COGNITIVE NEUROSCIENCE, 2015
Vol. 6, Nos. 2–3, 100–110, http://dx.doi.org/10.1080/17588928.2015.1056519

Red, green, blue equals 1, 2, 3: Digit-color synesthetes can use structured digit information to boost recall of color sequences

A. Lina Teichmann[1,2], Mark R. Nieuwenstein[2], and Anina N. Rich[1,3]

[1]Perception in Action Research Centre & Department of Cognitive Science, Macquarie University, Sydney, Australia
[2]Faculty of Behavioural and Social Sciences, Department of Experimental Psychology, University of Groningen, The Netherlands
[3]ARC Centre of Excellence in Cognition & its Disorders, Macquarie University, Sydney, Australia

Digit-color synesthetes report experiencing colors when perceiving letters and digits. The conscious experience is typically unidirectional (e.g., digits elicit colors but not *vice versa*) but recent evidence shows subtle bidirectional effects. We examined whether short-term memory for colors could be affected by the order of presentation reflecting more or less structure in the associated digits. We presented a stream of colored squares and asked participants to report the colors in order. The colors matched each synesthete's colors for digits 1–9 and the order of the colors corresponded either to a sequence of numbers (e.g., [red, green, blue] if 1 = red, 2 = green, 3 = blue) or no systematic sequence. The results showed that synesthetes recalled sequential color sequences more accurately than pseudo-randomized colors, whereas no such effect was found for the non-synesthetic controls. Synesthetes did not differ from non-synesthetic controls in recall of color sequences overall, providing no evidence of a general advantage in memory for serial recall of colors.

Keywords: Synesthesia; Digits; Color memory; Short-term memory; Bidirectional; Sequences; Serial recall.

Synesthesia is a rare phenomenon in which specific stimuli evoke unusual additional experiences within the same or in another sensory modality relative to the inducer (Grossenbacher & Lovelace, 2001; Ramachandran & Hubbard, 2001; Rich & Mattingley, 2002). Grapheme-color synesthesia is a common form of synesthesia in which letters and digits evoke highly consistent perceptions of specific colors (Barnett et al., 2008; Rich, Bradshaw, & Mattingley, 2005; Simner et al., 2005, 2006; see Chiou & Rich, 2014; for a recent review). Synesthetic experiences are usually described as being unidirectional, meaning a digit may evoke the perception of a color but a color does not elicit the perception of a digit (Mills, Boteler, & Oliver, 1999). However, empirical studies over the past decade suggest that the link between colors and graphemes can have subtle reverse effects in the absence of a reverse-conscious experience (Brugger, Knoch, Mohr, & Gianotti, 2004; Cohen Kadosh et al., 2005; Gevers, Imbo, Cohen Kadosh, Fias, & Hartsuiker, 2010; Johnson, Jepma, & De Jong, 2007; Knoch, Gianotti,

Correspondence should be addressed to: Anina N. Rich, Perception in Action Research Centre & Department of Cognitive Science, Macquarie University, Sydney, NSW 2109, Australia. E-mail: anina.rich@mq.edu.au

No potential conflict of interest was reported by the authors.
ALT was supported by a Marco Polo scholarship and the Groningen University Fund. ANR acknowledges the support of the Menzies Foundation.

Mohr, & Brugger, 2005; McCarthy, Barnes, Alvarez, & Caplovitz, 2013).

Most of the studies on bidirectional effects in synesthesia used speeded judgments and show subtle interference effects. It is also possible, however, that synesthetes can use this link more strategically. McCarthy et al. (2013) tested 10 digit-color synesthetes on a task that consisted of simple mathematical problems (e.g., "2 + 3 = 5") where participants had to verify or reject the solution. In different conditions, parts or all of the digits were replaced with the corresponding synesthetic colors. The results showed that digit-color synesthetes *were* able to calculate with colors only, but it was a cognitively effortful process: On average, an additional 250 ms per item was necessary to succeed in the task. Thus, it seems that although subtle interference effects occur in speeded tasks, presumably reflecting implicit activation of digit information by synesthetic links, retrieving the digit associated with a color requires conscious effort.

Here, we tested a group of digit-color synesthetes using a color memory task to test whether digit information linked to color could aid short-term memory for colors. Our approach is based on findings in non-synesthetes demonstrating that briefly presented structured ascending and descending digit sequences are significantly easier to recall than randomly generated digit sequences (Bor, Cumming, Scott, & Owen, 2004). We test the hypothesis that synesthetic links between colors and associated digits result in better performance for sequences of colors that match ascending or descending digit sequences relative to pseudo-random sequences. Furthermore, we investigate whether using the link between synesthetic color and digit is effortful, requiring additional time, or whether it occurs rapidly at time frames that do not allow strategic translation of color to digit.

There have been claims that synesthetes have superior memories compared to controls. There is still debate about the extent of any advantage and whether it is general (overall better memory) or specific to the domain of either their inducers (e.g., letters, words) or the synesthetic experiences themselves (concurrents; e.g., color; for a recent review see Rothen, Meier, & Ward, 2012). Case-studies seem to suggest that synesthetes have superior memories (e.g., Baron-Cohen et al., 2007; Luria, 1968; Mills, Innis, Westendorf, Owsianiecki, & McDonald, 2006; Smilek, Dixon, Cudahy, & Merikle, 2002). Baron-Cohen et al. (2007), Smilek et al. (2002), and Mills et al. (2006) each document cases of individual synesthetes with superior performance for material that induced their synesthesia (i.e., digits and words). We need to be cautious in generalizing from these single-case data, however, as there may be some selection bias: Such individuals tend to come to the attention of a research group because of their superior memories.

There is also evidence from group studies that synesthetes score higher in specific memory tasks than non-synesthetes (Gross, Neargarder, Caldwell-Harris, & Cronin-Golomb, 2011; Radvansky, Gibson, & McNerney, 2011; Rothen & Meier, 2010, 2009; Yaro & Ward, 2007). The extent of this advantage, however, seems to be more moderate than suggested by single cases. For instance, a recent large-scale group study shows that although synesthetes score higher than average on standardized memory tests, they do not typically fall in the superior or extraordinary range (Rothen & Meier, 2010). Evidence is mixed regarding memory in the domain of the inducer (e.g., graphemes for grapheme-color synesthetes). Group studies have found an advantage for synesthetes recalling word lists (Gross et al., 2011; Radvansky et al., 2011; Yaro & Ward, 2007), but not for recalling digits (Gross et al., 2011; Rothen & Meier, 2009, 2010; Yaro & Ward, 2007), although both elicit colors. In the domain of the concurrent (e.g., colors for grapheme-color synesthetes), Yaro and Ward (2007) found that synesthetes have better recognition memory for colored chips and their positions in a color matrix. Rothen and Meier (2010) found synesthetes had enhanced memory for abstract shape-color associations. Rothen et al. (2012) review other data implying synesthetes might generally be better at recalling visual information relating to abstract patterns.

