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Digit-colour synaesthesia only enhances memory for colours in a specific context: A new method of duration thresholds to measure serial recall

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Abstract

For digit-colour synaesthetes, digits elicit vivid experiences of colour that are highly consistent for each individual. The conscious experience of synaesthesia is typically unidirectional: Digits evoke colours but not *vice versa*. There is an ongoing debate about whether synaesthetes have a memory advantage over non-synaesthetes. One key question in this debate is whether synaesthetes have a general superiority or whether any benefit is specific to a certain type of material. Here, we focused on immediate serial recall and asked digit-colour synaesthetes and controls to memorise digit and colour sequences. We developed a sensitive staircase method manipulating *presentation duration* to measure participants' serial recall of both overlearnt and novel sequences. Our results show that synaesthetes can activate digit information to enhance serial memory for *colour* sequences. When colour sequences corresponded to ascending or descending digit sequences, synaesthetes encoded these sequences at a faster rate than their non-synaesthetic counterparts and faster than non-structured colour sequences. However, encoding colour sequences is approximately 200 ms slower than encoding digit sequences directly, independent of group and condition, which shows that the translation process is time-consuming. These results suggest memory advantages in synaesthesia require a modified dual coding account, in which secondary (synaesthetically-linked) information is only useful if it is more memorable than the primary information to be recalled. Our study further shows that duration thresholds are a sensitive method to measure subtle differences in serial recall performance.

Keywords: Immediate serial recall; synaesthesia; digits; colours; short-term memory; bidirectionality; staircase

Public Significance Statement

This study shows that our ability to recall information presented rapidly in series is better when there is structure, such as ascending or descending digit sequences, than when there is no structure. It shows that in a special group of *synaesthetes*, for whom digits elicit consistent and involuntary experiences of colour, serial memory is not better for digits than non-synaesthetic controls, but is better for colours when there is an underlying structure based on their digit-colour associations (e.g., ‘red, green, blue’ if red = 1, green = 2, and blue = 3). This suggests that additional associations need to be more memorable than the primary information to enhance memory. This study presents a new method for measuring serial memory that can detect subtle differences between groups that will be useful for both research and clinical tests of memory.

Introduction

In synaesthesia, an ordinary stimulus results in an extraordinary experience (Grossenbacher & Lovelace, 2001; Ramachandran & Hubbard, 2001; Rich & Mattingley, 2002). For example, a sound (the 'inducer') can elicit a coloured shape (Chiou, Stelter, & Rich, 2013) (the 'concurrent') , or letters, digits and words elicit colours. These experiences are typically highly consistent over time (Baron-Cohen, Burt, Smith-Laittan, Harrison, & Bolton, 1996) and can occur within a modality or across different modalities. Here, we focus on colours elicited by digits to examine whether synaesthesia can enhance serial recall for either inducers (digits) or concurrents (colours).

Over the past three decades, there has been considerable progress in understanding the cognitive and neural mechanisms underpinning synaesthesia. The link between digits and their elicited colours is thought to depend critically on attention to the inducer (Edquist, Rich, Brinkman, & Mattingley, 2006; Mattingley, Payne, & Rich, 2006; Rich & Mattingley, 2010; Sagiv, Heer, & Robertson, 2006). Once an inducer is attended, though, synaesthetic colours occur involuntarily, such that they influence colour naming times (e.g., Chiou et al., 2013; Mattingley, Rich, Yelland, & Bradshaw, 2001; Mills, Boteler, & Oliver, 1999; Odgaard, Flowers, & Bradman, 1999; Wollen & Ruggiero, 1983). Although the conscious synaesthetic experience is typically unidirectional (digits evoke colours but not *vice versa*), there is evidence that the link between the two can result in subtle bidirectional effects (Brugger, Knoch, Mohr, & Gianotti, 2004; Cohen Kadosh et al., 2005; Knoch, Gianotti, Mohr, & Brugger, 2005). For example, Cohen Kadosh et al. (2005) showed that a modified size congruency paradigm works with colours for digit-colour synaesthetes. In their task, synaesthetes were presented with two coloured digits and had to indicate which of the two had a higher numerical value. If the colours corresponded to two digits with a larger numerical distance, synaesthetes were faster than when the colours matched the numerical value and therefore gave no additional numerical distance information. Control participants intensively studied the digit-colour associations of their synaesthetic counterpart but still did not show this effect. This suggests that colours can facilitate numerical magnitude judgment.

McCarthy, Barnes, Alvarez, and Caplovitz (2013) showed that in addition to subtle influences of colours on reaction times, synaesthetes can also make deliberate use of the backward link between colours and digits. In their study, participants had to verify or reject solutions of simple mathematical problems (e.g., “2 + 3 = 5”). On some trials, synaesthetic colours that matched particular digits replaced parts of the equation. The results showed that digit-colour synaesthetes were able to calculate with colours only. However, performing this verification task with colours came at a cost: an additional 250 ms on average was necessary for each colour that had to be translated back to a digit.

The high consistency of synaesthetes’ colours over time makes this group of participants particularly interesting for memory research. Each synaesthete is an expert on an individual set of inducer-concurrent pairs, and some studies suggest that this additional information leads synaesthetes to have enhanced memory in comparison to non-synaesthetes. Case-studies, in particular, show that synaesthetes can have extraordinary memories (Baron-Cohen et al., 2007; Luria, 1968; Mills, Innis, Westendorf, Owsianiecki, & McDonald, 2006; Smilek, Dixon, Cudahy, & Merikle, 2002). Some group-studies also show that synaesthetes have an enhanced memory in comparison to non-synaesthetes (Gross, Neargarder, Caldwell-Harris, & Cronin-Golomb, 2011; Radvansky, Gibson, & McNerney, 2011; Rothen & Meier, 2009, 2010; Yaro & Ward, 2007), although generally, the advantage is not as extreme as in single cases. However, at this point, there is no clear picture as to (a) whether there is a consistent memory advantage for synaesthetes over non-synaesthetes; and (b) what the characteristics of any such memory advantage are. One possibility is that any memory advantage is specific to stimuli that evoke synaesthesia. Alternatively (or in addition), it may be for stimuli within the domain of experiences that are elicited due to synaesthesia, or a general, overall superiority.

