.341; 18.061)$, $G = (0.287; 0.609; 52.860)$, and $B = (0.150; 0.073; 6.145)$. A chin- and forehead rest was used to keep the viewing distance of 100 cm constant for the duration of the experiment. A black cardboard tunnel led directly from the monitor to the chin- and forehead rest and overlapped it by 20 cm at the top and both sides to shield peripheral vision.

Participants used their own personal computers or laptops to autonomously complete the daily grapheme-colour engagement phase at home. Different sessions consisted of different tasks. The materials are described separately for each task in the sections below.

2.2.1. Continuous consistency test. The continuous consistency test (Figure 1a) was used in the pre- and post-session. It was programmed in HTML/ PHP and JavaScript and consisted of the graphemes (A - Z and 0 - 9). A grapheme was always accompanied by a continuous colour palette and a scale to adjust the luminance of the colour, representing all colours that could possibly be presented on the screen. The colour palette included a circle which could be moved with the computer mouse to select a different colour. Two buttons were positioned below the colour palette. The left button included the word “OK” and the right button included the words “keine Farbe” (i.e., “no colour” in German). The general instructions of the continuous consistency task were, to select a colour for each letter of the alphabet and each digit from 0 - 9 based on gut feeling. Moreover, participants were instructed not to use the “no colour” button. Instructions for the explicit group and the control group additionally included to memorize the selected colours and to try to always select the same colour for a specific grapheme. By contrast to standard versions of this test, which exclusively include potential inducers, our stimulus material additionally consisted of five trials presenting different colour squares, which were not relevant for the current study and hence, are not further discussed.

please place Figure 1 here

2.2.2. Categorical consistency test. The categorical consistency test (Figure 1b) was programmed and presented on the internet platform Soscisurvey (<https://www.soscisurvey.de/>). It included a categorical colour palette and was adapted from Simner et al. (2006; see also Meier, Rothen, & Walter, 2014; Rothen, Wantz, & Meier, 2011; Simner & Bain, 2013; Simner et al., 2009). Graphemes (A - Z, 0 - 9) were presented in a non-serif black font against a white background, above a palette of 13 colours (black [RGB: 0, 0, 0], blue [RGB: 0, 0, 153], brown [RGB: 153, 51, 0], grey [RGB: 128, 128, 128], green [RGB: 0, 128, 0], light blue [RGB: 0, 204, 255], light green [RGB: 102, 255, 102], magenta [RGB: 255, 0, 255], orange [RGB: 255, 161, 23], purple [RGB: 128, 0, 128], red [RGB: 255, 0, 0], white [RGB: 255, 255, 255], and yellow [RGB: 255, 255, 0]). On the left side of each colour was a radio button. At the bottom of the page was a button which included the word “weiter” (i.e., “continue” in German). The instructions for the categorical consistency test were conceptually identical as for the continuous consistency test (i.e., the explicit group had to memorize the selected colours, and to try to always select the same colour for a specific grapheme, the implicit group received no further instructions).

2.2.3. Word recognition task. Stimulus presentation was programmed and controlled with E-Prime 2.0 Psychology Software Tools (Schneider, Eschman, & Zuccolotto, 2012). Responses were registered with a QWERTZ keyboard. The stimulus material for the task consisted of two sets of 100 nouns each. In each set, 50 words were used as old (i.e., presented during the study phase) and 50 words were used as new (i.e., not presented during the study phase). The resulting four lists were controlled for word-frequency (frequency class between five and twelve; ‘Leipzig Wortschatz Corpus’, <http://wortschatz.uni-leipzig.de/de>) and word length (ranging from six to twelve letters). Means and standard deviations for frequency class and

word length are presented in Table 1. Twenty additional words were used to create primacy and recency trials. Primacy and recency trials were only part of the study phase and not further analysed. Words were presented in black 18-point bold Courier New font against a grey background. For the study phase, the instruction was to memorize the words for a subsequent recognition test. The instruction for the test phase was to indicate if a word was old or new, respectively and to provide a confidence rating for each response.

Table 1

Means and standard deviations for frequency class and word length of the word lists used in the word-recognition-memory task.

	Frequency class			Length	
	N	M	SD	M	SD
list a	50	10.66	1.49	8.30	1.80
list b	50	10.38	1.32	8.00	1.80
list c	50	10.34	1.35	8.76	1.99
list d	50	10.82	1.17	7.94	1.72

2.2.4 Fractal recognition task. Stimulus presentation was programmed and controlled with E-Prime 2.0 Psychology Software Tools (Schneider et al., 2012). Responses were registered with a QWERTZ keyboard. The stimulus material was collected by means of an internet search for the term “fractals”. Fractal images were grey-scaled and resized to 380 x 380 pixels. Further, average spatial frequency and luminance was equalized with The SHINE toolbox (see Willenbockel et al., 2010). Two-hundred fractals were used to create two sets of 100 fractals. In each set, 50 fractals were used as old (i.e., presented during the study phase) and 50 fractals as new (i.e., not presented during the study phase), respectively. Additionally, a primacy

and a recency list of 10 fractals each was used. Primacy and recency trials were only part of the study phase and not further analysed. The instructions for the fractal recognition task were equivalent with those for the word recognition task.