A synesthete memory advantage could be due to greater visual or color sensitivity, which translates into better or more detailed recall (e.g., Pritchard, Rothen, Coolbear, & Ward, 2013; Terhune, Wudarczyk, Kochuparampil, & Kadosh, 2013). Alternatively (or perhaps as well), it may be that the additional information helps retention and recall, as has been proposed more generally as the dual coding theory of memory (Paivio, 1969). Here, we look at whether the activation of a digit upon presentation of a color can be used to enhance memory for a sequence of colors that is associated with either an ascending or descending sequence of digits. This paradigm allows a conceptual replication of recent studies testing whether synesthetes do indeed have better memory for color than non-synesthetes (Rothen & Meier, 2010; Yaro & Ward, 2007), as well as exploring the extent to which the structure of the associated information affects serial color memory. It is also relevant for the field of serial recall, in which a recent focus has been on the way structure or experience interacts with memory for sequential information (e.g., Botvinick & Plaut, 2006). By using synesthesia, in which the potentially beneficial structure is not physically presented, we can gain insights into the way such information influences learning and memory.

METHOD

Participants

We recruited 12 digit-color synesthetes (nine female; all right-handed; mean age = 34.5 years; *SD* = 12.4 years; range: 18–67 years) and 13 non-synesthete controls. We initially tested 12 controls but one was replaced due to mean accuracy in the color recall task in the slow condition being > 3*SD* lower than mean accuracy of the control group. All controls were matched to a synesthete in age, sex, and handedness (mean age = 34.0 years; *SD* = 12.4 years; range: 18–67 years) for the experiment. Overall, the participant groups did not differ significantly with regard to age ($t(22) < 1$, n.s). All participants reported normal or corrected-to-normal vision and color vision. None of the synesthetic participants experienced explicit bidirectionality: All synesthetes stated that digits evoke the additional experience of consistent colors but not *vice versa*. The synesthetes were highly consistent (*M* = 97.22%; *SD* = 0.07) in reporting their digit-color associations over a test-retest period varying from 3 to 64 months (*M* = 14.92 months; *SD* = 20.88). Basic characteristics of our synesthetes are summarized in Table 1.

All participants gave informed consent prior to the experiment and were paid $15/hour. This study was approved by the Human Research Ethics Committee of Macquarie University.

Apparatus

A Dell Optiplex 9010 computer running MATLAB 7.5 with Psychtoolbox3 (Brainard & Pelli, 1997; Kleiner et al., 2007) was used for stimulus presentation and response collection. Stimuli were presented on a 27-inch Samsung LCD monitor with a refresh rate of 120 Hz.

TABLE 1
Characteristics of our synesthete participants

Participant	*Gender*	*Age (years)*	*Handedness*	*Types of synesthesia*
S01	Female	30	Right	Grapheme-color*, auditory-visual
S02	Female	67	Right	Grapheme-color
S03	Male	35	Right	Grapheme-color
S04	Female	22	Right	Grapheme-color
S05	Female	39	Right	Grapheme-color
S06	Male	41	Right	Grapheme-color
S07	Male	30	Right	Grapheme-color, auditory-visual, touch-visual, olfactory-visual, gustatory-visual
S08	Female	28	Right	Grapheme-color, auditory-visual, olfactory-visual
S09	Female	38	Right	Grapheme-color
S10	Female	28	Right	Grapheme-color, auditory-visual
S11	Female	18	Right	Grapheme-color
S12	Female	38	Right	Grapheme-color

Note: *All synesthetes experienced colors induced by both letters and digits.

General procedure

All participants completed two separate behavioral tasks in a set order. The first task was designed to determine (1) whether synesthetes can use color-digit associations to improve their recall accuracy of color sequences, and (2) whether the process of translating the colors back to digits is strategic and time-consuming or quick and effortless. The second task was the synesthetic congruency task using colored digits (e.g., Mattingley, Rich, Yelland, & Bradshaw, 2001) to give a measure of strength of the digit-color links in these participants.

For the purpose of acquiring standardized scores of working memory performance, all participants were tested on the Digit Span Forward (DSF) and Digit Span Backward (DSB) subtests of the Wechsler Adult Intelligence Scale IV (WAIS-IV) and the Symbol Span (SS) task of the Wechsler Memory Scale IV (WMS-IV).

Synesthetic congruency task

Stimuli

We administered the synesthetic congruency task to ensure that all synesthetes tested had robust involuntary responses in the primary direction (digit to color) providing a basis for potential reverse, bidirectional effects (color to digit). Previous studies have demonstrated that synesthetes are slower to name the display color of a letter or digit when this color is incongruent with the synesthetic color than when the two colors match (Dixon, Smilek, & Merikle, 2004; Mattingley, Payne, & Rich, 2006; Mattingley et al., 2001; Mills et al., 1999; Rich & Karstoft, 2013; Wollen & Ruggiero, 1983).

Each of six digits were presented either in the color that matched the synesthetic color of each digit (previously matched by the synesthetes; *congruent condition*) or in one of the other colors (a single incongruent color for each digit; *incongruent condition*). The incongruent color was selected at random from the other five colors in the set with the restriction that it was not similar to the congruent color (e.g., red/orange) and did not start with the same sound (e.g., blue/brown). All stimuli were displayed in 140 pt Arial font on a light gray background (RGB triplet: 128, 128, 128).

Procedure

Each trial began with the presentation of a black fixation dot for 250 ms. Following this, a colored digit was displayed in the middle of the screen. Participants were instructed to name the display color of the colored digit as quickly and accurately as possible into the microphone. It was stressed that the physical color should be attended while the synesthetic color should be ignored. Errors were recorded manually and discarded. First, participants practiced for two blocks of 10 trials each. Then they completed 96 experimental trials with a short break after half the trials. An equal number of congruent and incongruent trials were randomly intermingled within each block.

