British Journal of Psychology (2018), 109, 118–136
© 2017 The British Psychological Society

The British
Psychological Society

www.wileyonlinelibrary.com

Do children with grapheme-colour synaesthesia show cognitive benefits?

Julia Simner[1,2]* and Angela E. Bain[2]
[1]School of Psychology, University of Sussex, Falmer, UK
[2]Department of Psychology, University of Edinburgh, UK

Grapheme-colour synaesthesia is characterized by conscious and consistent associations between letters and colours, or between numbers and colours (e.g., synaesthetes might see *A* as red, *7* as green). Our study explored the development of this condition in a group of randomly sampled child synaesthetes. Two previous studies (Simner & Bain, 2013, *Frontiers in Human Neuroscience*, 7, 603; Simner, Harrold, Creed, Monro, & Foulkes, 2009, *Brain*, 132, 57) had screened over 600 primary school children to find the first randomly sampled cohort of child synaesthetes. In this study, we evaluate this cohort to ask whether their synaesthesia is associated with a particular cognitive profile of strengths and/or weaknesses. We tested our child synaesthetes at age 10–11 years in a series of cognitive tests, in comparison with matched controls and baseline norms. One previous study (Green & Goswami, 2008, *Cognition*, 106, 463) had suggested that child synaesthetes might perform differently to non-synaesthetes in such tasks, although those participants may have been a special type of population independent of their synaesthesia. In our own study of randomly sampled child synaesthetes, we found no significant advantages or disadvantages in a receptive vocabulary test and a memory matrix task. However, we found that synaesthetes demonstrated above-average performance in a processing-speed task and a near-significant advantage in a letter-span task (i.e., memory/recall task of letters). Our findings point to advantages for synaesthetes that go beyond those expected from enhanced coding accounts and we present the first picture of the broader cognitive profile of a randomly sampled population of child synaesthetes.

Synaesthesia is a condition characterized by unusual cross-modal experiences. For example, synaesthetes might experience tastes in the mouth or colours in the visual field when they hear sounds (Simner & Ward, 2006; Ward, Simner & Auyeung, 2005). The condition has a known neurological profile (e.g., Hubbard, Arman, Ramachandran, & Boyton, 2005) with synaesthetes showing greater functional activity than controls in (inter alia) sensory regions as well as relatively widespread differences in resting state network connectivity (Dovern *et al.*, 2012), white matter cohesion (e.g., Rouw & Scholte, 2007) and grey matter volume (e.g., Weiss & Fink, 2009). There are a number of different types of synaesthesia (e.g., Cytowic & Eagleman, 2009) and this study focuses on a variant known as *grapheme-colour synaesthesia* in which graphemes (i.e., letters or digits) trigger experiences of colour. For a grapheme-colour synaesthete, the letter *A* might be a certain shade of

---

*Correspondence should be addressed to Julia Simner, School of Psychology, University of Sussex, Pevensey Building, Falmer BN1 9QH, UK (email: j.simner@sussex.ac.uk).

DOI:10.1111/bjop.12248

red for example, *B* might be blue, *C* might be green and so on (e.g., Simner, Glover, & Mowat, 2006). In scientific parlance, graphemes are the *inducer* (i.e., trigger) for this type of synaesthesia and colour is the *concurrent* (i.e., percept). Grapheme-colour synaesthetes also experience colours for whole words and these colours tend to be related to their synaesthetic colours for graphemes (e.g., Simner *et al.*, 2006; Ward, Simner, & Auyeung, 2005). Synaesthetic colours can be experienced either in the mind's eye or mentally projected out into space (Dixon, Smilek, & Merikle, 2004), but in either case, these colours are automatically elicited when graphemes are encountered and are typically consistent over time (e.g., Simner *et al.*, 2006). Although an impressive number of studies now describe synaesthesia in adults (for review see Simner & Hubbard, 2013), almost none have looked at the condition in children (but see Green & Goswami, 2008; Spector & Maurer, 2011). In this study, we ask whether grapheme-colour synaesthesia in childhood is linked to other types of advantages or disadvantages in cognition. Our focus therefore is whether synaesthetic children are different from their peers in ways that go beyond synaesthesia itself.

A body of empirical work has shown certain costs and benefits associated with adult synaesthesia. For example, one study (Dixon, Smilek, Cudahy, & Merikle, 2000) showed that grapheme-colour synaesthete 'C' took longer to solve visually presented calculations (e.g., 5 + 2 = ?) when they were presented alongside colour patches that mismatched the synaesthetic colour associated with the solution (e.g., in 5+2, responses were slower alongside red patches than yellow patches, given the participant's synaesthetically yellow 7). Notwithstanding this slight deficit, the majority of research on adult synaesthetes appears to show that synaesthesia offers cognitive benefits and it is important to understand these effects for our study here. For example, synaesthetes perform better than controls when recalling words from memory, both from simple word lists or paired-associate lists (Gross, Neargarder, Caldwell-Harris, & Cronin-Golomb, 2011; Mills, Innis, Westendorf, Owsianiecki, & McDonald, 2006; Rothen & Meier, 2010; Radvansky, Gibson, & McNerney, 2011; Yaro & Ward, 2007). Synaesthetes may also perform well in digit recall, although these findings have been more mixed. Early case studies (e.g., Luria, 1968; Mills *et al.*, 2006; Smilek, Dixon, Cudahy, & Merikle, 2002) showed adult synaesthetes with superior memory in recalling digits from large matrices (e.g., 50 digits presented in rows and columns, e.g., Luria, 1968; Smilek *et al.*, 2002). Additionally, Dixon and colleagues presented a digit matrix not only in the usual black font, but coloured either congruently to match the synaesthesia or incongruently. Incongruent digits were remembered worse than congruent digits, an effect that was not observed in controls. However, recent group studies have had mixed results replicating both types of effects. Yaro and Ward (2007) administered digit matrices to synaesthetes and found no significant difference between congruent and incongruently coloured digits and also that memory for graphemes was not particularly pronounced for synaesthetes when compared to controls. This pattern of findings is echoed in several additional group studies showing synaesthetes were no better than non-synaesthetes in immediate or delayed recall of digits (Rothen & Meier, 2009, 2010; Gross *et al.*, 2011) and they did not perform differently for congruently coloured digits over incongruent (Rothen & Meier, 2009).