2.3. Procedure

2.3.1. General Procedure. Participants were randomly assigned to one of three groups, two experimental groups (i.e., explicit and implicit group) and a control group. During the pre-session, the three groups completed a demographic questionnaire followed by the continuous consistency test to assess baseline grapheme-colour consistency performance. The explicit and implicit group further completed the categorical consistency test to direct them how to complete the test during the grapheme-colour engagement phase over the course of the following ten working days. The control group did not complete this task. Further, all participants completed the word and fractal recognition tasks to determine that any potential differential effects are not due to pre-existing differences in memory performance. The order of the recognition tasks and the lists of old and new stimuli were counterbalanced between the participants of the different groups.

Next, participants of both experimental groups were required to complete the categorical consistency test on the following ten subsequent working days at home in a quiet environment (i.e., home sessions). Thereafter, they completed the post-session in the laboratory. If it was not possible to conduct the post-session immediately after the home sessions on the eleventh day (e.g., when the date fell on a holiday), participants were instructed to continue with the home sessions until a day before the actual post-session. This applied to five participants of the explicit group (max. 13 home sessions) and four participants of the implicit group (max. 13 home sessions), who completed eleven to thirteen home sessions. For reasons of compatibility, the

eleventh home-session of the categorical consistency test was regarded as the post-session in all analyses for these participants. The post-session was identical to the pre-session, except for the omission of the demographic questionnaire. The stimulus lists for the recognition tasks were different from the first session and counterbalanced between the participants of the different groups. The control group completed the continuous consistency test and the recognition tasks after an unfilled interval of approximately ten days to assess the effect of test repetition without an experimental intervention.

2.3.2. Continuous consistency test. During the continuous consistency test (Figure 1a), participants were presented with the graphemes in random order and had to select a colour for each according to their group-specific instructions. When a colour was selected, the black contour of the grapheme was filled with the selected colour. Clicking on the “OK” button submitted the selected colour and initiated the next trial. The whole procedure was immediately repeated within the same session, after a screen indicating the start of a second round.

2.3.3. Categorical consistency test. The categorical consistency test (Figure 1b) started immediately with the presentation of the graphemes in randomized order. Participants were required to select a colour for each of the graphemes according to their respective instructions by clicking on the adjacent radio button and to advance to the next trial by clicking on the continue button. The ordering of the different colours on the screen changed randomly on a trial-by-trial basis. After a first round, the procedure was repeated immediately in a new randomized order within the same session.

For the internet-based sessions at home, participants were required to wait for a daily e-mail which included a link to start the task. This procedure was implemented

to better control when participants advanced with the next session during the grapheme-colour engagement phase.

2.3.4. Recognition tasks. The word and fractal recognition tasks followed the same specific procedures. Testing order (word vs. fractal), stimulus sets (pre- vs. post-session) and lists (old vs. new status) were counterbalanced between participants, groups, and testing sessions. The study phase consisted of 70 trials, 10 primacy trials, 50 study trials, and 10 recency trials. A study trial started with a central fixation cross for 500 ms, followed by the presentation of the stimulus for 1000 ms. After the stimulus, a blank screen appeared, until the next trial was initiated by pressing the space key. Exemplary study trials are depicted in Figure 2a and b, respectively. The study phase was immediately followed by the test phase. The test phase consisted of 100 trials. Fifty trials were old (i.e., presented during the study phase) and 50 trials were new (i.e., not presented during the study phase). Old and new trials were randomly intermixed. A test trial started with a central fixation cross for 500 ms, followed by the stimulus presented for 1000 ms. Thereafter, participants were required to indicate if a trial was old or new by pressing one of two keys (“Y” = old, “N” = new). After the keypress, participants were prompted to indicate how confident they felt with their response on a 10-point scale (i.e., number keys 0 - 9). After this keypress, the next trial was initiated. See Figure 2c and d for exemplary trials of the test phase.

please place Figure 2 here

2.4. Analysis

The raw data of the current study are publicly available in anonymized form. They can be retrieved from <https://osf.io/p5xsd/>.