Evidence for a memory advantage for material that is related to the inducer is mixed. Some results show enhanced memory for word lists in synaesthetes (Gross et al., 2011; Radvansky et al., 2011; Yaro & Ward, 2007) but not for digits (Gross et al., 2011; Rothen & Meier, 2009, 2010; Teichmann, Nieuwenstein, & Rich, 2015; Yaro & Ward, 2007), despite the fact that both words and digits evoke colours. Evidence for a specific memory advantage for material that is related to the concurrent comes, for example, from a study by Rothen and Meier (2010) who administered the Wechsler Memory Scale (WMS-R) to a large sample of synaesthetes (n = 44). The WMS-R is divided into three scales, the short-term, verbal, and visual memory scales. In the short-term memory scale participants have to repeat information immediately (e.g., digit span). In the verbal and visual memory scales participants are asked to recall verbal and visual information immediately *and* with a delay of 30 minutes (e.g., logical memory or visual reproduction). In the short-term memory scale, synaesthetes did not show an advantage compared to controls but in the verbal and visual scales, synaesthetes performed slightly better than non-synaesthetes (within one standard deviation above the mean). Only in one of the tests (immediate visual paired associate learning) did synaesthetes perform in the extraordinary range (more than one standard deviation above the mean). This test involves making associations between colours and line drawings; in the test phase, colours for the specific line drawings have to be recalled. More evidence for a specific memory benefit in the domain of the concurrent comes from a study by Yaro and Ward (2007) who showed that synaesthetes performed better than non-synaesthetes both in recognising a colour chip with a specific hue among distractor colour chips and in recalling positions of colours within a matrix. The superior memory performance on these tasks suggests that synaesthetes have an advantage for recalling information related to the concurrent (colours).

In a recent study, we asked synaesthetes and non-synaesthetes to complete an immediate serial recall (ISR) task with colour stimuli (Teichmann et al., 2015). We found that synaesthetes did not outperform controls recalling colour sequences in general, although within the synaesthete group they were better for colour sequences which would have a meaningful structure if translated back to digits relative to sequences without such structure. We used two set durations (500 ms and 200 ms), and measured overall accuracy, which limited sensitivity for detecting differences between the groups. In the current study, we aimed for a more sensitive test by developing a new methodology for studying ISR. Specifically, we used interleaved staircases in which we manipulated presentation duration to measure each participant's ‘serial memory duration threshold’ (SMDT). These thresholds are an indication of how fast each item in the sequence can be presented for the participant to be able to recall sequences correctly. First, to validate our method, we investigated whether sequences of digits stored in long-term memory have an effect on ISR. We tested whether synaesthetes and non-synaesthetes perform better when digit sequences contain items in a well-known order (ascending or descending) in comparison to a pseudo-randomised order. Second, to shed light on the debate regarding synaesthetes' potential memory superiority relative to non-synaesthetes, we examined whether synaesthetes performed better than matched controls in recalling colour and digit sequences. We further examined the SMDTs to see how long the translation from colours to digits takes for synaesthetes. Our novel method showed that (a) digit sequence recall is influenced by known structure; (b) synaesthetes can use their synaesthesia to recall colour sequences and outperform controls; and (c) the synaesthete advantage is due to a relatively slow translation of colours to digits. The measurement of SMDTs represents a sensitive new approach to address questions in the broader field of ISR.

Method

Participants. We tested a group of twelve digit-colour synaesthetes (all female, mean age = 29.58 years, SD = 11.39 years, all right-handed) and a group of thirteen control participants, matched for sex, age (mean age = 29.41 years, SD = 7.15 years), and handedness. One control was replaced because she was unable to do the task, leaving us with 12 matched synaesthete-control pairs. All participants reported normal or corrected-to-normal visual acuity and colour vision. The synaesthetes experienced colours in response to digits but did not experience digits when looking at specific colours. For all synaesthetes, each digit evoked a non-identical hue. Synaesthetes registered their interest to participate in studies by signing up for the online synaesthesia participant pool of the Synaesthesia Research Group at Macquarie University. They completed a questionnaire and selected colours matching their experiences for the digits 0-9 prior to the experiment. Synaesthetes were highly consistent in the colour they reported for each digit on two separate test occasions (mean consistency across group = 99.15%; SD= 0.03%; test-retest range at least 4 months). The study was approved by the Macquarie University Human Research Ethics Committee. All participants gave informed consent prior to the experiment and were reimbursed with $15/hour for participation.

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

General procedure. Participants completed two memory tasks: the *Digit Recall* and the *Colour Recall* Task. The order of the tasks was counterbalanced across synaesthetes. All controls completed the tasks in the same order as their corresponding synaesthetes.

The trials were self-paced, with a mouse click starting each trial. At the beginning of each trial, a fixation cross was displayed in the centre of the screen for 500 ms. A sequence of five colour or digit stimuli then appeared, for colour and digit blocks respectively. We used an adaptive 2-up-2-down staircase procedure to vary the presentation duration of the stimuli. In the 2-up-2-down staircase, the presentation duration decreased when sequences of two previous trials of a particular condition were recalled with 100% accuracy and it increased when these trials yielded less than 100% accuracy. The step sizes decreased after the first, third, and fifth reversal. After the fifth reversal, the presentation duration was increased or decreased by a single refresh (8.33ms). Pilot data showed that participants were more accurate recalling sequences at slower than fast presentation durations up to a point. If items were presented >1000 ms per item, participants had difficulty recalling the sequences in the right order, presumably because too much time had elapsed over the course of the trial. We therefore used an upper limit of 1000 ms; the presentation duration for each item could not be slower than the upper limit. After each stimulus there was a 50 ms inter-stimulus-interval (constant across stimulus durations). After presentation of the five item sequence, a response screen was shown with all nine possible stimuli in an invisible 3 x 3 grid (Figure 1). Participants had to select the items they saw in the correct order. We randomised the order of the stimuli on the response screen on a trial-to-trial basis to prevent selection based on learned motor sequences. When a stimulus was selected, a light grey square framed the item to confirm that the participant had clicked it. To move on to the next trial, participants had to choose five stimuli, even if they were unsure. After the last item had been clicked, feedback on accuracy was displayed for 500 ms in the centre of the screen. When the participant recalled all five stimuli in the correct order the word “correct” was displayed, otherwise the word “incorrect” was shown (see Figure 1 for the depiction of Digit Recall (1A) and Colour Recall (1B) trials). In the following sections, we will first outline the procedure for the Digit Recall Task and then describe the Colour Recall Task.