One study, by Gibson, Radvansky, Johnson, and McNerney (2012), did find superior performance in grapheme recall in a group of synaesthetes. Synaesthetes with coloured letters but not digits showed superior letter (but not digit) span. Gibson *et al.* concluded that superiority in the synaesthesia-linked stimuli (i.e., letters not digits) might be best accounted for by a dual-coding theory, in which synaesthesia enables an enhanced level of encoding through a greater number of memory cues (see also Radvansky *et al.*, 2011). Alternatively, it has been suggested that synaesthetes may possess an increased ability to perceptually organize information and this could make retention and recall more efficient (Ramachandran & Azoulai, 2006). This 'improved organization' hypothesis means synaesthetes might not only show memory benefits for synaesthetic inducers, but also additional perceptual and/or cognitive benefits beyond the synaesthesia itself, and this we test here.

The interest for our study is whether cognitive advantages or disadvantages can be seen in synaesthetes who are still children; that is, we ask whether models designed to capture adult synaesthesia behaviour can also be tested in synaesthete children. One previous study has considered this issue of whether children with synaesthesia show cognitive differences compared to other children. Green and Goswami (2008) tested a small group of grapheme-colour synaesthetes between 7 and 15 years (see Table 1) and age-matched non-synaesthete controls. Children saw 4×4 digit matrices in which digits were either achromatic (black against white), or coloured congruently/incongruently with respect to each individual child's synaesthesia. Participants were given blank grids and were scored for the number of correctly recalled digits in correct locations (7-year-olds were given 3×3 grids and their scores prorated). Although grapheme-colour synaesthetes did not perform overall better than controls, they alone showed poor performance when digits were presented in incongruent colours. On the face of it then, children with synaesthesia appeared to have no *a priori* memory advantages, but performed differently to non-synaesthetes when recalling certain types of coloured digits. Other findings by Green and Goswami, however, showed very strong cognitive advantages within child synaesthetes. We present their data below, then we analyse their data and then we explain why their sampling methods might call for a closer inspection of their findings.

Table 1. Analysis of data from Green and Goswami (2008). Table shows data for three psychometric tests (BPVS, WISC blocks/arithmetic) for 10 synaesthetes with coloured digits, described below by age and test score. The final line shows Wilcoxon *T*-statistics and corresponding p values for each test, comparing participants to published control norms (Population means = 100 (BPVS, *SD* 15) or 10 (WISC, *SD* 1.5)

Synaesthete age (years)	BPVS	WISC blocks	WISC arithmetic
7.33	92	19	11
9.83	104	14	8
9.33	125	12	–
11.66	100	10	10
13.58	160+	10	18
15.33	160+	17	17
9.33	101	14	–
11.08	119	12	16
14.16	131	10	10
14.16	119	11	12
	$T = 2.79$, $p = .02$	$T = 28$, $p = .02$	$T = 18.5$, $p = .09$

Statistical investigation

Green and Goswami reported a table of data which they did not analyse (Green & Goswami, 2008; table 1, p. 465). This table showed individual scores for 10 grapheme-colour synaesthetes[1] aged 7–15 years in three different cognitive tasks: British Picture Vocabulary Scale (BPVS; e.g., Dunn, Dunn, Whetton, & Pintilie, 1982) and two subtests of the Wechsler Intelligence Scales for Children (WISC, e.g., Wechsler, 2003) – the WISC blocks task (which measures perceptual reasoning) and arithmetic subtests. The first task requires children to correctly select a named object (e.g., leaf) from four pictured objects; the second task requires them to arrange blocks that have colour patterns on their sides to match a target pattern; the third task is timed mental arithmetic. For their unanalysed data, Green and Goswami commented only that 'some of the synesthetes scored extremely highly on these measures' (p. 466). We find these data particularly compelling as they represent the first indication of how synaesthetic children might perform on standardized psychometric tests of cognition. In other words, their unanalysed data are valuable in its own right, and for this reason, we preface our own study by first statistically analysing the data of Green and Goswami (2008) in comparison with published baseline norms. Our analyses are shown in Table 1 below, along with the original data from Green and Goswami (2008).

Table 1 shows that the child synaesthetes recruited by Green and Goswami performed significantly better than their standardized population means on all three tasks or were trending in that direction. In combination with their earlier finding of a colour congruency effects in digit matrix recall, Green and Goswami's study appears to suggest that child synaesthetes have a specific profile of assets (in vocabulary, perceptual reasoning and arithmetic) and a deficit (difficulty with incongruently coloured materials).

The motivation for our study comes from a consideration of how Green and Goswami recruited their participants. There are two possible methods for recruiting child synaesthetes: one is to screen very many hundreds of randomly sampled children, using an objective test for synaesthesia, which would identify the very small percentage of synaesthetes from among this very large sample. To our knowledge, only one research group has used this screening method (e.g., Simner *et al.*, 2009; Simner & Bain, 2013) which is large scale, effortful and time-consuming. As there is no description of any such method in the paper reported by Green and Goswami (whose recruitment is described only as 'six grapheme-color (GC) synesthetes, four girls and two boys, took part in the study', p. 466), our logical inference is that they used the alternative recruitment method, which is to advertise for known child synaesthetes to be brought forward by their parents (and we will refer to this henceforth as self- or parental-referral).