For the continuous consistency test, we assessed grapheme-colour consistency as the average Euclidean distance in CIELUV colour space for the colours of the different instances of each grapheme. Thus, smaller values indicate that the colour choices for the different instances of each grapheme were more consistent (compare Rothen et al., 2013). For the categorical consistency test, we assessed grapheme-colour consistency as the proportion of identical colour choices for the different instances of each grapheme. Thus, higher values indicate that the colour choices for the different instances of each grapheme were more consistent (compare Meier et al., 2014). For recognition-memory performance, *d*-prime (*d'*) was calculated as the difference of *z*-transformed hit rate (old items judged as old) and *z*-transformed false alarm rate (new items judged as old). In order to avoid hit rates of 1 and false alarm rates of 0, we used the formula, hit rate = (hits + 0.5) / (total old + 1) (cf. Snodgrass & Corwin, 1988). For the false alarms, we calculated the correct rejections first, applying a similar formula, correct rejection rate = (correct rejections + 0.5) / (total new + 1). The false alarm rate was then calculated by subtracting the corrected rejections from 1.

The alpha level was set to .05 for all the statistical analyses. Greenhouse-Geisser correction was applied where the assumption of sphericity was violated on tests involving repeated measure factors with more than two levels. Reported effect sizes denote partial eta squared (η_p^2) for analyses of variance (ANOVAs), Cramer's *V* for χ^2 -tests, Cohen's *d* for *t*-tests and Pearson's *r* for correlations.

To confirm the null-hypothesis, where important, we calculated the Bayes factor (BF) as the likelihood ratio of the data given the null hypothesis against the probability of the data given the alternative hypothesis (Rouder, Morey, Speckman, & Province, 2012; Rouder, Speckman, Sun, Morey, & Iverson, 2009). Thus, BF s can be interpreted supporting the null-hypothesis, if they are lower than 1 or the alternative hypothesis, if they are higher than 1. According to Jeffreys' suggestion, odds higher than 3 (or lower than $1/3$ for $BF < 1$) are regarded as “substantial evidence”, whilst odds between 1 and 3 (or $1/3$ and 1 for $BF < 1$) are regarded as “anecdotal” (Jeffreys, 1961 according to Wetzels et al., 2011).

3. Results

3.1. Continuous consistency test

The continuous consistency test was used to assess baseline performance in the pre-session and a potential transfer of benefits in the post-session, due to the engagement phase with discrete colours. Descriptive statistics for the continuous consistency test are shown in Figure 3a as a function of *Group* (explicit, implicit, control) and *Session* (pre vs. post). For comparison, data of a synaesthetic sample are provided in Figure 3a. A two-factorial ANOVA for mixed measures with the between subject factor *Group* and the within subjects factor *Session* revealed a significant main effect of *Group*, $F(2, 62) = 5.24, p = .008, \eta_p^2 = .14$. Subsequent *t*-tests comparing overall performance between the different groups revealed that the effect was due to significant differences between the explicit group in comparison to the other groups: relative to the control group, $t(42) = 3.27, p = .002, d = 0.99$, relative to the implicit group, $t(40) = 2.09, p = .043, d = 0.65$. The comparison between the control group and the implicit group did not reach significance, $t(42) = 1.25, p = .219, d = 0.38$. That is, the explicit group generally outperformed the other two groups across both testing

sessions. Also, the main effect *Session* reached significance, $F(1, 62) = 247.06, p < .001, \eta_p^2 = .80$, because grapheme-colour consistency generally increased from pre- to post-session. Most importantly the analysis revealed a significant *Group x Session* interaction, $F(2, 62) = 43.25, p < .001, \eta_p^2 = .58$, due to a significantly larger increase in consistency performance in the explicit and the implicit group in comparison to the control group as the following analyses confirmed. That is, the three groups did not significantly differ in the pre-session according to a one-way ANOVA with the factor *Group*, $F(2, 62) = 3.05, p = .055, \eta_p^2 = .09$. More importantly, a one-way ANOVA showed that the three groups significantly differed in their consistency performance in the post-session, $F(2, 62) = 25.53, p < .001, \eta_p^2 = .45$. Subsequent *t*-tests comparing the groups revealed that, the implicit and explicit group differed significantly from the control group, due to better consistency performance: explicit group, $t(42) = 7.03, p < .001, d = 2.12$, implicit group, $t(42) = 4.60, p < .001, d = 1.39$. By contrast, consistency performance did not significantly differ between the explicit and the implicit group, $t(40) = 1.54, p = .130, d = 0.48$, and the $BF = 0.78$ indicates that the experimental results cannot distinguish between the null and alternative models. Next, we conducted paired *t*-tests for the comparisons between pre- and post-sessions. They revealed significant differences for the explicit group, $t(20) = 12.28, p < .001, d = 3.79$, and for the implicit group, $t(20) = 10.43, p < .001, d = 3.22$, and also for the control group, $t(22) = 2.39, p = .026, d = 0.70$. These results indicate that the engagement phase with discrete colours lead to a transfer of benefits to a more fine-grained version of the consistency test (i.e., with a continuous response space). The slight improvement in the control group highlights the sensitivity of this consistency test to test-repetition.