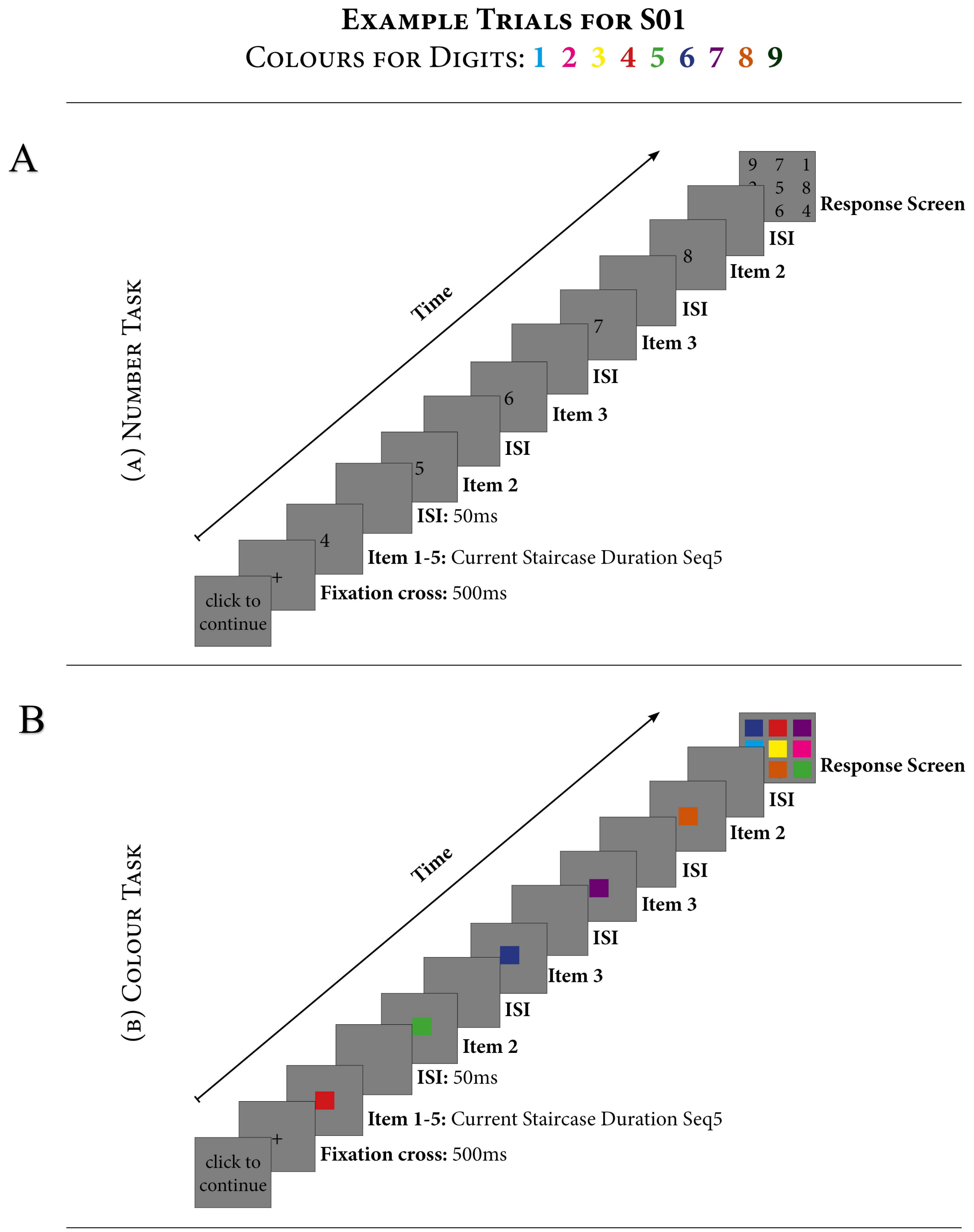


Figure 1: Example trials for S01. Five stimuli were shown consecutively in the centre of the screen. The task was to recall the items in the correct order. The presentation duration for each item varied on a trial-to-trial basis, depending on the condition and the current staircase duration. In the top row, the synaesthetic colours for digits 1-9 for S01 are shown. In panel (A), a Structured5 trial of the Digit Recall Task is depicted. In panel (B), the identical Structured5 sequence is shown for the Colour Recall Task. Sequences of the two different tasks (i.e., Digit Recall and Colour Recall) were shown in separate blocks. Sequence conditions (i.e., Structured5, Structured4, Non-Structured5, and Non-Structured4) were intermingled within a block.

Digit Recall Task

Stimuli. In the Digit Recall Task, black digits in 95-pt. Calibri font were used as stimuli. Viewing distance was approximately 75cm, making the size of the digits ~2.56 degrees of visual angle. Stimuli were shown on a grey background (RGB: 128, 128, 128). All digits from 1 to 9 were used.

Procedure and Design. Participants completed practice trials, a pre-test and a main test. Before the main test, participants looked at examples of different types of sequences, and were instructed that some sequences would be fully structured (e.g., ascending or descending digits) whereas others would have partial structure or have no apparent structure.

First, each participant completed five practice trials. The digit sequences for the practice trials were randomly generated and each digit was shown for 500 ms. The data from these practice trials were not analysed. After the practice trials, all participants completed a pre-test to determine the starting duration for the main test (see Figure 2 for sample pre-test data). In the pre-test, only randomly generated digit sequences were used. We used a 2-up-2-down staircase procedure to vary the presentation duration of the stimuli. In the first two trials, stimuli were presented for 500 ms. The initial step size was set to 200 ms and was modified after the first, third, and fifth reversal to 100 ms, 50 ms, and 25 ms, respectively. A reversal was defined as a trial at which the step direction changed (e.g., when the presentation duration was increased in response to poor performance after it had been decreased before in response to correct performance). Each participant completed a maximum of 50 trials in the pre-test. If the participant reached seven reversals before getting to the 50th trial, the pre-test finished immediately. To obtain the starting duration for the main test, we averaged the stimulus presentation durations of the last five pre-test trials and added 50 ms. This way, participants could start at a duration that was close to their performance limit for unstructured sequences, which made the staircase procedure in the main test more efficient and reliable.