In this study, we argue here that this second type of (self-/parental-referral) recruitment method may have limited scientific validity because the type of child participant this recruits is unlikely to represent the population of child synaesthetes at large. Instead, by definition, children referred by their parents would be children

---

[1] Four of these participants (listed last in Table 1, aged 9.33, 11.08, 14.16 years) were described by Green and Goswami as 'phoneme-colour synaesthetes', but this may be based on an incorrect definition that their colours are experienced only when digits are heard rather than read. In fact, both grapheme-colour AND phoneme-colour synaesthetes can be triggered by spoken or written language and this is not the basis of the distinction (see Simner, 2007). The distinction between grapheme/phoneme-colour synaesthesia is best explained in terms of letters rather than digits: grapheme-colour synaesthetes have the same colour for letters irrespective of their phonemic quality. Hence, they would have the same colour for the letter 'a' whether its pronunciation was/æ/as in 'apple' or/ej/as in 'ace'. In contrast, phoneme-colour synaesthetes are specifically sensitive to this difference and so would have different synaesthetic colours for 'a' depending on the phonemic instantiation (i.e., different colours for 'a' in the words 'apple' vs. 'ace' – irrespective of whether the word were written or spoken aloud).

from family environments led by parents with some degree of motivation to engage themselves in scientific research (Simner *et al.*, 2009) – either because they are interested in the science of synaesthesia per se, or perhaps because there are in a peer-group with university researchers. It would therefore be reasonable to assume that this population does not represent average children in the population at large. More importantly, these children would be from families where synaesthesia is known about and discussed – because this is necessarily how parents would know that their child had synaesthesia. Importantly, a child with synaesthesia in a family where synaesthesia is discussed may become particularly attuned to his/her synaesthesia, and this in itself may reinforce synaesthetic experiences, either by directly increasing their vibrancy or simply because they are allocated greater attention. This attention might encourage such children to learn to organize their cognition around synaesthesia in a way they might otherwise not (e.g., using synaesthetic colours as an aide-memoire when required to recall numbers). For all these reasons, the children, their family environments and the children's synaesthesia may be non-representative of what we might expect from the average synaesthete child, randomly sampled. In summary, although Green and Goswami showed a convincing superiority in cognitive tasks for their cohort of child synaesthetes and although they took a significant first step in raising interest in synaesthesia in children, it remains an open question whether their findings could be generalized to the wider population of child synaesthetes at large. This type of generalized finding would first require finding a random sample of child synaesthetes who could be tested and this is the approach we take here.

We tested five randomly sampled child grapheme-colour synaesthetes aged 10–11 years, who were identified in previous studies which screened over 600 children for grapheme-colour synaesthesia (Simner & Bain, 2013; Simner *et al.*, 2009). Although our group of synaesthetes was small, they represent the only existing randomly recruited population of child synaesthetes at the time of writing and hence were a highly valuable population for research purposes. By testing synaesthetes identified from wide-scale screening, we avoided the self-referral bias described above. At the same time, we also avoided a motivation confound because children we tested were not told whether they were synaesthetes or not and nor were they told that synaesthesia was the focus of our study – indeed they were told nothing about synaesthesia whatsoever. Synaesthetes were simply tested alongside controls without indication of which category each child fell into (we return to this issue of motivation in the Discussion).

In our test battery, we included two tests used previously by Green and Goswami (2008) and two additional tests to extend the range of assessments. The tests we administered were a letter matrix task (based on the digit matrix of Green & Goswami, 2008; Smilek *et al.*, 2002), the BPVS vocabulary test (BPVS-II; Dunn, Dunn, Whetton, & Burley, 1997), a letter-span task (adapted from a digit-span task in the Working Memory Test Battery for Children; WMTB-C; Pickering & Gathercole, 2001) and a test of processing speed (WISC-IV 'Cancellation Task'; Wechsler, 2003). We selected these tasks not only to mirror Green and Goswami (2008) but also to include two different types evaluation; one tapping into cognitive functions related to this variant of synaesthesia (letter matrix, letter span and BPVS, which involve synaesthetic inducers) and those drawing upon abilities *not* related to synaesthesia (Cancellation). A dual-coding theory would predict advantages only for the former, while the broader 'improved organization' theory would predict advantages even in the latter task, which does not involve synaesthetic constructs.

EXPERIMENTAL INVESTIGATION

Methods

Participants

We tested five child grapheme-colour synaesthetes aged 10–11 years. These participants had grapheme-colour synaesthesia for either letters and/or digits and their individual profiles are shown in Table 2. Our participants were identified as synaesthetes from a large-scale screening study described in detail in Simner *et al.* (2009) and Simner and Bain (2013) in which 615 children aged 6–7 years were screened for grapheme-colour synaesthesia using an objective test. Synaesthetes and matched controls (see below) were tested aged 6–7 years and again aged 7–8 and again aged 10–11 years. In this study, we evaluated the cognitive profiles of five of the grapheme-colour synaesthetes aged 10–11 years who were identified as such throughout all 4 years of our testing.

In two of our four tasks (*WISC-IV Cancellati*on and *BPVS-II*), we tested only synaesthetes, because these tests come with available norms against which to compare our synaesthetes' performance. In the other two tasks (*letter span* and *letter matrix*), no such norms exist, so we therefore also tested a total of 42 control participants. These were non-synaesthetic children taken from the same population as our synaesthetes and who had also been tested for synaesthesia at ages 6–7, 7–8 and 10–11 years (and who did not have synaesthesia). Half the children were 'high-memory controls', and the other half were 'average-memory controls'. These classifications were determined in the earlier papers according to how children had performed in an on-screen paired-association task the first time we tested them age 6–7 years (see Simner & Bain, 2013; Simner *et al.*, 2009). In this task, children paired a colour with each of 36 graphemes (a-z, 0–9) in two sessions separated by 10 s. Those children who were highly consistent in their associations across 10 s but were not synaesthetes (e.g., making A green in both sessions but from memory alone) were classified as *high-memory controls*, while those who were only as consistent as the average child were classified as *average-memory controls*. In all cases, we also ensured that none of our control children were synaesthetes (using the detailed methods described in Simner *et al.*, 2009; Simner & Bain, 2013; see Table 2). Hence, in all four tasks, we tested our five synaesthetes, while in the letter-span task, we additionally tested 40 control participants (balanced orthogonally for sex, age group and memory:

Table 2. Table shows our five grapheme-colour synaesthetes described by their sex (M = male; F = female) and age (in years). There were two male synaesthetes aged 10 years, described as M10a and M10b. Columns 2 and 3 indicate their variants of grapheme-colour synaesthesia, for letters and/or digits

Synaesthetes* by sex (M/F) and age (years)	Letter-colour synaesthesia	Digit-colour synaesthesia
F10	x	x
M10b	x	
M10a	x	
F11	x	
M11	x	x

Note. *Synaesthetes were identified in Simner *et al.* (2009; Simner & Bain, 2013) using the behavioural 'gold standard' test which relies on the fact that the synaesthetic colours of graphemes (e.g., A = red) tend to remain consistent over time for any given synaesthete. Children ($n = 615$) selected a 'matching' colour for each of 36 grapheme (A–Z, 0–9) from an on-screen colour palette, then repeated the task after a delay of 10 s, 1 and 4 years. Synaesthetes were significantly more consistent over 1 and 4 years than their peers had been over just 10 s.

high/average), and in the letter matrix task, we additionally tested 20 controls (four controls per synaesthete matched on age/sex, two high memory and two average memory). Our controls were matched by age because all our participants came originally from two different age groups (10–11 years; see Simner *et al.*, 2009). Eighteen controls took part in both tests.