In order to compare consistency of the non-synaesthetic sample with genuine synaesthetes, Figure 3a additionally includes data of 29 grapheme-colour synaesthetes. They were tested with the same consistency test in an ongoing study (average age = 29 years, $SD = 12.50$, range = 52.00, 27 women, 2 left-handed). Comparing post-session performance of the experimental groups (i.e., explicit and implicit) with the performance of the synaesthetes, t -tests revealed no significant difference for the explicit group, $t(48) = 0.83$, $p = .413$, $d = 0.23$, $BF = 0.38$, and the implicit group, $t(48) = 1.23$, $p = .225$, $d = 0.35$, $BF = 0.53$, indicating that their level of consistency was approaching that of genuine synaesthetes, and the BF s indicating that the results cannot distinguish between the null (no difference to the synaesthetes) and the alternative models (difference to the synaesthetes). This was not the case for the control group that differed significantly from the sample of genuine synaesthetes, $t(50) = 7.56$, $p < .001$, $d = 2.10$, in the post-session.

please place Figure 3 here

3.2. Categorical consistency test

The categorical consistency test was used to assess the developmental trajectory of grapheme-colour consistency during the engagement phase. Descriptive statistics of grapheme-colour consistency in this test as a function of *Group* (explicit vs. implicit) and *Session* (pre, 1, 2, 3, ..., 10, post) are shown in Figure 3c. To test if both groups started and finished at comparable performance levels, we conducted a 2 x 2 ANOVA with the between subject factor *Group* (implicit vs. explicit) and the within subject factor *Session* (pre vs. post). The analysis revealed a significant main effect *Session*, $F(1, 40) = 95.16$, $p < .001$, $\eta_p^2 = .70$, due to better performance in the

post- relative to the pre-session. The main effect *Group*, $F(1, 40) = 2.64$, $p = .112$, $\eta_p^2 = .06$, $BF = 0.67$, and the *Group* x *Session* interaction, $F(1, 40) = 1.49$, $p = .230$, $\eta_p^2 = .04$, $BF = 0.93$, were not significant. The ANOVA indicates that both groups showed similar performance in the pre- and post-sessions and the *BF*s indicate that the experimental results cannot distinguish between the null and alternative model. Numerically, the explicit group outperformed the implicit group, supporting the effectiveness of the respective instruction for the two groups.

Next, we conducted a 2 x 10 ANOVA with the between subject factor *Group* (implicit vs. explicit) and the within subject factor *Session* (1-10) to assess the developmental trajectory of grapheme-colour consistency across the engagement phase. The analysis revealed a significant main effect *Group*, $F(1, 40) = 7.09$, $p = .011$, $\eta_p^2 = .15$, due to overall higher grapheme-colour consistency in the explicit compared to the implicit group, again in line with the respective instructions of the two groups. Furthermore, a significant main effect *Session* was found, $F(9, 360) = 37.90$, $p < .001$, $\eta_p^2 = .49$, due to an increase in grapheme-colour consistency over the different sessions. Also, the *Group* x *Session* interaction reached significance, $F(9, 360) = 3.82$, $p = .014$, $\eta_p^2 = .09$, indicating different developmental trajectories of grapheme-colour consistency between the implicit and explicit groups across the different sessions. Subsequent *t*-tests revealed significant performance differences between the two groups for the first five sessions and less consistent performance differences during the following sessions, as source of the interaction (for individual *t*-tests see Table 2). Overall, the analyses revealed different developmental trajectories between the two groups over the course of the engagement phase, with a faster learning rate in the explicit group relative to the implicit group, but comparable performance levels across the pre- and post-session.

Table 2

Independent t-test comparisons between the explicit and the implicit group across home sessions.

Session	<i>t</i> (40)	<i>P</i>	Cohen's <i>d</i>
1	2.67	.011	0.82
2	2.55	.015	0.79
3	3.06	.004	0.94
4	2.03	.049	0.63
5	2.56	.014	0.79
6	1.26	.214	0.39
7	2.44	.019	0.75
8	1.80	.080	0.56
9	1.29	.206	0.40
10	2.60	.013	0.80