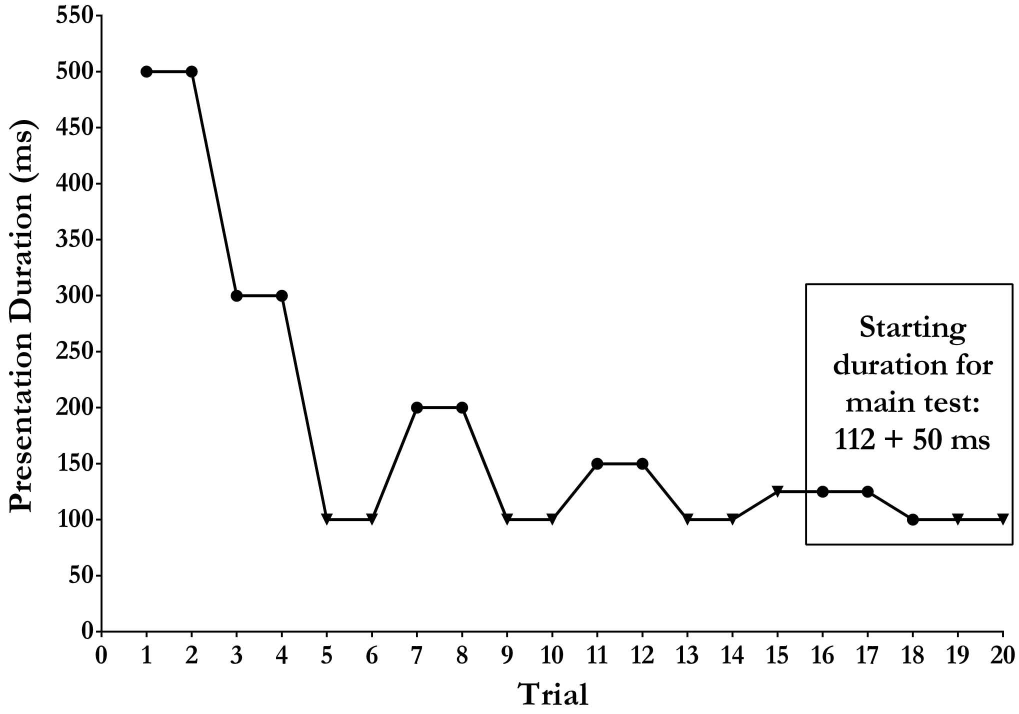


Figure 2: Example pre-test data from the Digit Recall Task for S08. Presentation duration is plotted across trials. Dots symbolise a correct trial and triangles an incorrect trial. A 2-up-2-down staircase was used to change the presentation duration depending on performance. Step sizes were reduced after the first (trial 6), third (trial 10), and fifth (trial 14) reversal. The pre-test for S08 finished after 20 trials because seven reversals were reached. The pre-test data was used to obtain the starting duration for the main test: The starting point was the averaged presentation duration of the last five trials plus 50 ms (black rectangle).

In the main test, we tested the effect of structure on serial memory. There were four sequence types that differed in degree of structure. Degree of structure was defined by the number of items in ascending or descending order within a sequence. In each condition, there were ten different sequences (see Table 1) and each sequence was shown five times on average throughout the experiment. In the fully structured (Structured5) condition, the sequences were completely ascending or descending (e.g., 4-5-6-7-8). To prevent participants from guessing in ascending or descending order, we included a condition with partially structured sequences. In the partially structured (Structured4) condition, four items of each sequence were in ascending or descending order (e.g., 1-5-6-7-8). The ordered part within each Structured4 sequence could either be positioned in the beginning or the end (e.g., 1-5-6-

7-8 *or* 5-6-7-8-1). This condition allowed us to measure how frequently participants guessed an ascending or descending order just based on partial recall of the items.

Table 1: Digit sequences used in all four conditions. Lines indicate (pseudo-) structured elements. Structured sequences were based on ascending number line of digits 1-9. Non-structured sequences were based on a pseudo-randomised number line.

Structured Digit Sequences		Non-Structured (Pseudo-Randomised) Digit Sequences	
Sequences based on: 1 2 3 4 5 6 7 8 9		Sequences based on: 5 8 1 6 2 9 3 7 4	
Structured5 Condition	Structured4 Condition	Non-Structured5 Condition	Non-Structured4 Condition
1 2 3 4 5	1 2 3 4 7	5 8 1 6 2	5 8 1 6 3
2 3 4 5 6	9 2 3 4 5	8 1 6 2 9	4 8 1 6 2
3 4 5 6 7	3 4 5 6 8	1 6 2 9 3	1 6 2 9 7
4 5 6 7 8	2 4 5 6 7	6 2 9 3 7	8 6 2 9 3
5 6 7 8 9	5 6 7 8 1	2 9 3 7 4	2 9 3 7 5
9 8 7 6 5	9 8 7 6 4	4 7 3 9 2	4 7 3 9 6
8 7 6 5 4	3 8 7 6 5	7 3 9 2 6	1 7 3 9 2
7 6 5 4 3	7 6 5 4 9	3 9 2 6 1	3 9 2 6 4
6 5 4 3 2	8 6 5 4 3	9 2 6 1 8	7 9 2 6 1
5 4 3 2 1	7 4 3 2 1	2 6 1 8 5	3 6 1 8 5

As structured sequences could only be ascending or descending, there was an unpreventable imbalance of pair frequencies. For instance, the combination of 3-4 occurred in six sequences but the combination 1-2 only occurred twice. To control for this, the non-structured sequences were constructed by randomising all nine digits (e.g., 5-8-1-6-2-9-3-7-4) and then using the identical series as the structured sequences (see Table 1). Thus, Non-Structured4 and Non-Structured5 contained the same degree of imbalance in pair frequencies as the structured conditions but were based on the randomised number set. As a consequence, the pseudo-randomised, “non-structured” conditions actually did have a structure - the structure in these trials was just not meaningful. Over time, participants might have learnt that some patterns occurred more often than others over the course of the experiment (e.g., red follows blue more often than red follows green). This type of long-term learning of sequences over the course of an experiment has been observed in previous ISR studies (Hurlstone, Hitch, & Baddeley, 2014), and may well occur in the current experiment, but although it would improve performance in the baseline condition relatively to a truly random sequence, it should affect both synaesthetes and controls. Note that neither the Non-Structured5 nor the Non-Structured4 condition contained any obvious mathematical structure.