Materials and procedure

Our study was approved by the local ethics board at the University of Edinburgh. Children were tested individually on the following four tasks in order (see Table 3 for a summary of tasks and participants).

WISC-IV cancellation

This is a task of processing speed (WISC-IV 'Cancellation Task'). In this task, we tested our five synaesthetes only. This task requires children to scan two different arrays of pictures showing animate and inanimate objects. The *unstructured array* shows items scattered randomly across the page, and the *structured array* shows items arranged in rows and columns. Children are instructed to mark all target items (animals) within a time limit of 45 s for each array. The experimenter first demonstrated the task by drawing a line through each target item in a sample array. Children were then asked to do exactly the same on a practice set of items and then on the unstructured and structured arrays. Participants were told to work as quickly as possible without making any mistakes and to tell the experimenter when they were finished. Participants were stopped after 45 s if they had not already indicated that they were finished.

BPVS-II

We tested only our five synaesthetes in this task. The BPVS-II (Dunn *et al.*, 1997) is a test of receptive vocabulary and contains 14 sets (corresponding to age ranges between 2.5–21 years) each consisting of 12 target words. Each of these words describes one of four simple black and white pictures presented to participants on each trial. Participants are required to select the picture they think best illustrates the meaning of the target word spoken by the experimenter and they could indicate by either pointing or saying the corresponding number. Children began with two training plates which acted as practice sets before the main task was administered. On successful completion of these plates, children moved on to testing sets that corresponded to their age. Testing continued until a ceiling level was established (8 or more errors). Scores are calculated by deducting the

Table 3. Summary of tasks, participants and group sizes where relevant

Task	Description	Synaesthetes	Controls
WISC-IV Cancellation	Processing speed	5	Published norms
BPVS-II	Receptive vocabulary	5	Published norms
Letter-span task	Short-term memory for letters read aloud	5	40 (20 high memory; 20 low memory)
Letter matrix task	Short-term memory for letters shown visually in spatial matrices	5	20 (10 high memory; 10 low memory)

total number of errors made from the participant's ceiling score which translates into standardized scores, percentile ranks and test-age equivalents.

Letter-span task

We tested our five letter-colour synaesthetes and 40 controls (see above). Our task was devised to mirror the digit recall subtest of the WMTB-C (Baddeley & Hitch, 1974). This subtest measures phonological loop function, which is responsible for holding verbal information for short periods of time. The original task required participants to immediately repeat back a series of digits which are read aloud by the experimenter at a rate of 1 digit per second. For our purposes, we used letters rather than digits because the majority of our synaesthete participants had coloured letters rather than digits. Hence, letters were randomly generated and assigned to each trial to replace what had been digits in subtest of the WMTB-C.

The task contains six trials within each span set (ranging from 1 to 9 letters in length) and participants are required to recall at least four of the six trials correctly in order to progress on to the next set. After three incorrect responses, testing is discontinued. Scores can be obtained by calculating both the maximum digit-span set (the set before testing is discontinued; maximum = 9) and the number of correct trials achieved in total (maximum = 54). Performance can be expressed both in terms of standardized scores and percentiles. Here, testing began with a span set of four letters, given the children's ages and progressed until children failed to recall four of six trials correctly.

Letter matrix task

We tested five synaesthetes and 20 controls (see above). Participants were told they would see a grid on the screen filled with letters. Children were also given a paper copy of an empty grid. They were instructed that they would see the on-screen grid for 1 min, and then, the screen would go black, at which point they should start filling in the paper grid with as many of the letters/numbers they could remember in the right spaces. No limit was put on the time children were allowed to recall these letters. Children were told that if they could not remember they should fill all spaces as best they could.

Matrices were modelled on those used by Green and Goswami (2008). We created grids of 16 (4×4) graphemes and presented these on a computer screen for 60 s. Graphemes were all letters in Times New Roman bold font and of size 60 and were centred within each cell of the matrix. Note that our matrices were designed using letters rather than digits (in contrast to Green & Goswami, 2008) because all five synaesthetes had coloured letters, but only two had coloured digits. Each cell in the matrix was 3.8 × 5.4 cm. Four of our letter-colour synaesthetes and their matched controls were given matrices containing 16 different letters and one was given matrices containing 13 different letters of which three were repeated at random to fill all 16 cells of the matrix. Young children do not have a full complement of coloured graphemes (Simner *et al.*, 2009) and synaesthete *M10a* happened to have only 13 consistently coloured letters at the time of testing.

Children received their matrix in three conditions, in a fixed order: neutral, congruent and incongruent. In the neutral condition, letters were presented in black font, while in the congruent condition, they were displayed to match each child's synaesthesia; that is, matrices were tailored to each synaesthete individually, see below and controls saw the colours of their matched synaesthete. Finally, in the incongruent condition, graphemes were coloured contrary to those reported by the synaesthete. Specifically, the colours corresponded to letters one greater than the letter presented (e.g., P appeared in the colour the child associated with Q). Matrices were devised using detailed information about each synaesthete's specific grapheme-colour associations. These were elicited using *The Synesthesia Battery* and online testing tool (at www.synesthete.org; Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007) which gathers colour data from synaesthetes. In this battery, our child synaesthetes were shown letters (and digits, if they had both variants) individually. For each grapheme, they were required to select their synaesthetic colour from an on-screen colour palette of 16.7 million colours. From the output of this programme, we were able to determine the specific synaesthetic colour for each child's letters in terms of their RGB (red, green, blue) vector values. From these colour values, we constructed our memory matrices as described above. The precise colours were collected from our synaesthete participants in an initial session after we had performed cancellation, BPVS and letter span. We then programmed our matrix task and returned to our participants to run this in a second session.