3.3. Cross-test consistency

To assess consistency for grapheme-colour associations between the continuous and the categorical consistency test, we computed Euclidean distances between each colour choice for a specific grapheme from the first run of each test. Averaged Euclidean distances as a function of *Group* and *Session* are depicted in Figure 4. A two factorial ANOVA for mixed measures with the between factor *Group* (explicit vs. implicit) and the within factor *Session* (pre vs. post) revealed a significant main effect *Session*, $F(1, 40) = 226.89, p < .001, \eta_p^2 = .85$, due to smaller Euclidean distances in the post-session compared to the pre-session. However, no significant main effect *Group*, $F(1, 40) = 0.17, p = .686, \eta_p^2 < .01$, and the $BF = 0.30$ indicating substantial evidence for the null model, and no significant interaction *Group* x *Session*, $F(1, 40) = 0.73, p = .398, \eta_p^2 = .02$, and the $BF = 0.44$ indicating that the results cannot distinguish between the null and the alternative model, were found. Thus, these

analyses revealed larger Euclidean distances between colour choices for each grapheme across the two consistency tests in the pre-session compared to the post-session. Euclidean distances in the pre- and post-session were similar between the explicit and the implicit group. Overall, these analyses strongly indicate a transfer of benefit of the engagement with the categorical consistency test to the continuous consistency test.

please place Figure 4 here

3.4. Grapheme-colour associations

Given our interest in repeated engagement with grapheme-colour associations as a core mechanism for the development of synaesthetic consistency, we further explored if the specific grapheme-colour associations in the continuous consistency test matched the non-random pattern of associations frequently reported in grapheme-colours synaesthesia (e.g., Mankin & Simner, 2017; Root et al., 2018; Simner et al., 2006; Witthoft et al., 2015). For the purpose of comparison with previous studies (cf. Root et al., 2018; Simner et al., 2005), we focused on letter-colour associations based on eleven basic colour terms (black, blue, brown, grey, green, magenta, orange, purple, red, white, and yellow; Berlin & Kay, 1991). Thus, originally selected colours were reduced to these colour terms by means of finding the smallest Euclidean distance between a chosen colour and the term of the nearest colour in CIELUV colour space of the continuous consistency test. Only letter-colour associations that were consistent within a given session and participant entered the following analysis. To test for non-random letter-colour associations, we followed the procedure described by Root et al. (2018). With an omnibus chi-squared goodness-of-fit test, we

compared the distribution of colour choices for every letter (Supplemental Figure 1 in SupplementalInformation.pdf) per group and session to the overall distribution of all chosen colours in the respective group and session (Figure 5a). The null hypothesis was that the distribution of the chosen colour for a certain letter was similar to the probability distribution of the chosen colours over all graphemes in the respective group and session. To further determine the specific letter-colour associations which accounted for the significant deviations in the distributions of colour choices, we computed cell-wise z -tests on the standardized Pearson residuals as post-hoc tests for the letters with a significant omnibus chi-square. Individual results for all experimental conditions *Group* (explicit, implicit, control), *Session* (pre vs. post), *Grapheme* (A - Z) and *Colour* (black, blue, brown, grey, green, magenta, orange, purple, red, white, and yellow) are provided in Supplemental Table 1 (SupplementalTable1.xlsx). A summary of the results is provided in the following paragraphs.

please place Figure 5 here

Letters with a significant deviation from the expected distribution are depicted in Figure 5b. In the pre-session, the omnibus chi-squared goodness-of-fit tests (see Supplemental Table 1 for all results) revealed significant differences to the overall colour-distributions for the letters A, $\chi^2 = 10.05$, $p = .038$, $V = 2.51$, and Z, $\chi^2 = 13.83$, $p = .038$, $V = 2.51$, in the explicit group, for the letter Z in the implicit group, $\chi^2 = 25.62$, $p < .001$, $V = 4.62$, and for the letter Z in the control group, $\chi^2 = 31.69$, $p < .001$, $V = 4.76$. In the post-session, the omnibus chi-squared goodness-of-fit tests revealed significant differences in the colour-distributions for the letters A, B, I, R, X,

and Z in the explicit group, all χ^2 s ≥ 16.04 , $ps \leq .033$, $Vs \geq 2.76$, of the letters A, B, I, S, X, and Z in the implicit group, all χ^2 s ≥ 17.35 , $ps \leq .006$, $Vs \geq 3.26$, and the letters R, V, X, Y, and Z in the control group, all χ^2 s ≥ 13.33 , $ps \leq .023$, $Vs \geq .3.09$. No other letters showed significant differences in the distribution of their colour associations compared to the distribution of the overall colour choices, all χ^2 s ≤ 6.78 , $ps \geq .077$, $Vs \geq 2.74$.