Design

The synesthetic congruency task had a mixed factorial design. There was one between-subjects factor (*Group*) and one within-subjects factor (*Congruency*). Vocal naming onset times were recorded as the dependent variable. The significance threshold was set to p = .05.

Recalling color sequences

Stimuli

During each trial, five colored squares (5 cm × 5 cm) were displayed in quick succession in the center of the screen on a light gray background (RGB triplet = 128, 128, 128). Viewing distance was approximately 75 cm, making the squares ~3.82° of visual angle. After each trial, participants were asked to report the colors in the correct order by clicking with the computer mouse on the colors on a response screen (Figure 1). The colors corresponded to the synesthetic colors for the digits 1–9, tailored for each individual synesthete. Each synesthete's colors were also used for a matched non-synesthete control participant.

Stimulus presentation rates varied on a trial to trial basis between two duration conditions: Slow and fast. In both conditions, the colors were presented for 150 ms, but the inter-stimulus-interval (ISI) varied

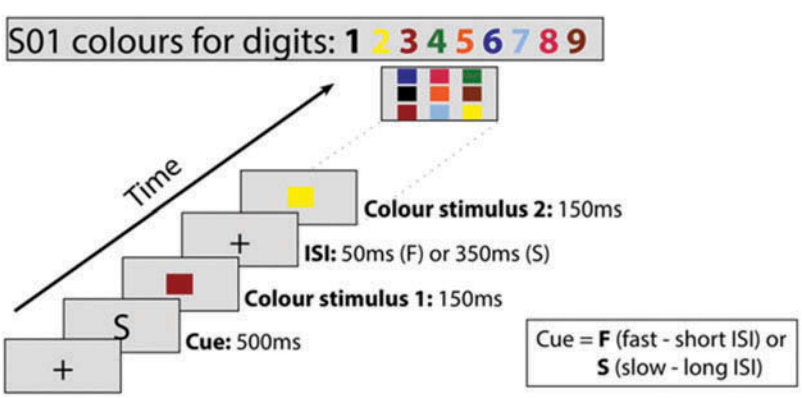

Figure 1. Example trial for S01. Each trial consists of a sequence of five colors. Here, only two are shown for simplicity. Each stimulus was displayed for 150 ms followed by either a 50 ms (*fast: 200 ms*) or 350 ms (*slow: 500 ms*) blank inter-stimulus interval. After all five color patches had been presented, the response screen appeared with the nine possible colors in random locations on a grid. Participants had to click on the colors in the correct order.

leading to a total presentation duration of 500 ms in the slow condition and 200 ms in the fast condition.

Structured sequences were defined as color sequences corresponding to an ascending or descending order of numbers (e.g., colors corresponding to digits 1-2-3-4-5-6-7-8-9 or colors corresponding to digits 9-8-7-6-5-4-3-2-1). We defined four different conditions, each containing a different degree of structure. One third of the structured trials contained five (e.g., black-yellow-red-green-orange = 1-2-3-4-5), one third contained four (e.g., brown-black-yellow-red-green = 9–1–2-3-4), and one third contained three (e.g., black-yellow-red-navy-brown = 1-2-3-6-9) colors corresponding to ascending or descending ordered digits. The position of the ordered part of the sequence varied (Figure 2). In the final condition ("Non-Structured"), the colors within the sequences were pseudo-randomized. All four conditions were randomly intermingled within a block. This ensured that synesthetes could not just remember a few colors of the sequence and then guess the correct order by choosing the remaining colors in sequential order.

As structured sequences were defined as being ascending or descending only, they had an unavoidable unevenness in the distribution of colors. For instance, the Structured 5 condition (Figure 2) contains the color for digit 1 only twice, whereas the color corresponding to digit 6 appears in eight sequences. Therefore, the non-structured sequences were pseudo-randomized by permuting the digits beforehand. Following this, the non-structured sequences were designed in exactly the same way as the structured sequences (Figure 2). The permutation of the digits resulted in a pseudo-randomized set of colors (e.g., colors corresponding to digits 5-8-1-6-2-9-3-7-4). Based on this pseudo-randomized order, we constructed color sequences that contained varying degrees of "pseudo-order." Similar to the structured sequences, one third of the non-structured sequences contained five (e.g., orange-maroon-black-navy-yellow = 5-8-1-6-2), one third contained four (e.g., orange-maroon-black-navy-red = 5-8-1-6-3), and the last third contained three (e.g., orange-maroon-black-blue-red = 5-8-1-7-3) "pseudo-ordered" items. Note that the three, four, and five pseudo-ordered trial conditions are actually all non-sequential, and therefore together form a baseline condition for measuring performance on this color short-term memory task without sequences of digits. However, the careful matching of our conditions ensures an equal presentation frequency of color pairs in the structured and non-structured conditions. For each of the six different trial types, there were 10 sequences (Figure 2). The sequence order within each condition was randomized. After presentation of each sequence once, the sequence order within each condition was randomized again for the next presentation.

In cases where two digits evoked an identical synesthetic color, one of these colors was removed, meaning the colors for eight digits instead of nine were used. This was only possible when either digit

S01: Synaesthetic colours for digits & sequences

Colour digits structured			Colour digits pseudo-randomised		
1 2 3 4 5 6 7 8 9			5 8 1 6 2 9 3 7 4		
Structured 5	Structured 4	Structured 3	Non-Structured 5	Non-Structured 4	Non-Structured 3
1 2 3 4 5	1 2 3 4 7	5 1 2 3 7	5 8 1 6 2	5 8 1 6 3	2 5 8 1 3
2 3 4 5 6	9 2 3 4 5	3 4 5 8 1	8 1 6 2 9	4 8 1 6 2	1 6 2 7 5
3 4 5 6 7	3 4 5 6 8	9 2 4 5 6	1 6 2 9 3	1 6 2 9 7	4 8 6 2 9
4 5 6 7 8	2 4 5 6 7	1 6 7 8 5	6 2 9 3 7	8 6 2 9 3	5 9 3 7 2
5 6 7 8 9	5 6 7 8 1	2 4 7 8 9	2 9 3 7 4	2 9 3 7 5	8 6 3 7 4
9 8 7 6 5	9 8 7 6 4	5 2 9 8 7	4 7 3 9 2	4 7 3 9 6	2 8 4 7 3
8 7 6 5 4	3 8 7 6 5	8 7 6 4 2	7 3 9 2 6	1 7 3 9 2	7 3 9 6 8
7 6 5 4 3	7 6 5 4 9	1 6 5 4 9	3 9 2 6 1	3 9 2 6 4	5 9 2 6 4
6 5 4 3 2	8 6 5 4 3	4 3 2 5 8	9 2 6 1 8	7 9 2 6 1	6 1 8 2 7
5 4 3 2 1	7 4 3 2 1	8 3 2 1 6	2 6 1 8 5	3 6 1 8 5	7 1 8 5 9

Figure 2. Example stimulus set for the three structured and the non-structured (baseline) conditions for synesthete 01. Top section: The colors elicited by each digit for this synesthete; Bottom section: The colors corresponding to these digits presented in the different conditions, with underlining highlighting the (pseudo-)structured sections. Note in the actual trial, the colors corresponding to these digits were presented, not the digits themselves.