The careful matching of the conditions ensured an identical probability of digit pairs in all conditions. To further discourage guessing 'in order', participants were informed that some of the trials would be only partially ascending and descending and therefore that it would be important to attend to the whole sequence. Furthermore, we analyse the errors within the Structured4 condition to see how frequently participants still guessed in order. All participants were aware of the different sequence types and were presented with a sample sequence of every sequence type before they started the experiment. We displayed the response screen with all possible colours to the synaesthetes and controls and explained that these colours correspond to the digits 1-9 for the synaesthete. Thus, both synaesthetes and controls were fully informed about the potential presence of structure in the sequences, although only for the synaesthetes was this information likely to be useful.

For the main task, all participants completed a further eight practice trials, two of each condition, to get used to the different types of sequences. In the practice trials, each digit was presented for each participant's starting duration (pre-test threshold + 50 ms). In the experimental trials, four adaptive staircases were interleaved, one for each condition, to obtain the serial memory duration threshold per condition (see Figure 3 for a sample data set). All participants completed a fixed number of 20 trials per staircase to ensure they had equal exposure to the sequences of all conditions. The different types of trials were randomly intermingled so that participants could not predict whether a structured or a non-structured trial was next. The first two trials of each staircase started with the individual starting duration of the pre-test. Then we used 2-up-2-down staircases to change the presentation duration depending on performance separately for each condition (i.e., 4 interleaved staircases), with smaller step sizes as the participant approached threshold. The initial step size was set to 100 ms, which was reduced to 50, 25, and 8.33 ms after the first, third, and fifth reversal, respectively (these steps correspond to 12, 6, 3, and 1 frames of the refresh rate). We averaged the presentation durations of the last five trials of each staircase to obtain our measure of performance, which we term the Serial Memory Duration Threshold (SMDT), for each condition. These SMDTs indicate how fast the digits could be presented for each participant to recall the sequences in the correct order with 100% accuracy in half of the trials. The 2-up-2-down staircase converges at 50% binary accuracy, meaning that of two sequences, one would have been recalled correctly (100%) and the other one incorrectly (any accuracy below 100%). Each participant completed two blocks of experimental trials. The SMDTs were averaged across blocks.

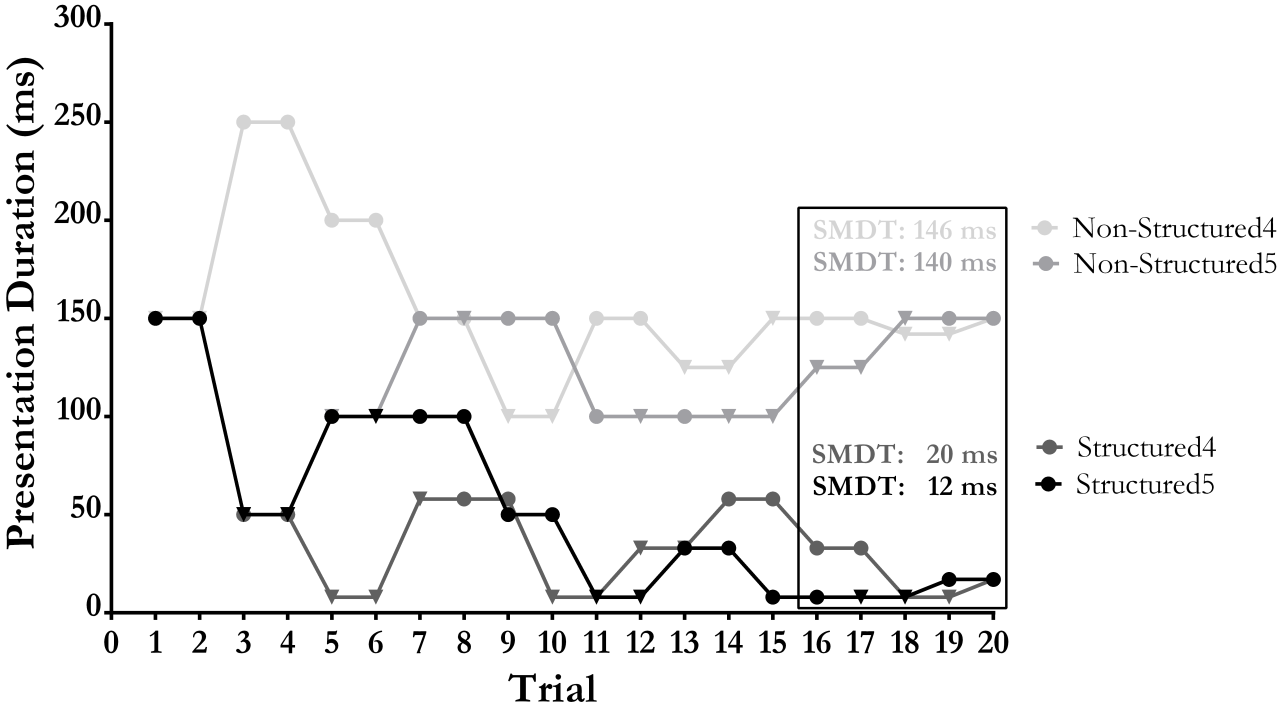


Figure 3: Data from one block of the Digit Recall Task of S10 as an example. There were four interleaved 2-up-2-down staircases, one for each sequence condition. The trial numbers within each staircase are shown on the x-axis. Dots symbolise accurate recall whereas triangles symbolise incorrect recall of the sequence. The starting duration for each participant was determined based on the pre-test performance. Step sizes were decreased after the 1st, 3rd and 5th reversal. The Serial Memory Duration Thresholds (SMDTs) were calculated by averaging the presentation durations of the last five trials in each staircase. The black rectangle frames the trials that were used to calculate the SMDTs.

It is possible that participants may realise that the presentation duration is varied for each sequence type separately. If this was the case, they could guess according to their prediction and the structured trials would get faster than the non-structured trials. Such a bias would match our hypothesis that the SMDTs for fully structured sequences would be shorter than for non-structured sequences. To avoid this, we added 20 catch trials per block that were trials of each condition presented at the current staircase duration of another condition. For instance, a Structured5 catch trial would be a fully sequential trial shown at the current staircase duration of Non-Structured5. Half of the catch trials were structured trials, randomly selected from the

Structured4 and Structured5 lists and shown at the duration of the Non-Structured4 and Non-Structured5 conditions, respectively. The other half were non-structured trials, randomly selected from the Non-Structured4 and Non-Structured5 lists, presented at the duration of the Structured4 and Structured5 condition, respectively. The catch trials were inserted at random positions after the 10th trial of each block. These trials were not part of any staircase, and therefore did not influence the presentation durations of a specific condition. However, they minimised the risk that participants predicted the condition even if they realised that some trials were faster than others.