Pearson standard residuals of letters with a significant deviation from the expected distribution were further analysed with cell-wise z -tests to determine the specific colours that led to the deviation in the distribution of colour choices. The tests were Bonferroni corrected for the 11 colours, which resulted in a corrected $\alpha = 0.0045$, and a critical value $z = 2.61$. Standard residuals of all experimental conditions are reported in Supplemental Table 1. For the pre-session, the tests revealed significant residuals for the grapheme-colour associations Z-black in all groups, all $zs \geq 3.57$, all $ps < .001$. No other grapheme-colour associations revealed significant residuals, all $zs \leq 2.45$, all $ps \geq .007$. Analysing the post-session, significant residuals for the letter-colour associations A-red, A-brown, B-blue, I-yellow, X-black, and Z-black were found in the explicit group, all $zs \geq 2.66$, all $ps \leq .004$, for the associations A-red, B-blue, I-yellow, S-yellow, and Z-black in the implicit group, all $zs \geq 4.12$, all $ps < .001$, and for the associations R-red, V-grey, Y-grey, X-black, and Z-black in the control group, all $zs \geq 3.43$, all $ps < .001$. No other grapheme-colour associations revealed significant residuals, all $zs \leq 2.58$, all $ps \geq .005$. The significant grapheme-colour associations, except the V-grey and the Y-grey in the control group, were comparable to the colour choices of a non-synaesthetic German speaking sample tested in a previous study (Simner et al., 2005). Interestingly, the grapheme-colour associations, A-red, B-brown, B-blue, S-yellow, X-black, and Z-black, found in the

explicit and the implicit group were also more prominent in the synaesthetic sample of the same study (Simner et al., 2005).

3.5. Recognition tasks

To demonstrate that the groups did not differ in terms of their memory abilities, we were interested in their performance in two recognition tasks (for fractals and words, respectively) in the pre-session before the engagement phase. Previous studies suggested that synaesthesia is associated with enhanced memory (e.g., Bankieris & Aslin, 2016; Meier & Rothen, 2013; Pritchard, Rothen, Coolbear, & Ward, 2013; Radvansky, Gibson, & McNerney, 2011; Rothen & Meier, 2010; Rothen, Meier, & Ward, 2012a; Ward, Hovard, Jones, & Rothen, 2013). Thus, we further included the recognition tasks in the post-session to explore the possibility whether an increase in grapheme-colour consistency is associated with enhanced memory performance. For reasons of completeness, response bias analyses can be found online in the Supplemental Results section (SupplementalInformation.pdf).

Descriptive statistics of memory performance (d') as a function of group and session are depicted in Figure 6a and b. A mixed three-factorial ANOVA with the between factor *Group* (explicit, implicit, control) and the within factors *Task* (word vs. fractal) and *Session* (pre vs. post) revealed a significant main effect *Session*, $F(1,62) = 7.49$, $p = .008$, $\eta_p^2 = .11$, due to better memory performance in the post-session than in the pre-session and a significant main effect *Task*, $F(1,62) = 169.40$, $p < .001$, $\eta_p^2 = .73$, due to better performance in the word-recognition task than in the fractal-recognition task. The main effect *Group* did not reach significance, $F(2,62) = 0.27$, $p = .762$, $\eta_p^2 = .01$. The interactions were not significant with *Group* x *Session*, $F(2,62) = 0.07$, $p = .928$, $\eta_p^2 < .01$, *Group* x *Task*, $F(2,62) = 0.11$, $p = .893$, $\eta_p^2 < .01$,

Session x Task, $F(1,62) = 0.18$, $p = .677$, $\eta_p^2 < .01$, and *Group x Session x Task*, $F(2,62) = 0.37$, $p = .694$, $\eta_p^2 = .01$.

Due to theoretical and practical interests, we further conducted separate ANOVAs for both recognition tasks. A mixed two-factorial ANOVA with the between factor *Group* (explicit, implicit, control) and the within factor *Session* (pre vs. post) for the word-recognition task revealed no significant effects, with *Group*, $F(2,62) = 0.07$, $p = .928$, $\eta_p^2 < .01$, and the $BF = 0.25$ indicating substantial evidence for the null model, *Session*, $F(1,62) = 2.02$, $p = .160$, $\eta_p^2 = .03$, and *Group x Session*, $F(2,62) = 0.06$, $p = .945$, $\eta_p^2 < .01$, indicating that the groups performed on a comparable level in both sessions. Interestingly, the same ANOVA for the fractal-recognition task revealed a significant main effect *Session*, $F(1, 62) = 7.35$, $p = .009$, $\eta_p^2 = .11$, due to better memory performance in the post-session. There was no significant main effect *Group*, $F(2,62) = 0.73$, $p = .486$, $\eta_p^2 = .02$ or *Group x Session* interaction, $F(2,62) = 0.55$, $p = .582$, $\eta_p^2 = .02$. Due to the suggestive pattern, we further conducted paired sample *t*-tests to measure the change in memory performance within the three different groups: the tests revealed a significant increase in memory performance for the implicit group, $t(20) = 2.64$, $p = .016$, $d = 0.82$, but not for the explicit group, $t(20) = 1.48$, $p = .153$, $d = 0.46$, or the control group, $t(22) = 0.79$, $p = .438$, $d = 0.23$.