1 or 9 was identical in color to another digit. This occurred for two of our synesthetes and in these two stimulus sets only eight sequences in the Structured 5 and Non-Structured 5 conditions could be constructed (S02 & S03). For two additional synesthetes, the identical synesthetic colors were evoked for two digits that were neither 1 nor 9. In these cases one color could not simply be eliminated since doing so would interrupt multiple structured sequences. Hence, the synesthetes affected by this (S07 & S12) completed the normal stimulus set with all nine colors despite the repetition of colors. S12 reported that the identical colors caused some ambiguity and therefore hampered her ability to translate the colors back to the digits in the short time frame. S07 did not believe that the identical colors impacted his performance. In all cases, the matched control viewed the identical stimuli as the appropriate synesthete.

Procedure

Before the experiment, examples of structured and non-structured sequences were shown. Each participant completed 30 practice trials (which were not analyzed) followed by 240 experimental trials. Five sequences from each condition were presented in the practice trials, which introduced a random factor to the frequency at which a particular sequence was shown in the experimental trials. As a result, each of the 10 sequences appeared either four or five times in the actual experiment. Participants were provided with feedback on their performance during practice only.

At the beginning of each trial, a black fixation cross was displayed in the middle of the screen. Participants initiated the trial by clicking the mouse. After clicking, the fixation cross stayed on the screen for another 500 ms, followed by a visual cue for 500 ms, indicating whether the upcoming trial would be fast (visual cue: “F”) or slow (visual cue: “S”; Figure 1). In the fast condition, each of the five colored squares was presented for 150 ms with an ISI blank screen of 50 ms (200 ms condition). In the slow condition, each of the colored squares was also presented for 150 ms but now the ISI was 350 ms (500 ms condition). The different types of sequences (i.e., structured and non-structured), and different presentation durations (i.e., 200 ms and 500 ms) appeared 20 times each and were randomly intermingled.

Following the stream of stimuli, participants were asked to report the colors in order using the computer mouse to click the colors on a response screen. This response screen had the nine possible colors displayed in a 3 × 3 grid. The squares were presented in the same dimensions (5 cm × 5 cm) as they were during stimulus presentation. Grid locations were pre-specified, however, the position of each individual color varied on a trial-to-trial basis to avoid recall of specific motor sequences. The response grid remained on the screen until all five responses were made.

Design

The experiment has a mixed factorial design. There was one between-group factor (*Group*) and two within-subject factors (*Sequence Structure* and *Duration*). Accuracies were calculated as the dependent variable. The accuracy of recall was scored as the percentage of colors that was reported in the correct serial position for each trial, and then the average accuracy calculated for each condition. This conservative measure of color memory was deliberately selected as we are interested in the potential benefit synesthetes have in recalling the correct *sequence* of colors. The significance threshold was set at $p = .05$.

RESULTS

For both digit spans (forward, backward) and the symbol span, scores are standardized according to the normative data provided in the WMS. Both synesthetes and controls showed average working memory capacities for their age. Consistent with results of previous studies (e.g., Rothen & Meier, 2010), there was no significant difference between the groups (Table 2).

TABLE 2
Summary of scaled mean scores (*SD*) of digit span forward, digit span backward, and symbol span for synesthetes and controls. Scaled scores of 10 reflect an average score with scores between 7 and 13 being in the average range (10 ± 1*SD*). The *t*-tests compare the mean scaled scores of the groups. There were no significant differences

	Groups				
	Synesthetes	*Controls*	*t*	*df*	*p*
Digit Span Forward	11.0 (3.72)	10.67 (2.06)	0.27	22	.79
Digit Span Backward	11.41 (2.84)	11.25 (2.86)	0.14	22	.89
Symbol Span	11.08 (2.64)	11.0 (2.92)	0.07	22	.94

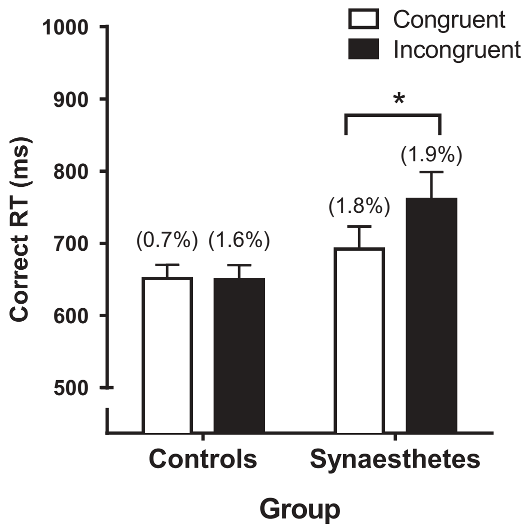

Figure 3. Mean correct color naming times (in milliseconds) for controls and synesthetes in the two congruency conditions. Percentage of incorrect responses is shown in parentheses above each bar. Asterisk indicates a significant difference at a threshold of 0.05. Error bars reflect standard error of the mean.

Synesthetic congruency task

Microphone errors and incorrect responses were coded manually. Prior to data analysis, an average of 1.42% (SD = 1.92) of trials were removed due to microphone errors. We calculated the percentage of incorrect responses from the remaining trials (shown in parentheses in Figure 3).