Results

Cancellation task

As a reminder to the reader, this is a test of processing speed in which participants are required to quickly cross out target items and to ignore non-targets. Participants are scored on how many targets they clearly cross through, with deductions for any items crossed through that are not targets (Wechsler, 2003). Bonus points are awarded according to the time in which participants complete the task (4 extra points if completed within 0–29 s, 3 points within 30–34 s, 2 within 35–39 s, 1 within 40–44 s and 0 if completed after this). None of our synaesthetes completed this task before the 45-s time limit and so no bonus points were given. The maximum score for each array is 68 (i.e., there were 68 target animals). A maximum total raw score is calculated by combining scores from both random and structured arrays (maximum = 136). Results are expressed as standardized scores which give test-age equivalents and (see Table 4).

Table 4 shows that in all cases, synaesthetes were performing considerably better than expected for their age. A nonparametric related-samples Wilcoxon signed rank test showed that test ages were significantly higher than their chronological age ($T = -15$, $p = .04$) suggesting that synaesthetes show superiority in this task.

BPVS-II

The BPVS is a test of receptive vocabulary that yields a standardized score (mean 100, *SD* 15) as well as percentile ranks and test reading-age equivalents. Table 5 shows that four of

Table 4. Table shows WISC-Cancellation scores of our five grapheme-colour synaesthetes described by their ID, age (years: months) and their test-age equivalent. (M10a and M10b are two male synaesthetes aged 10 years)

ID	Age	Test-age equivalent
F10	10:05	11:10
M10a	10:01	16:10
M10b	10:09	16:02
F11	11:03	13:02
M11	11:11	15:02

Table 5. Table shows BPVS scores of our five grapheme-colour synaesthetes described by their ID, age (years: months), standardized score, percentile rank and their reading-age equivalent. (M10a and M10b are two male synaesthetes aged 10 years)

ID	Age	Standardized score	Percentile rank	*Z*	Reading-age equivalent
F10	10:05	97	42	−0.2	09:11
M10a	10:01	120	91	1.3	13:06
M10b	10:09	115	84	1.0	13:01
F11	11:03	110	74	0.7	12:10
M11	11:11	103	58	0.2	12:04

five synaesthetes had a test reading age higher than their chronological age, but this failed to reach significance ($t(4) = -2.07$, $p = .11$). We performed a nonparametric one-way test on percentile scores to assess if synaesthetes' percentile ranks were likely to fall within the upper 50%, and this difference was tending towards significance (Wilcoxon $T = 13.5, p = .10$). This last test is the same test we carried out above on the data of Green and Goswami (2008), which did yield a significant effect for that group of subjects (at $p = .02$), although they had twice as many participants as tested here (given the ease with which self-referred participants can be collected compared to randomly recruited synaesthetes).

Letter-span task

In this task, participants immediately recalled lists of letters spoken aloud by the experimenter. We tested five synaesthetes and 40 controls balanced orthogonally for sex, age group and memory: high/average, but one male average-memory control was removed from our analysis because we found he had been incorrectly categorized (he was in fact a high-memory participant). Figure 1 shows the mean number of letters recalled (i.e., mean letter span) by children in our three groups: synaesthetes, high-memory controls, average-memory controls.

We conducted a nonparametric one-way Kruskal–Wallis test ANOVA contrasting performance across groups (synaesthetes, high memory and average memory) and we

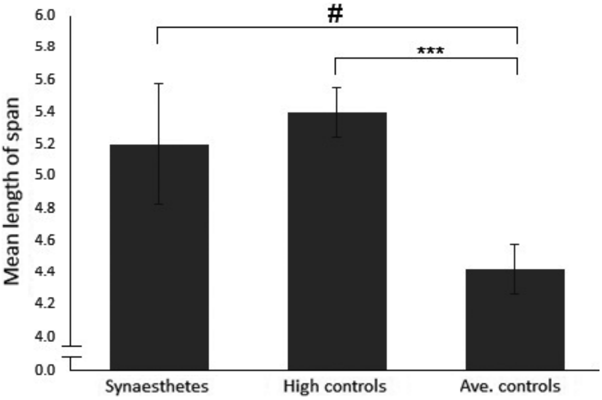

Figure 1. Mean number of letters correctly recalled in the letter-span task, for synaesthetes; average-memory controls; high-memory controls, respectively. Bars show standard errors of the mean. $p < .001^{***}$; $p = .06^{\#}$.

found a significant main effect ($\chi^2 = 14.345$, df = 2, $p < .001$). Subsequent pair-wise comparisons using the Mann–Whitney U-test correcting for ties showed a significant advantage for high-memory over and average-memory controls ($Z = -3.7$, $p < .001$), a near-significant advantage for synaesthetes over average-memory controls ($Z = -1.9$, $p = .06$) and no difference between synaesthetes and high-memory controls ($Z = -.4$, $p = .7$).

Letter matrix task

We tested five synaesthetes and 20 matched controls (half high memory, half average memory). Participants were required to recall the contents of three different 4×4 letter matrices. The letters were presented either in black font (in the neutral condition), or they were coloured congruently or incongruently with each child's synaesthesia. The number of letters recalled successfully in each condition of the matrix task is illustrated in Figure 2.

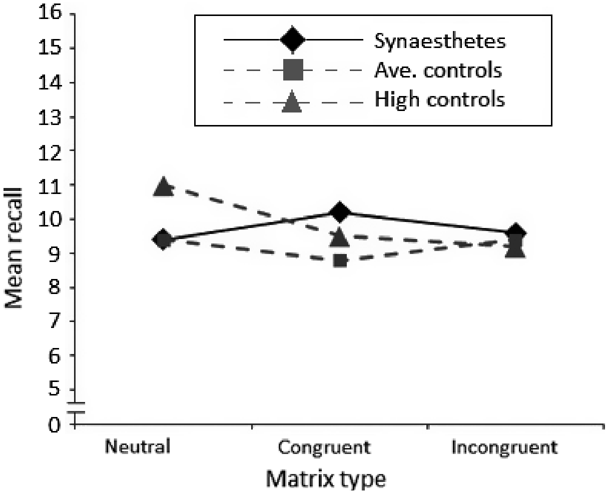

Figure 2. Letter matrix task: Mean number of letters correctly recalled in each group (synaesthetes; average-memory controls; high-memory controls, respectively) across three conditions (letters coloured neutral, congruent or incongruent with respect to synaesthesia). The minimum and maximum values on the *y*-axis are 0 and 16.