Colour Recall Task

Stimuli. In the Colour Recall Task, five coloured squares (5cm x 5cm) were displayed in the centre of the screen. Viewing distance was approximately 75cm, making the size of the squares ~3.82 degrees of visual angle. The colours corresponded to each synaesthete's colours associated with the digits 1-9.

Procedure and Design. The procedure and design of the colour block was almost identical to the digit block, with a few exceptions. First, before the pre-test, we showed the participants the response screen with all possible colours so that they had an opportunity to label the colours and get used to differences between colours (some synaesthetes had more difficult colour sets with multiple digits having similar colours, e.g., three different greens). Second, because pilot testing showed the Colour Recall Task to be harder than the Digit Recall Task, we set the starting duration in the practice trials to 800 ms instead of 500 ms and participants completed 15 instead of five practice trials. Third, in the main test, the four conditions (Structured5, Structured4, Non-Structured5, Non-Structured4), were constructed in the same way as in the digit block, but this time we used the colours corresponding to digits for each synaesthete and the matched control (see Figure 1B for an example).

Results

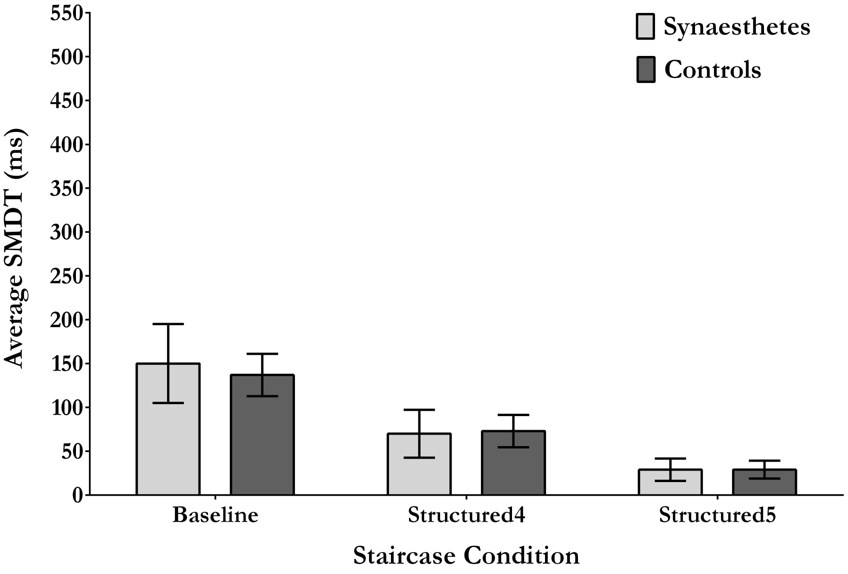
The Serial Memory Duration Threshold (SMDT) was defined as the average presentation duration of the last five trials of each staircase condition. We calculated the SMDTs for each participant and condition separately. The staircases successfully converged at approximately 50% accuracy in all conditions in both groups (range: 42-61%). That means that on average, participants recalled two to three sequences out of five with 100% accuracy when they reached the end of the staircase. Thus, the SMDT is an estimate of the duration at which a participant can recall approximately half of the sequences with 100% accuracy.

In the Non-Structured4 condition of the Digit Recall Task, one participant (S12) had a SMDT that was more than three standard deviations above the group mean. Therefore, we excluded this data point as an outlier from the analysis. We collapsed across the two non-structured conditions (Non-Structured4 and Non-Structured5) to form a single baseline condition for each participant, separately for the Digit and Colour Recall Tasks.

To examine the effects of synaesthesia and structure on SMDTs for colour and digit sequences, we conducted a repeated-measures ANOVA with *Task* (Digit Recall and Colour Recall) and *Structure* (Baseline, Structured4, and Structured5) as within-subject factors and *Group* (synaesthetes and controls) as a between-subjects factor. There was no significant main effect of *Group* ($F[1, 22] = 2.2$ $p = 0.152$) but significant main effects of *Task* ($F[1, 22] = 81.32$, $p < 0.001, \eta_p^2 = 0.79$) and *Structure* ($F[1.47, 32.34] = 26.83$, $p < 0.001$, $\eta_p^2 = 0.49$; Greenhouse-Geisser correction applied for violation of sphericity). There were no two-way interactions between *Task* and *Group* ($F[1, 22] = 2.08$, $p = 0.163$) or *Task* and *Structure* ($F[1.46, 32.07] = 1.58$, $p = 0.223$), but there was a significant interaction between *Structure* and *Group* ($F[1.47, 32.34] = 7.31$, $p = 0.005, \eta_p^2 = 0.25$). Most importantly, there was a significant three-way interaction between *Structure, Task,* and *Group* ($F[1.46, 32.07] = 9.73$, $p = 0.001$, $\eta_p^2 = 0.31$), which shows that the influence of structure differed between the synaesthetes and controls, but this influence differed between the tasks.

To identify the source of the interaction, we first tested for differences between the groups by breaking the interaction down by *Task* and comparing the groups at each level of structure. For the Digit Recall Task, synaesthetes did not differ from controls (Figure 4A) at any level (Baseline, Structured4, or Structured5; all ps > 0.809). For the Colour Recall Task (Figure 4B), synaesthetes and controls did not differ in the Baseline or Structured4 condition, but synaesthetes performed significantly better than controls in the Structured5 condition (p = 0.014). These results show that when colour sequences have an implicit structure in the associated digits, synaesthetes have superior recall for colour sequences relative to controls.