The mean correct reaction times were calculated per participant (Figure 3). A repeated measures two-way ANOVA revealed no significant main effect of *Group,* $F(1, 22) = 3.87$, $MSE = 18001.62$, but a significant main effect of *Congruency,* $F(1, 22) = 12.4$, $MSE = 1092.7$, $p = .002$, $\eta_P^2 = 0.36$, tempered by a significant two-way interaction with *Group,* $F(1, 22) = 13.67$, $MSE = 14933.96$, $p = .001$, $\eta_P^2 = 0.38$. Post hoc comparisons showed a significant effect for synesthetes ($p < .0001$) and no effect for controls ($p = .9$).

Recalling color sequences

As described in the methods, we scored the percentage of colors correctly reported in the right position for each trial, and then calculated the average accuracy for each condition for each participant. Chance performance of reporting all five colors correctly in the correct position is ~11%.

We first consider the data of the pseudo-randomized sequences to ensure we can collapse across the different versions into a single baseline condition for each duration. We conducted a three-way repeated measures ANOVA on accuracy data with *Pseudo-Structure* (Non-Structured 3, Non-Structured 4, Non-Structured 5; Figure 1) and *Duration* (200 ms and 500 ms) as within-subjects factors and *Group* (synesthetes and controls) as a between-subjects factor. There were no significant effects of *Group,* $F(1, 22) < 1$, n.s., and *Pseudo-Structure,* $F(2, 44) < 1$, n.s., but a significant effect of *Duration,* $F(1, 22) = 135$, $MSE = 187.67$, $p < .0001$. There were no significant interactions (all Fs < 1). As there was no difference between the degrees of *Pseudo-Structure* in the sequences but a significant difference between the two *Duration* conditions, the mean score of the accuracies across the non-structured conditions was calculated for each duration and used as the baseline condition.

The full dataset is shown in Figure 4 for the fast (Figure 4a) and slow (Figure 4b) conditions. A three-way ANOVA with between-subject factor *Group* (synesthetes and controls) and within-subjects factors *Duration* (200 and 500 ms) and *Structure* (Baseline, Structured3, Structured4, Structured5) revealed no significant effect of *Group,* $F(1, 22) < 1$, n.s., but a significant main effect of *Duration,* $F(1, 22) = 196.1$, $MSE = 210.42$, $p < .0001$, $\eta_P^2 = 0.9$, and *Structure,* $F(3, 66) = 5.62$, $MSE = 33.57$, $p = .002$, $\eta_P^2 = 0.2$. The interaction between *Duration* and *Group* was not significant, $F(1, 22) < 1$, n.s. reflecting the unsurprising finding that both synesthetes and controls perform better at the longer than shorter duration. Importantly, however, there was a significant interaction between *Group* and *Structure,* $F(3, 66) = 4.19$, $MSE = 33.57$, $p = .009$, $\eta_P^2 = 0.16$. The three-way interaction between *Group, Duration*, and *Structure* was not significant, $F(3, 66) < 1$, n.s.

The significant interaction between *Group* and *Structure* demonstrates that synesthetes and controls are affected differently by the manipulation of sequences. We conducted simple main effects (post hoc comparisons) for each group separately. Synesthetes were significantly better in recalling colors in; Structured 5 condition and the Structured 4 condition relative to the baseline ($p < .001$, $p = .01$ respectively), but there was no significant difference between the baseline and the Structured 3 condition ($p = .56$). There was a significant difference between the Structured 3 and Structured 4 ($p = .02$) and between the Structured 3 and the Structured 5 conditions ($p = .001$) but there was no significant difference between the Structured 4 and Structured 5 conditions ($p = .09$). Thus, only for synesthetes is

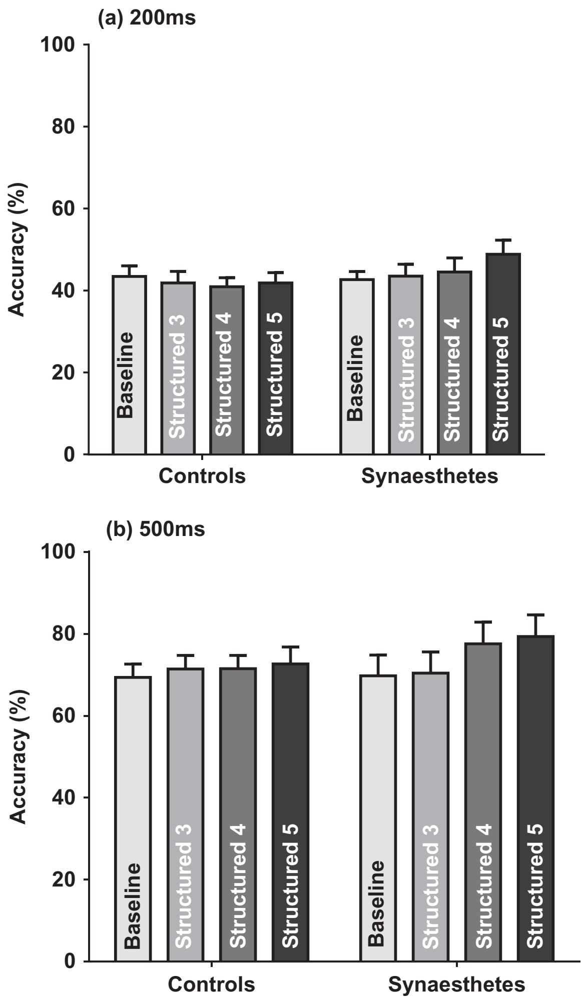

Figure 4. Recall accuracies for baseline and structured sequences per group. (a) Results from the fast condition (200 ms). (b) Results from the slow condition (500 ms). Note that reporting a color was only considered accurate if it was reported in the correct position. The baseline condition corresponds to the mean performance in the three non-structured conditions. Error bars reflect standard error of the mean.

there an effect of sequence structure, and this only occurs when at least four out of the five colors form a sequence. If we compare the performance of the two groups at each level of structure, using a between-subjects comparison, we do not find evidence that synesthetes are better than controls, even at high levels of structure (all *p*s > .18). This lack of a between-group difference is likely to reflect a lack of statistical power. Although synesthetes were able to benefit from the presence of high levels of structure relative to no or low structure, this benefit was not sufficiently large to produce a significant recall benefit compared to the non-synesthetic controls with the sample sizes used in the current study.