We analysed our results in a 3×3 mixed design ANOVA with the within-subjects factor of letter colouring (neutral, congruent, incongruent) and the between-subjects factor of group (synaesthetes, average-memory controls, high-memory controls). Mauchly's test indicated that the assumption of sphericity had been violated, $\chi^2(2) = 7.5$, $p = .023$, so we corrected degrees of freedom using Greenhouse–Geisser estimates. Our data showed there was no significant effect of colouring, $F(1.5, 33.8) = .28$, $p = .7$, nor group, $F(2, 22) = .175$, $p = .8$, and no interaction, $F(3.1, 33.8) = .579$, $p = .64$, suggesting that synaesthetes did not outperform controls in letter recall and nor were they affected by the colour of the letters with respect to their synaesthesia.

As our findings appear to conflict with those of Green and Goswami (2008), we have combined their data with our own to illustrate the pattern of results across both studies. Figure 3 shows the results of our own synaesthetes alongside the synaesthetes and controls of Green and Goswami (2008; taken from their figure 1; p. 468). We point out that

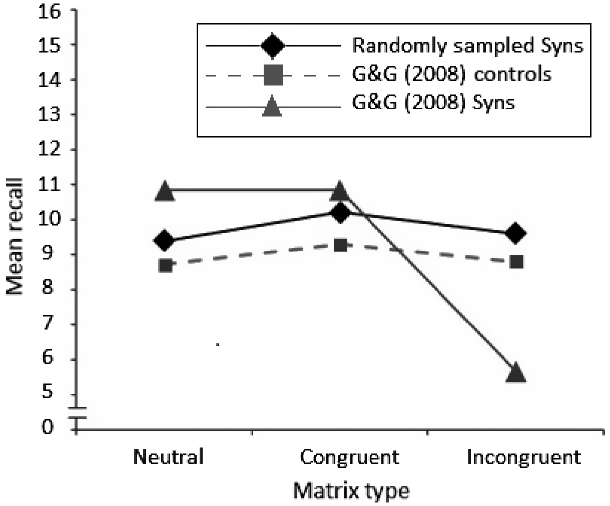

Figure 3. Cross-study comparison of matrix task: mean number of graphemes correctly recalled in each group (randomly sampled synaesthetes from our own study; synaesthetes from Green & Goswami, 2008; controls from Green & Goswami, 2008) across three conditions (letters coloured neutral, congruent or incongruent with respect to each child's synaesthesia).

the nature of the task differed slightly across studies (letter recall here, digit recall in Green & Goswami, 2008). It is nonetheless possible to compare the overall pattern of findings across each study. The figure shows that synaesthetes in Green and Goswami (2008) were adversely affected by incongruently coloured graphemes, but there is no suggestion of a similar effect for our own synaesthetes tested here.

Given our small sample size, our null effect could have resulted from insufficient power. We therefore entered our data into a Bayes analysis, which allows us to evaluate the extent to which our data have sufficient power to support the null hypothesis (Dienes, 2014; Rouder, Speckman, Sun, Morey, & Iverson, 2009). We looked particularly at synaesthetes' data in the neutral and incongruent conditions because this is where our findings diverged from Green and Goswami (2008). They found 'a significant decrease... in the incongruent condition for the grapheme-color synesthetes only (10.83 vs. 5.65)' (p. 468) and we used this decrease as the estimate for a Bayes analysis on our own data (neutral condition = 9.4; incongruent condition = 9.6). Our analysis produced a Bayes factor of 0.18. Following Jeffreys (1961; Dienes, 2014), a Bayes factor of less than 0.33 provides strong support for the null hypothesis, a Bayes factor >3 provides support for the alternative hypothesis and values in between indicate no firm conclusions should be drawn. Our Bayes factor was 0.18, indicating support for the null hypothesis. Our data therefore suggest that synaesthetes' memory span for graphemes is unaffected by their presentation colour, but only if those synaesthetes are randomly recruited like our own, rather than self-referred.

Discussion

In this study, we tested randomly recruited child grapheme-colour synaesthetes aged 10–11 years. This is the first time to our knowledge that this type of cohort has been evaluated on their cognitive functioning. We compared their performance to baseline norms where these were available (*WISC-IV Cancellati*on and *BPVS-II*) or to our own samples of non-synaesthete controls where no such norms exist (*letter span* and *letter matrix*). Our controls were non-synaesthetes with either an average memory span or a high-memory span, as determined by their performance in a previous task (Simner *et al.*, 2009; Simner & Bain, 2013; pairing colours to graphemes, then calling those pairings). We administered four tests and we review the data for each test in turn below.

We found clear evidence that child synaesthetes performed better in the WISC-IV *Cancellation Task* compared to baseline norms. In this test – where participants score through target items at speed – children with synaesthesia performed at an average test age that was 3 years 9 months older than their chronological age and every synaesthetes showed the effect. Given that the test materials were unrelated to synaesthesia per se (i.e., not inducers or concurrents), we can draw two key conclusions for theories of synaesthesia. The first is that the cognitive benefits of synaesthetes are not limited to synaesthesia itself, and related to this, such advantages are best captured by a model of improved perceptual/cognitive organization (Ramachandran & Azoulai, 2006) rather than dual-coding (Radvansky *et al.*, 2011). Our finding fits alongside other studies showing synaesthetes have cognitive advantages in tasks unrelated to their synaesthesia. For example, Brang and Ramachandran (2010) found that synaesthetes performed especially well in a hidden objects task and in a task of change detection, while Gross *et al.* (2011) found that synaesthetes performed well in the Rey Complex Figure Test (Rey, 1941). Like the cancellation task here, none of these test constructs would have evoked synaesthesia. Furthermore, materials entirely unrelated to synaesthesia (e.g., patches and check pattern; Barnett *et al.*, 2008; see also Rothen & Meier, 2013 for Discussion) also cause differences in synaesthetes' early visual processing using electroencephalography. And structural imaging studies, too, show that differences in brain structure in synaesthetes are not limited solely to regions linked with concurrents and inducers, but extend into broader synaesthetic networks (Jäncke, Beeli, Eulig, & Hänggi, 2009; Rouw & Scholte, 2007, 2010; Weiss & Fink, 2009). We therefore conclude, with Rothen and Meier (2013) that even beyond the synaesthesia and its related skills, 'some aspects of the information processing system of synaesthetes work fundamentally differently' (p. 704) and that there is a broader synaesthetic neural profile which may give rise to generalized differences beyond those linked to the synaesthesia per se (e.g., Rouw, Scholte, & Colizoli, 2011).