(A) Digit Recall Task



(B) Colour Recall Task

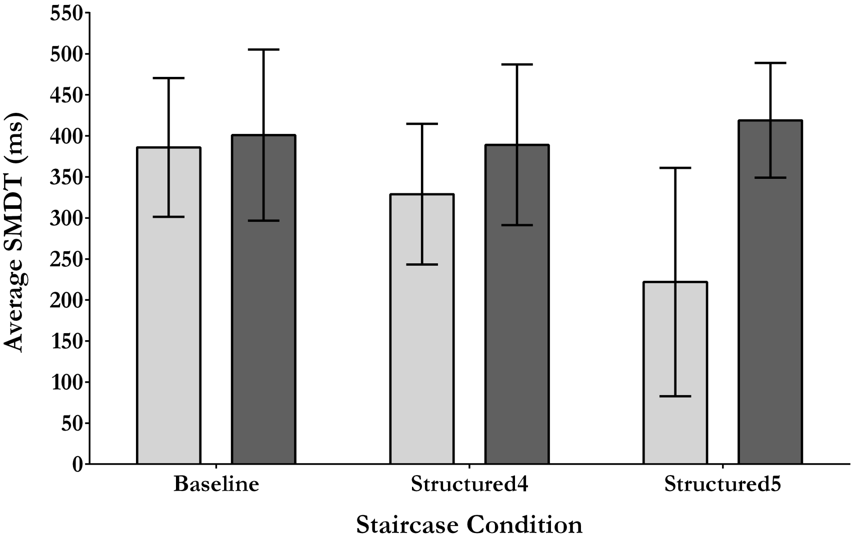


Figure 4: Serial Memory Duration Thresholds (SMDTs) in milliseconds for both groups. The SMDTs are the averaged presentation durations of the last five trials for each staircase. They represent the level at which ~50% of the sequences were recalled with 100% accuracy. 4A shows the results of Digit Recall Task and 4B of the Colour Recall Task. The Baseline condition corresponds to the mean performance of the two non-structured conditions. Error bars reflect 95% confidence intervals.

To identify whether performance was significantly better in structured than in less structured trials, we then broke the interaction down by *Group*. For both synaesthetes and controls separately, in the Digit Recall Task, all three conditions differed, with SMDTs for Structured5 < Structured 4 < Baseline (all *p*s < 0.001). In contrast, in the Colour Recall Task, controls showed no difference in SMDT between the three conditions (all *p*s > 0.39). However, synaesthetes showed the same pattern as for the digits: SMDTs for Structured5< Structured4 < Baseline (all *p*s < 0.008). These results demonstrate that both groups benefited from structure in the Digit Recall Task but only synaesthetes were able to use the structure in the Colour Recall Task to boost their memory.

To confirm the pattern clear in Figure 4, we tested whether there was a difference between the Digit and the Colour Recall Tasks by breaking the interaction down by *Structure*. The results showed that there was a significant difference between the Digit Recall Task and the Colour Recall Task for both groups. In the Baseline, Structured4, and Structured5 conditions, controls had longer SMDTs in the Colour Recall Task than in the Digit Recall Task (all *p*s < 0.001). Synaesthetes showed the same effect ($p < 0.001$, $p < 0.001$, and $p = 0.001$, respectively). This suggests that both groups required more time to encode colour in comparison to digit sequences across all structure conditions.

Finally, we examined whether the enhanced performance for fully structured sequences could be due to guessing. If we look at the partially structured (Structured4) sequences, we can determine how many times participants falsely completed a Structured4 sequence with a fully sequential order (e.g., if the sequence was “4-5-6-7-2” and the participant reported “4-5-6-7-8”). We calculated the percentage of this type of false alarm out of all Structured4 trials, to test whether this type of guessing strategy could drive our effect. In the Digit Recall Task, synaesthetes reported 2.08% (SD = 0.21%) and controls 4.37% (SD = 0.32%) of Structured4 trials in completely ascending or descending order, falsely completing the partially structured sequence as completely structured. In the Colour Recall Task, synaesthetes had 3.3% (SD = 0.3%) and controls 0.21% (SD < 0.001%) of false alarms. This false alarm analysis demonstrates that, on average, a maximum of 1.75 out of 40 Structured4 sequences were reported erroneously in ascending or descending order. Thus, the benefit in the Structured5 condition is unlikely to be driven purely by a guessing strategy. In the Colour Recall Task, only synaesthetes erroneously reported occasional colour sequences in ascending or descending order, which is not surprising as controls do not have the colour-digit associations. However, synaesthetes reported, on average, less than one colour sequence falsely in ascending or descending order, which makes it unlikely that the effect is driven by guessing. Importantly, the catch trials in our design also discouraged such a strategy.

Together, these results show that both groups clearly benefit from structure in the Digit Recall Task. In the Colour Recall Task, synaesthetes and controls do not differ in baseline performance, suggesting that there is no overall benefit to colour memory. However, synaesthetes have an advantage over controls when recalling fully structured sequences, demonstrating that digit-colour synaesthetes can use their synaesthesia to boost colour memory. For synaesthetes, the SMDTs for recalling fully structured colour sequences are slower than for recalling fully structured digit sequences.

Discussion

In this study, we used a novel method to examine whether synaesthetes can use their associations between colours and digits to enhance serial recall for specific colour sequences, measured by Serial Memory Duration Thresholds (SMDT). Our results show that both synaesthetes and non-synaesthetes can correctly recall structured sequences of digits (ascending or descending in order) when presented at a faster rate than novel, non-structured (pseudo-randomised) sequences. Synaesthetes showed a similar benefit for structured colour sequences (corresponding to ascending and descending digit sequences) over non-structured colour sequences (corresponding to pseudo-random digit sequences). Non-synaesthetes did not show any performance difference in structured and non-structured colour sequences.

Hence, our results demonstrate that digit-colour synaesthetes can use the link between colours and digits to boost memory for specific colour sequences.

Usually, the differences in performance in ISR tasks are measured in terms of recall accuracy. Here, we obtained our data with a method new to the field of serial recall, a staircase procedure varying presentation duration depending on performance. Previous use of staircases in ISR studies has been through varying sequence length to adjust task difficulty. Although this method is suitable to examine, for example, differences between multiple types of stimuli (e.g., Li, Schweickert, & Gandour, 2000), it is not very sensitive to subtle differences. This type of staircase can only add whole items to the sequence and can measure whether, for example, 6 or 7 items can be recalled accurately. Here, we showed that detecting subtle differences in serial recall performance is possible by using a staircase procedure that manipulates presentation duration, which allows us to measure serial memory duration thresholds (SMDT).