The lack of a three-way interaction between our factors could be because the same pattern of results occurs at both fast and slow durations *or* it could reflect a lack of power to detect a difference between the durations.[1] As our key question was whether there was an effect of sequence structure with and without sufficient time for strategic translation of colors to digits, we conducted a further exploratory two-way ANOVA with *Group* as between-subjects factor and *Structure* as a within-subjects factor separately on data from the two durations. In the fast condition (Figure 4a), there were no significant effects of *Group,* $F(1, 22) = 0.74$, $MSE = 67.44$, or *Structure,* $F(2.06, 45.21) = 1.4$, $MSE = 50.14$ (Greenhouse-Geisser corrected for violation of sphericity), and no interaction between the two, $F(2.06, 45.21) = 1.87$, $MSE = 50.14$.

The analogous analysis on data from the slow condition (Figure 4b) showed no significant effects of *Group,* $F(1, 22) = 0.26$, $MSE = 216.95 < 1$, n.s., but a significant effect of *Structure,* $F(3, 66) = 8.17$, $MSE = 26.68$, $p < .0001$, $\eta_P^2 = 0.27$, and a significant interaction between *Group* and *Structure,* $F(3, 66) = 3.42$, $MSE = 26.68$, $p = .02$, $\eta_P^2 = 0.14$. To identify the source of the interaction, we separated the data by *Group*. Simple main effects on the control group showed no effect of structure, $F(3, 33) < 1$, n.s. However, synesthetes' accuracy depended on sequence structure, $F(3, 33) = 12.0$, $MSE = 23.88$, $p < .0001$. Synesthetes performed significantly better in the fully structured (Structured 5) sequences compared to the baseline condition ($p = .002$) and to the Structured 3 condition ($p = .002$). There was no significant difference between the Structured 3 and baseline conditions ($p = .69$) or between the Structured 5 and Structured 4 conditions ($p = .43$). Furthermore, the synesthetes had higher recall accuracy for sequences in the Structured 4 condition in comparison to the baseline condition ($p = .002$) and to the Structured 3 condition ($p = .001$). Again, post hoc analyses by *Structure* did not show significant differences between synesthetes and controls (all *p*s > .33). Although we expected to see an effect at least at the Structured 5 condition, the difference in

[1]We also calculated Bayes Factors (BF; Love et al., 2015) for the key contrasts. 200 ms Structured 5 vs. Baseline: Synesthetes $BF_{10} = 1.14$, Controls $BF_{10} = 0.41$; 500 ms Synesthetes $BF_{10} = 21.79$, Controls $BF_{10} = 0.57$. A BF of ~1 is an indication that we do not have enough power to differentiate whether there is evidence for the null or alternative hypothesis (Dienes, 2011) for synesthetes in the 200 ms case. We therefore only have clear evidence that there is no effect for controls in either condition, and that structure affects synesthetes in the 500 ms condition.

means is 6.67%, making it likely we would require more power to detect such a subtle effect in between-subjects comparisons.

To examine whether the synesthetes were better in the structured than baseline condition simply because of a bias toward reporting the colors in an order that matches an ascending or descending sequence of the associated digits in the synesthete group (as seen in Knoch et al., 2005), we compared false alarms of structure in two ways. We looked at pseudo-random trials in the slow condition with a low accuracy (40% or lower). In those trials we compared the frequencies of cases in which at least four colors were falsely reported in ascending or descending order.[2] The control group mistakenly chose colors in ascending or descending order in 1.61% (*SD* = 3.69%) of the pseudo-random trials with low accuracy. Synesthetes reported an ascending or descending color structure in 2.18% (*SD* = 4.62%) of those trials. There was no significant difference between the groups in the percentages of these false alarms, $t(18) = 0.31$, $p = .76$, and the low rates of the occurrence of counting false alarms suggest our effects are unlikely to be due to a counting bias for synesthetes. In addition, we checked the responses in the Structured 4 condition to see whether synesthetes were biased toward reporting fully ascending or descending color sequences when they recognized two or three colors in order (despite our design reducing the benefit of such a strategy by including Structure 3 and 4 conditions). Such a strategy could artificially boost performance for the Structured 5 condition. However, for the 500 ms condition, synesthetes only erroneously reported a full sequence on 2% of all Structured 4 trials. Controls reported fully ascending or descending sequences in 1.5% of the Structured 4 trials. There was no significant difference between the groups with regard to false alarms in the Structured 4 condition ($t(18) = 0.325$, $p = .75$). The low rate and similar performance across the groups further suggests that over-reporting of fully structured sequences does not drive our synesthete effect.

DISCUSSION

In this study we addressed the question of whether the activation of digits by colors can improve recall of color sequences in digit-color synesthetes. Synesthetes showed a specific memory benefit for structured sequences compared to unstructured sequences. Synesthetes were not, however, significantly better than controls at the task overall, suggesting this is not a general superiority in color memory or enhanced perceptual sensitivity, but rather is related to strategic use of the link between a color and the digit that elicits it. Consistent with previous findings (Gross et al., 2011; Rothen & Meier, 2010; Yaro & Ward, 2007), we did not find any differences between synesthetes and controls on standardized memory tasks (i.e., digit span forward and backward, symbol span). A previous study showed an advantage for synesthetes in recalling spatial positions of colors (Yaro & Ward, 2007), Here, we show that under specific circumstances, namely when digits form a structured sequence and there is sufficient time, synesthetes can use their link between colors and digits to improve sequential memory. Thus, this study provides evidence that synesthetes can use the connection between a digit and a color to enhance short-term memory for colors, in the absence of any overall superiority in color memory in this task or standardized working memory tasks.

A visual sensitivity account of enhanced memory in synesthetes suggests that synesthetes perform better than controls because they have, either in general or in the category of the concurrent, greater sensitivity to visual stimuli (Pritchard et al., 2013; Rothen et al., 2012; Terhune et al., 2013). In our task, such an account predicts that synesthetes should be better at remembering color sequences regardless of whether the digits associated with these colors are sequential. A general dual-coding account, based on Parvio's (1969) hypothesis, could require the additional (redundant) information to be consciously perceived, but if one accepts that implicit activation of additional information is sufficient (Rothen et al., 2012), such an account would also predict better performance in general for synesthetes on our task. Our data, however, do not support either a visual sensitivity or dual-coding account of synesthete enhanced performance, unless one allows for a more circumscribed dual-coding hypothesis: The additional information is only useful if it is more memorable or easier to recall than the original information. We find clear evidence that synesthetes can use the link between digits and colors to boost color memory provided that there is sufficient time to retrieve the digits strategically and that the digits form an ascending or descending sequence. This effect did not, with our sample size, give them a clear advantage over controls even when the sequence was completely structured.