Our *BPVS-II task* was a test of receptive vocabulary in which children identified pictures depicting spoken target words. If there were an advantage for synaesthetes in vocabulary acquisition, this could be tied to previous findings of superiority in other word-related tasks (e.g., Radvansky *et al.*, 2011) which have been explained in terms of dual-coding benefits (because words trigger colours, which could enrich the word's memory trace). Alternatively, special vocabulary skills could also be accounted for within the model we have supported above, of superior organization of perceptual information as proposed by Ramachandran and Azoulai (2006). This is because vocabulary acquisition springs from the ability to conceptualize and categorize objects in the environment, a developmental function closely tied to perceptual organization (e.g., Taverna & Peralta, 2013). Child synaesthetes recruited by Green and Goswami (2008) scored exceptionally highly in this task. In our own study, we found a similar trend in that all but one child performed higher than the standardized mean, to approximately the same degree. However, perhaps due to our sample size ($n = 5$), this difference just missed significance at $p = .10$. These facts suggest to us that vocabulary development could be a key area to explore with a larger – and again, randomly sampled – participant group in future studies and this is something we are currently pursuing in our laboratory.

In the *letter-span task,* our high-memory controls performed significantly better, as expected, than our average-memory controls. Synaesthetes showed a near-significant advantage over average-memory controls, at $p = .06$, and were performing just as well as the high-memory controls. Because this type of finding represents superiority in a task tied to the synaesthetic inducer, it can be explained in terms of dual-coding models (e.g., Radvansky *et al.*, 2011) but again is equally compatible with a model where synaesthetes have improved organization (e.g., Ramachandran & Azoulai, 2006). Our results can be compared to an adult study conducted by Gibson *et al.* (2012) who found significantly longer letter spans in adult letter-colour synaesthetes. Our own study suggests that this capacity may be emerging even in children as young as 10–11 years. Although this superiority was not found across-the-board in our synaesthetes (one scored close to the mean for average memory children), synaesthesia appears to convey a group-level advantage that brings children with synaesthesia in line with the behaviour of children with superior memory spans. This may represent an important class-room advantage for children with synaesthesia, making them better in literacy or numeracy where this relies on memory recall (e.g., in spelling). We are now exploring this possibility directly by assessing the literacy and numeracy skills of a very large sample of (~3,000) children with and without synaesthesia.

The letter matrix task required children to recall grids of 16 black or coloured letters, which were coloured either congruently or incongruently with the child's synaesthesia. Synaesthetes were no better in recall compared to non-synaesthetes, and they were not sensitive to the colour of the font. We point out that our non-significant finding in *Matrix* recall contrasts with our near-significant finding in *letter span*. This pattern also perfectly mirrors findings in the adult literature: no superiority in matrix recall (Rothen & Meier, 2009; Rothen & Meier, 2010; Yaro & Ward, 2007) but superior performance in span tasks (Gibson *et al.*, 2012). This difference across tasks may stem from the fact that matrices typically contain many more graphemes than span sets and so may exceed any enhanced memory span capacity of synaesthetes. Alternatively, it may stem from the fact that responses in the matrix task involve not only recall of graphemes, but also placing each grapheme in its correct grid location. It may be that synaesthetes are limited in their performance in the matrix task precisely because they do not have particularly strong recall of spatial location. Indeed, one study suggests exactly this: Gibson *et al.* have shown that grapheme-colour synaesthetes perform at average levels in recalling the spatial component (only) of grid tasks (but see Gross *et al.*, 2011). Although our matrix task allowed us to examine recruitment differences with Green and Goswami (2008; see below), we suggest that a matrix task may not be an ideal test of the theories under investigation here – because although our models predict superior performance in dual-coded graphemes, the spatial requirements of the test may serve as a 'bottle-neck' to prevent synaesthetes performing well. Indeed a second study (Pritchard, Rothen, Coolbear, & Ward, 2013) found evidence that adult synaesthetes excel in the recall of coloured objects (as in our span task) but not in their location. We therefore suggest that future studies might unpick the relative influences of string length and spatial location, by presenting not only span tasks and grid tasks, but matching for item length and allowing grids to be recalled either with or without spatial information.

Our data from the matrix task failed to replicate those of Green and Goswami (2008), where synaesthetes in this earlier study were poorer in the incongruent condition. What can be concluded from this? One small difference is that number-colour synaesthetes were tested in Green and Goswami but letter-colour synaesthetes were tested here. However, both forms are recognized as a single variant of synaesthesia ('grapheme-colour synaesthesia') and both tasks required recall of graphemes, so it is not clear how this minor difference would cause the different pattern of results. We also point out that the different results across studies do not obviously stem from differences in statistical power as in this particular task, our study had almost the same number of synaesthete participants as Green and Goswami ($n = 5$ and $n = 6$, respectively) and controls (5 per synaesthete and 4 per synaesthete, respectively) and both sets of controls performed similarly across studies. Most importantly, our Bayes analysis allows us to conclude that our study was powered enough to support the null hypothesis, rather than being inconclusive. Hence, for these reasons, we suggest that our study presents what is likely to be an accurate picture of performance of randomly sampled synaesthetes in this particular task. Finally, we point out the findings of Green and Goswami have not been replicated in subsequent adult cohorts. Like us, Yaro and Ward (2007), Rothen and Meier (2009), Rothen and Meier (2010) and Gross *et al.* (2011) found no effect of font colour and no overall superiority in matrix recall. Only earlier case studies testing individual adult synaesthetes showed matrix effects (e.g., Luria, 1968; Smilek *et al.*, 2002), but these participants may have come to the attention of researchers precisely because they had a superior memory. We therefore conclude, like Rothen, Yaro, Gross and colleagues, that case-study subjects appear to have had additional cognitive abilities not typical of average synaesthetes, or at the very least, that their abilities are not seen in average developing child synaesthetes of the type tested here.[2]