To investigate the relation between the increase in consistency in the continuous consistency test and the increase in memory performance in the fractal-recognition task, we conducted a Pearson correlation analysis. Because the groups differed in their instructions for the consistency test, it was reasonable to expect group specific correlation effects. Thus, we computed the correlations for each group. The corresponding scatterplots are provided in Supplemental Figure 2

(SupplementalInformation.pdf). These analyses revealed no significant effects, with negligible effect sizes for the explicit group, $r(21) = -.07$, $p = .759$, and the control group, $r(23) = -.06$, $p = .780$, and a small effect size for the implicit group, $r(21) = .22$, $p = .331$. Importantly, the correlation coefficients need to be treated with caution due to the size of our samples (cf. Schönbrodt & Perugini, 2013).

please place Figure 6 here

4. Discussion

Synaesthetic consistency is the hallmark of synaesthesia and plays an important role in the definition and validation of synaesthesia. However, the exact nature of its development is still a matter of debate. The main finding of the present study is that repeated engagement in *autonomously* associating graphemes with colours can lead to highly consistent grapheme-colour associations in non-synaesthetes. An increase in grapheme-colour consistency was also observed when participants were not instructed to memorize the specific associations (implicit group). However, peak performance was reached later relative to participants who were explicitly instructed to memorize their associations. Interestingly, some of the specific associations that developed over the duration of the study closely resembled those observed in genuine grapheme-colour synaesthesia (e.g., A-red). Furthermore, we observed a transfer of benefit to a more fine-grained test of consistency, independent of the instruction condition. Moreover, there was an additional transfer of benefit to recognition memory for abstract fractal patterns, but not words. The results of the control group confirmed that the observed transfer of benefits exceeded performance improvements due to test repetition in the post-session.

The observed increase in consistency (incl. a transfer of benefit to a different version of the test) and the concomitant increase of non-random patterns of grapheme-colour choices support the assumption that the acquisition of initially unspecified grapheme-colour associations is based on consolidation processes. More specifically the results seem to suggest that, at the beginning, participants chose the colours for the graphemes based on cross-modal correspondences or simply by chance which later consolidated due to repeated engagement with grapheme-colour associations (cf. also Newell & Mitchell, 2016). This notion finds further support by the observed non-random patterns of grapheme-colour associations in our sample that were comparable to some of those also found in genuine synaesthesia (Mankin & Simner, 2017; Root et al., 2018; Simner et al., 2005; Witthoft et al., 2015). That is, the data are in line with the notion that genuine synaesthetic associations are often based on environmental contingencies (e.g., Witthoft & Winawer, 2006, 2013; Witthoft et al., 2015), which consolidate due to repeated engagement during childhood (Simner & Bain, 2013; Simner et al., 2009; Simner, Ipser, Smees, & Alvarez, 2017) for instance when mastering complex tasks such as the acquisition of reading skills (Watson, Akins, Spiker, Crawford, & Enns, 2014; Watson et al., 2017).

By contrast to previous training studies, which aimed at the acquisition of synaesthetic *phenomenology*, we focused on mechanisms underlying the development of synaesthetic *consistency*. An important difference to training studies where participants are required to learn predefined grapheme-colour associations is that our participants were instructed to choose the associations that just felt right. Furthermore, we included an implicit group that was not instructed to memorize their associations. That is, the chosen approach is closer to the natural mechanisms in developing consistent synaesthetic associations than the proceedings of synaesthesia training

studies, where artificially (i.e., experimentally) predetermined grapheme-colour associations are trained (e.g., Bor et al., 2014; Colizoli et al., 2014; Rothen et al., 2018). We must consider the possibility that the implicit group guessed the aim of the study, whereas the control group did not. In that case, we would expect similar developmental trajectories in consistency for the two groups. However, development of consistency across the engagement phase revealed significant group differences up to and with session five due to lower consistency in the implicit group compared to the explicit group. Also, in the subsequent sessions, the implicit group showed numerically lower consistency in comparison to the explicit group. Hence, it seems unlikely that the implicit group had guessed the actual aim of our study. Therefore, particularly the learning mechanism in our implicit group seems to reflect the mechanism behind the learning component in genuine synaesthesia.

The numerical differences in consistency performance between groups observed for the pre-session are in line with the specific instructions: the explicit group as well as the control group were instructed to memorize the associations already during their first contact with the consistency task. In contrast, cross test consistency in the pre-session was comparable for the explicit and the implicit group. This aligns with the fact that neither of the groups was instructed to choose the same colours across consistency tests. Notably, this also highlights the importance of the exact wording when instructing non-synaesthetic controls for consistency tests.