The current data demonstrate that synesthetes can translate sequences of colors into sequences of digits

[2]We were unable to calculate false alarms in this way for synesthetes S7 and S12 and their corresponding controls because they had two identical color associations that corresponded to two different numbers.

to cue recall of color. Although a significant benefit of structure was only observed in the slow condition in our exploratory analysis, the difference between the slow and fast conditions failed to reach statistical significance as an interaction in the main analysis.[3] Thus, although the strongest evidence is for a strategic translation of color to associated digit, we cannot rule out that more automatic processes might also be contributing.

Concerns about better synesthete performance potentially reflecting greater motivation or non-specific experimental effects (e.g., Gheri, Chopping, & Morgan, 2008) have been raised with regard to previous studies. Here, our synesthetes showed superior performance in one condition relative to their own baseline, in the context of similar performance to controls overall. They were unable to predict the condition of each trial due to the random intermingling, ruling out a selective bias account. Therefore, the advantage for synesthetes in our study cannot be accounted for by differences in motivation.

Our findings are consistent with previous studies on bidirectional effects of colors linked synesthetically with digits or letters. Although most of these examined implicit activation of digits by colors using speeded congruency measures (Brugger et al., 2004; Cohen Kadosh et al., 2005), there is one other study that examined whether numerical information could be accessed explicitly. McCarthy et al. (2013) found that synesthetes could use color patches to perform arithmetic operations. The findings of the present study corroborate the results of McCarthy et al. (2013) in demonstrating that synesthetes can translate sequences of colors into sequences of digits, but we need further research to determine the time course and automaticity of this translation process and whether it can be used to enhance performance relative to non-synesthetes. Such a strategy could be useful in studies of serial recall, in which researchers seek to understand the way in which our previous knowledge and experience influence the way we encode and recall sequential information.

In conclusion, despite equal performance on standardized working memory tests and overall color serial recall, digit-color synesthetes showed an advantage in recalling color sequences that correspond to a structured sequence of digits relative to less or unstructured sequences. This advantage was most pronounced when the color sequences were presented relatively slowly. These findings suggest that synesthetes can strategically activate digits when presented with synesthetic colors in order to boost their color memory.

Original manuscript received 4 December 2014
Revised manuscript received 26 May 2015
First published online 6 July 2015

[3]It is worth noting that the lack of a significant structure effect in the fast presentation condition is unlikely to be due to an inability to perceive a rapid sequence of ascending or descending digits in the correct order. Research has shown that participants have little difficulty in perceiving and remembering other types of structured sequences, such as sentences presented word by word at rates of up to 10 words per second (e.g., Potter, Nieuwenstein, & Strohminger, 2008).

REFERENCES

Barnett, K. J., Finucane, C., Asher, J. E., Bargary, G., Corvin, A. P., Newell, F. N., & Mitchell, K. J. (2008). Familial patterns and the origins of individual differences in synaesthesia. *Cognition*, *106*(2), 871–893. doi:10.1016/j.cognition.2007.05.003

Baron-Cohen, S., Bor, D., Billington, J., Asher, J., Wheelwright, S., & Ashwin, C. (2007). Savant memory in a man with colour form-number synaesthesia and asperger. *Journal of Consciousness Studies*, *14*(9–10), 237–251.

Bor, D., Cumming, N., Scott, C. E., & Owen, A. M. (2004). Prefrontal cortical involvement in verbal encoding strategies. *European Journal of Neuroscience*, *19*(12), 3365–3370. doi:10.1111/j.1460-9568.2004.03438.x

Botvinick, M. M., & Plaut, D. C. (2006). Short-term memory for serial order: A recurrent neural network model. *Psychological Review*, *113*(2), 201–233. doi:10.1037/0033-295X.113.2.201

Brainard, D. H., & Pelli, D. G. (1997). The psychophysics toolbox. *Spatial Vision*, *10*, 433–436. doi:10.1163/156856897X00357

Brugger, P., Knoch, D., Mohr, C., & Gianotti, L. R. (2004). Is digit-color synaesthesia strictly unidirectional? Preliminary evidence for an implicitly colored number space in three synaesthetes. *Acta Neuropsychologica*, *2*(3), 252–258.

Chiou, R., & Rich, A. N. (2014). The role of conceptual knowledge in understanding synaesthesia: Evaluating contemporary findings from a “hub-and-spokes” perspective. *Frontiers in psychology*, 5, 1–18 (article number 105). doi:10.3389/fpsyg.2014.00105

Cohen Kadosh, R., Sagiv, N., Linden, D. E., Robertson, L. C., Elinger, G., & Henik, A. (2005). When blue is larger than red: Colors influence numerical cognition in synesthesia. *Journal of Cognitive Neuroscience*, *17*(11), 1766–1773. doi:10.1162/089892905774589181

Dienes, Z. (2011). Bayesian versus orthodox statistics: Which side are you on? *Perspectives on Psychological Science*, *6*(3), 274–290. doi:10.1177/1745691611406920

Dixon, M. J., Smilek, D., & Merikle, P. M. (2004). Not all synaesthetes are created equal: Projector versus associator synaesthetes. *Cognitive, Affective, & Behavioral Neuroscience*, *4*(3), 335–343. doi:10.3758/CABN.4.3.335

Gevers, W., Imbo, I., Cohen Kadosh, R., Fias, W., & Hartsuiker, R. J. (2010). Bidirectionality in synesthesia: Evidence from a multiplication verification task.