We used our sensitive measure to explore the memory abilities of synaesthetes who have long-term associations between digits and colours. The data show that synaesthetes do not have a general memory benefit relative to non-synaesthetes in immediate recall. There is no difference in performance for digit sequences, with both groups showing improvement with structured over pseudo-random sequences, or for unstructured colour sequences. Synaesthetes do, however, perform better in recalling colours when the sequence of colours reflected an underlying digit structure. Other studies have shown that synaesthetes are better relative to controls when recalling material within the same domain as that evoked by their synaesthesia such as colours. For example, Yaro and Ward (2007) showed that synaesthetes have an advantage over non-synaesthetes when recalling colour matrices after a delay (and not on immediate recall). In another study, Rothen and Meier (2010) found that synaesthetes performed better than non-synaesthetes when recalling line-colour associations. In contrast to Yaro and Ward's (2007) findings, in this second study, the advantage for the synaesthetes was more pronounced immediately after the learning phase in comparison to delayed recall. Here, we find a very specific advantage for colours with an underlying structure that depends on the synaesthetic link to digits.

The specific advantage for colours that are associated with a structured sequence of digits might arise from synaesthetes having a benefit at recall, after the whole sequence has been presented, or during the encoding period, or both. The classic serial position effect is that the first and the last item of a sequence is usually recalled with a higher accuracy, whereas the items in the middle of the sequence are often recalled in the wrong order (Ebbinghaus, 1913). Here, synaesthetes may recall the first and last colours and then reconstruct the order of the items in the middle based on their long-term associations with the structured sequences. This would imply that our effect is due to a deliberate use of synaesthetic associations to boost recall accuracies of colour sequences. Alternatively, or in addition, synaesthetes might deliberately translate the colours back into digits to get the benefit of the underlying structure. All participants were aware that the sequences would have different degrees of structure, but only synaesthetes could translate colours to digits at the encoding stage to boost memory. This interpretation is in line with results from McCarthy et al. (2013) who showed that synaesthetes could translate colours to digits and solve arithmetic tasks with colours only. In this previous study, synaesthetes needed 250 ms per colour to translate them back to digits, which is consistent with our longer SMDTs for structured coloured sequences over digits.

We cannot rule out the possibility that the translation of colours to digits is due to a relatively slow but still automatic process. There certainly is good evidence from synaesthetic congruency paradigms that digits evoke colours involuntarily (e.g., Mattingley et al., 2001). There is also evidence that mismatching colour information can affect digit processing (e.g., Brugger et al., 2004; Cohen Kadosh et al., 2005), suggesting that there is implicit involuntary activation of digit information by the colours they usually evoke. Thus, the structure advantage for synaesthetes recalling colours could be because implicit activation of digit identity when looking at colours leads to a prediction of which item comes next in the sequence. Such predictive encoding methods (for a recent review see Clark, 2013) could account for our structure effect: Synaesthetes' expectations would be more accurate for the fully structured in comparison to the partially structured and non-structured conditions. Non-synaesthetes do not benefit from the structure in the Colour Recall Task because they do not have these colour sequences stored in long-term memory and hence cannot successfully predict which item comes next in the sequence. Although this is possible, it seems less likely in light of the relatively long SMDTs for colours relative to digits, which fit with previous strategic translation effects (McCarthy et al. (2013).

Two different theoretical frameworks could explain the advantage in colour encoding that leads to memory benefits observed for synaesthetes in comparison to non-synaesthetes. One suggestion is that synaesthetes' advantage in colour memory is due to higher sensitivity for visual information than non-synaesthetes (Pritchard, Rothen, Coolbear, & Ward, 2013; Rothen, Meier, & Ward, 2012; Terhune, Wudarczyk, Kochuparampil, & Kadosh, 2013). Previous studies have claimed that synaesthesia is associated with neuroanatomical differences in the ventral visual stream which may lead to enhanced visual processing (e.g., Jäncke, Beeli, Eulig, & Hänggi, 2009; Rouw & Scholte, 2007). As the ability to encode rapid sequences in the correct order depends on the rate at which the items can be identified and encoded into memory (Wyble, Bowman, & Nieuwenstein, 2009), in principle, any difference in visual sensitivity could improve memory for serial order. However, the enhanced visual processing account predicts that synaesthetes would be better at recalling *all* digit and colour sequences relative to non-synaesthetes, whereas our data show that the benefit is specific to the structured colour sequences. Thus, these data do not support the proposal that synaesthetes have generally enhanced visual processing relative to controls.

An alternative theory explaining memory benefits for synaesthetes is the dual-coding account of memory (based on Paivio, 1991), which suggests that synaesthetes could benefit from the additional information attached to items they have to remember (Rothen et al., 2012). However, a dual coding explanation predicts that synaesthetes should have an advantage when memorising digit sequences because of the additional colour cue. Consistent with earlier results (e.g., Rothen & Meier, 2010), we do not find any advantage for synaesthetes over controls when recalling digit sequences in general. Thus, the dual coding account does not fully explain the current findings either.

We propose that a modified version of the dual coding account is a more plausible explanation for the current data. Synaesthetes were only able to use the link between colours and digits to boost their serial recall of a colour sequences when the secondary information (i.e., digits in the Colour Recall Task) was more useful for task performance than the primary information (i.e., colours in the Colour Recall Task). Thus, we need a modified dual coding account that holds that *synaesthetes will have a benefit over non-synaesthetes only in situations where the synaesthetically-linked information is more memorable than the presented stimuli*.

Digits seem not to be available immediately when colours are presented as there was a difference in synaesthetes' SMDTs for structured sequences of digits (mean SMDT: 28 ms) and sequences of colours structured only by the underlying digit sequences (mean SMDT: 221 ms). This could be due to general differences between inducers and concurrents: Whereas a digit elicits one specific colour, that same colour could potentially be associated with more than one stimulus. For example, yellow might not only be associated with "2" but also with "Tuesday" or specific objects such as bananas. Although within the context of the experiment it was clear that each colour in the sequence represented a digit, the potential one-to-many relationship of colour-to-inducer could slow the translation of colours to digits. Thus, the difference between the Colour Recall and Digit Recall task for synaesthetes potentially reflects the process of interpreting the colours in terms of digits and translating them back.

Then, when the translated digit secondary information is more useful or memorable than the primary colour information, we see a benefit for synaesthetes over controls.

In sum, the current findings show that synaesthetes do not have an overall enhanced immediate memory for sequences of either digits or colours but they can use their synaesthesia to translate colours to digits to improve serial memory for colours. This translation process is quite slow: in comparison to encoding digit sequences directly, synaesthetes needed additional time to translate colours to digits when encoding colour sequences. We propose a modified dual coding account of memory advantage in synaesthesia such that synaesthesia will only enhance memory when the synaesthetically-linked information is more memorable than the primary information. Our study further shows that duration thresholds are a sensitive method to measure subtle differences in serial recall performance.

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