An interesting avenue for further research is the observation of enhanced fractal recognition in the post-session in comparison to the pre-session in our experimental groups (i.e., especially the implicit group). Although the finding has to be treated with caution due to the rather weak empirical evidence, it is in line with previous research suggesting an association between synaesthesia and enhanced

memory (e.g., Rothen et al., 2012). Notably, the effects of enhanced memory in synaesthesia are generally stronger for abstract fractals than words (Ward et al., 2013), which might explain why the effect was only found in the fractal recognition task but not in the word recognition task. Our results also align with previous studies that found superior memory in grapheme-colour synaesthesia for colours but not graphemes (Terhune, Wudarczyk, Kochuparampil, & Cohen Kadosh, 2013; Yaro & Ward, 2007). Moreover, the reliability of the effect is supported by the fact that both experimental groups show stronger effect sizes (i.e., medium to large effect sizes) than the control group (i.e., small effect size). However, an association between the increase in memory performance and the increase in consistency performance was only observed in the implicit group, based on a small effect. In case the effect proves to be reliable in future studies, it is suggestive of implicit learning processes during the development of consistency in genuine synaesthesia. In comparison to the experimental groups, a numerical advantage in fractal recognition was found for the control group in the pre-session. Due to this slight advantage in baseline recognition performance, one can reasonably expect the greatest impact of test repetition in the control group. However, this was not the case and test repetition can be excluded as an explanation for the observed increases in memory and consistency performance. Crucially, both experimental groups started at comparable performance levels in both recognition tasks, allowing for a straightforward comparison and interpretation of their results.

5. Conclusion

In summary, we established consolidation processes based on repeated engagement with *unspecified* synaesthetic inducer-concurrent pairings as a potential mechanism in the development of synaesthetic consistency. Crucially, the observed

pattern of the developmental trajectory in our non-synaesthetic adult sample closely mimicked the pattern of the developmental trajectory in genuine synaesthesia.

Interestingly, the acquisitions of consistent grapheme-colour associations through engagement with graphemes and colours from basic categories resulted in a transfer of benefits to a more fine-grained test of consistency with a continuous colour palette and to recognition memory.

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Footnotes

¹ By contrast, studies investigating drug-induced synaesthesia are usually unable to find consistent synaesthetic associations, although participants report synaesthetic phenomenology (for a review see Luke & Terhune, 2013). These results recently led to the suggestion that the absence of opportunity for consolidation may account for the lack of consistency in drug-induced synaesthesia (cf. Luke & Terhune, 2013; Terhune et al., 2016).

Figures

Figure 1. a) Example screen of the continuous consistency test including a grapheme, the continuous colour palette and luminance scale for colour adjustments. The buttons included the words “OK” and “keine Farbe” (German for “no colour”). Clicking on either button initiated the next trial. b) Example screen of the categorical consistency test including a grapheme and 13 basic colours. The button in the lower right corner included the word “weiter” (German for “continue”). Clicking on this button initiated the next trial.

Figure 2. Trial procedure for the study phase (a, b) and test phase (c, d) of the word recognition task (a, c) and of the fractal recognition task (b, d).

Figure 3. a) Average CIELUV distances in the continuous consistency test as a function of group (explicit, implicit, control) and session (pre vs. post). Additionally, data from a synaesthetic sample tested in an ongoing study are presented. Lower values correspond to greater grapheme-colour consistency. Dots represent individual participants. The dashed line represents the synaesthetic threshold, values below the threshold are regarded as synaesthetic (cf. Rothen et al., 2013). Averaged CIELUV distances of all groups were above the synaesthetic threshold in the pre-session. In the post-session, averaged CIELUV distances of the explicit and the implicit group were below the synaesthetic threshold, and similar to a sample of genuine synaesthetes. This was not the case for the control group. b) Developmental trajectory of average categorical grapheme-colour consistency over the course of the engagement phase as a function of session and group (explicit vs. implicit). Here, higher values correspond to greater grapheme-colour consistency. Error bars in both sub-figures represent standard errors.

Figure 4. Average Euclidean distances between the colour choices in the first run of the continuous consistency test and the first run of the categorical consistency test, as a function of group (explicit vs. implicit) and session (pre vs. post). Error bars represent standard errors. Dots represent individual participants.

Figure 5. a) Proportion of colour choices over all graphemes (letters) per group and session, with colour on the x-axis (actual colours correspond to colour choices) and proportion on the y-axis. b) Colour-distributions for the letters with significant differences in the distribution of colour choices compared to the expected colour choices (e.g., the distribution of colour choices over all graphemes per group and session, as depicted in Figure 5a), for each group and session. All χ^2 s ≥ 10.05 and $ps \leq .038$. The value in the bar represents the frequency with which the colour was chosen for this specific grapheme.

Figure 6. Average d-prime scores from the a) word-recognition and b) fractal-recognition task as functions of session (pre vs. post) and group (explicit, implicit, control). Error bars represent standard errors. Dots represent individual participants.