Experimental Psychology, *57*(3), 178. doi:10.1027/1618-3169/a000022
Gheri, C., Chopping, S., & Morgan, M. (2008). Synaesthetic colours do not camouflage form in visual search. *Proceedings of the Royal Society B: Biological Sciences*, *275*(1636), 841–846. doi:10.1098/rspb.2007.1457
Gross, V. C., Neargarder, S., Caldwell-Harris, C. L., & Cronin-Golomb, A. (2011). Superior encoding enhances recall in color-graphemic synesthesia. *Perception-London*, *40*(2), 196.
Grossenbacher, P. G., & Lovelace, C. T. (2001). Mechanisms of synesthesia: Cognitive and physiological constraints. *Trends in Cognitive Sciences*, *5*(1), 36–41. doi:10.1016/S1364-6613(00)01571-0
Johnson, A., Jepma, M., & De Jong, R. (2007). Colours sometimes count: Awareness and bidirectionality in grapheme–colour synaesthesia. *The Quarterly Journal of Experimental Psychology*, *60*(10), 1406–1422. doi:10.1080/17470210601063597
Kleiner, M., Brainard, D., Pelli, D., Ingling, A., Murray, R., & Broussard, C. (2007). What's new in Psychtoolbox-3. *Perception*, *36*(14), 1.
Knoch, D., Gianotti, L. R., Mohr, C., & Brugger, P. (2005). Synesthesia: When colors count. *Cognitive Brain Research*, *25*(1), 372–374. doi:10.1016/j.cogbrainres.2005.05.005
Love, J., Selker, R., Marsman, M., Jamil, T., Verhagen, A. J., Ly, A., & Wagenmakers, E.-J. (2015). JASP (Version 0.6.5).
Luria, A. (1968). *The Mind of a Mnemonist: A little book about a vast memory.* (L. Solotaroff, trans.) New York: Basic Books.
Mattingley, J. B., Payne, J. M., & Rich, A. N. (2006). Attentional load attenuates synaesthetic priming effects in grapheme-colour synaesthesia. *Cortex*, *42*(2), 213–221. doi:10.1016/S0010-9452(08)70346-0
Mattingley, J. B., Rich, A. N., Yelland, G., & Bradshaw, J. L. (2001). Unconscious priming eliminates automatic binding of colour and alphanumeric form in synaesthesia. *Nature*, *410*(6828), 580–582. doi:10.1038/35069062
McCarthy, J. D., Barnes, L. N., Alvarez, B. D., & Caplovitz, G. P. (2013). Two plus blue equals green: Grapheme-color synesthesia allows cognitive access to numerical information via color. *Consciousness and Cognition*, *22*(4), 1384–1392. doi:10.1016/j.concog.2013.09.005
Mills, C. B., Boteler, E. H., & Oliver, G. K. (1999). Digit synaesthesia: A case study using a Stroop-type test. *Cognitive Neuropsychology*, *16*(2), 181–191. doi:10.1080/026432999380951
Mills, C. B., Innis, J., Westendorf, T., Owsianiecki, L., & McDonald, A. (2006). Effect of a synesthete's photisms on name recall. *Cortex*, *42*(2), 155–163. doi:10.1016/S0010-9452(08)70340-X
Paivio, A. (1969). Mental imagery in associative learning and memory. *Psychological Review*, *76*(3), 241–263. doi:10.1037/h0027272
Potter, M. C., Nieuwenstein, M., & Strohminger, N. (2008). Whole report versus partial report in RSVP sentences. *Journal of Memory and Language*, *58*(4), 907–915. doi:10.1016/j.jml.2007.12.002
Pritchard, J., Rothen, N., Coolbear, D., & Ward, J. (2013). Enhanced associative memory for colour (but not shape or location) in synaesthesia. *Cognition*, *127*(2), 230–234. doi:10.1016/j.cognition.2012.12.012
Radvansky, G. A., Gibson, B. S., & McNerney, M. (2011). Synesthesia and memory: Color congruency, von Restorff, and false memory effects. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *37*(1), 219.
Ramachandran, V. S., & Hubbard, E. M. (2001). Synaesthesia–a window into perception, thought and language. *Journal of Consciousness Studies*, *8*(12), 3–34.
Rich, A. N., Bradshaw, J. L., & Mattingley, J. B. (2005). A systematic, large-scale study of synaesthesia: Implications for the role of early experience in lexical-colour associations. *Cognition*, *98*(1), 53–84. doi:10.1016/j.cognition.2004.11.003
Rich, A. N., & Karstoft, K.-I. (2013). Exploring the benefit of synaesthetic colours: Testing for "pop-out" in individuals with grapheme–colour synaesthesia. *Cognitive Neuropsychology*, *30*(2), 110–125. doi:10.1080/02643294.2013.805686
Rich, A. N., & Mattingley, J. B. (2002). Anomalous perception in synaesthesia: A cognitive neuroscience perspective. *Nature Reviews Neuroscience*, *3*(1), 43–52. doi:10.1038/nrn702
Rothen, N., & Meier, B. (2009). Do synesthetes have a general advantage in visual search and episodic memory? A case for group studies. *PLoS One*, *4*(4), e5037.
Rothen, N., & Meier, B. (2010). Grapheme–colour synaesthesia yields an ordinary rather than extraordinary memory advantage: Evidence from a group study. *Memory*, *18*(3), 258–264. doi:10.1080/09658210903527308
Rothen, N., Meier, B., & Ward, J. (2012). Enhanced memory ability: Insights from synaesthesia. *Neuroscience & Biobehavioral Reviews*, *36*(8), 1952–1963. doi:10.1016/j.neubiorev.2012.05.004
Simner, J., Mulvenna, C., Sagiv, N., Tsakanikos, E., Witherby, S. A., Fraser, C., & Ward, J. (2006). Synaesthesia: The prevalence of atypical cross-modal experiences. *Perception-London*, *35*(8), 1024–1034. doi:10.1068/p5469
Simner, J., Ward, J., Lanz, M., Jansari, A., Noonan, K., Glover, L., & Oakley, D. A. (2005). Non-random associations of graphemes to colours in synaesthetic and non-synaesthetic populations. *Cognitive Neuropsychology*, *22*(8), 1069–1085. doi:10.1080/02643290500200122
Smilek, D., Dixon, M. J., Cudahy, C., & Merikle, P. M. (2002). Synesthetic color experiences influence memory. *Psychological Science*, *13*(6), 548–552. doi:10.1111/1467-9280.00496
Terhune, D. B., Wudarczyk, O. A., Kochuparampil, P., & Kadosh, R. C. (2013). Enhanced dimension-specific visual working memory in grapheme–color synesthesia. *Cognition*, *129*(1), 123–137. doi:10.1016/j.cognition.2013.06.009
Wollen, K. A., & Ruggiero, F. T. (1983). Colored-letter synesthesia. *Journal of Mental Imagery*, *7*(2), 83–86.
Yaro, C., & Ward, J. (2007). Searching for Shereshevskii: What is superior about the memory of synaesthetes? *The Quarterly Journal of Experimental Psychology*, *60*(5), 681–695. doi:10.1080/17470210600785208