Our findings might serve as a flag to future researchers wishing to study synaesthesia in children. By comparing our data with that from Green and Goswami (2008), we conclude that their child participants were different from our own and we suggest these differences may lie in the way participants were recruited across studies. Those in Green and Goswami appear to have been self-referred in some way (i.e., referred by parents) and we infer this from the absence of any description in their study of the large-scale methodologically complex approach required for wide-scale screening of many hundreds of children to identify average synaesthetes, which is the method we used here. We have discussed the inherent problems with self-referred/non-random recruitment because this is likely to recruit child participants who are *a priori* cognitively different, given family backgrounds (i.e., from families who are motivated or interested enough to self-refer for scientific research) or given some type of special exposure to synaesthesia in their home. Unlike the parents in our own study, those in studies of self-referred cohorts are by definition aware of their child's synaesthesia prior to their child being tested. In other words, parents and children must have previously discussed synaesthesia, possibly for some time and this could reinforce the child's synaesthetic experiences. For example, if children are raised in a family where attention is drawn to synaesthesia at a young age, they may learn to attend to their synaesthetic colours more than they otherwise would. The pattern of data found by Green and Goswami in their matrix task appears to support this second possibility: their synaesthetic children were not cognitively superior in this task, but they were more attuned to their synaesthesia. In other words, they did not outperform

---

[2] *Only one previous group study has shown any differences between (adult) synaesthetes and controls (Gibson* et al.*, 2012) in a matrix-type task, although both their approach and their findings were somewhat different to those used by Green and Goswami (2008). Gibson and colleagues presented letter-colour synaesthetes with achromatic letters but deconstructed their matrix task into letter recall, then spatial recall, but also with an additional temporal component in the presentation of their materials (i.e., letters were presented sequentially rather than all at one). On this somewhat different task, Gibson* et al. *found synaesthetes had significantly better letter recall than controls, which makes their finding equivalent to the trend in our own letter-span task here, but quite different to the results in 'standard' matrix tasks where synaesthetes are not outperforming controls (see above, also Green & Goswami, 2008; Gross* et al.*, 2011; Rothen & Meier, 2009, 2010; Yaro & Ward, 2007).*

controls, but instead, they were more affected when colour was manipulated to conflict with their synaesthesia. A direct comparison of self-referred and randomly sampled child synaesthetes within the same study would allow a clearer understanding of how recruitment influences performance in this domain. However, our central aim has been to present the first cohort of 'average synaesthetic children' and to evaluate their performance.

A final advantage of large-scale screening over self- or parental-referral is that synaesthetes remain unaware they are a 'special population' for the research. Gheri, Chopping, and Morgan (2008) suggested that synaesthetes recruited as a special population may try harder in experiments, creating an effort confound. In our own study, synaesthetes could not realize they were a special population for many reasons. First, all children took a number of similar tests including the same test of synaesthesia and there was no feedback about our or results. Moreover, the assessment for synaesthesia took place a full 3 years before the cognitive tests performed here with no way to link the two sets of tests together (e.g., they were run by an entirely different set of researchers).[3] Although children might feel special simply by virtue of being tested, this was of course true of all the children we tested, whether synaesthete, high-memory control or average-memory control: but it was the synaesthetes who showed superiority in the tasks. In summary, there was no way for the children with synaesthesia to know they were targets within our study. Most importantly perhaps, our experience over the last decade has shown us that average synaesthetic children have no idea that other children do not share their experiences; they do not realize they are 'special' because they do not realize they are different at all. Although our recruitment methods have great advantages in sampling average (rather than self-referred) synaesthetes, the disadvantages are clearly in the sample size. Our findings based on a small population and should therefore be replicated in larger sample. Of course even 30 randomly sampled child synaesthetes would require a screening more than a three and a half thousand children, although this is precisely the approach we are now taking in our laboratory.

To summarize our findings, our data support previous studies showing cognitive advantages for synaesthetes over non-synaesthetes (e.g., Rothen & Meier, 2009; Radvansky *et al.*, 2011; Yaro & Ward, 2007) and we found no disadvantages. We found a near-significant advantage in a letter-span task which would be compatible with either a dual-coding account (in which synaesthetes perform better because their memory traces for graphemes are more richly encoded, e.g., Gibson *et al.*, 2012) or a theory of improved perceptual organization (in which synaesthetes perform better because this organization makes performance more efficient; Ramachandran & Azoulai, 2006). Importantly, however, we also found superior performance in an assessment of processing speed for stimuli unrelated to synaesthesia, which cannot accounted for within a dual-coding theory. As such, this set of data support only the theory of improved perceptual/cognitive organization (Ramachandran & Azoulai, 2006). We also found that the average child synaesthete performs similarly to adults in showing no superiority in matrix recall and no special sensitivity to coloured letters in this task. Given this, we suggest that previous data from non-randomly recruited child synaesthetes may be non-reflective of the abilities of child synaesthetes at large (Green & Goswami, 2008). We point out that the study by Green and Goswami was a crucial first step in drawing attention to the condition of

---

[3] *Although coloured letters were again elicited from synaesthetes and controls before our final (matrix) task, whether or not this alerted synaesthetes to our particular interest, it made no difference to their test scores – synaesthetes and non-synaesthetes performed identically on this task.*

synaesthesia in children. It enabled researchers to consider – for the first time – how this unusual condition develops and was the first study to ask whether childhood synaesthesia is accompanied by differences in cognition. Our findings have implication for education given that children with synaesthesia are found in surprisingly high numbers in schools (e.g., Simner *et al.*, 2009). Our study here has shown that models designed to capture adult synaesthesia behaviour can also be tested in synaesthete children and that such children show cognitive differences. We suggest that the full range of influences on learning and cognition that accompany synaesthesia should be identified in full so that the performance of these children is better understood in educational settings.

Acknowledgements

This research has received funding from the European Research Council for author JS under the European Union's Seventh Framework Programme (FP/2007-2013)/ERC Grant Agreement no. [617678].

References

Baddeley, A. D., & Hitch, G. J. (1974). Working memory. In G. Bower (Ed.), *The psychology of learning and motivation*, VIII (pp. 47–90). New York: Academic Press.

Barnett, K. J., Foxe, J. J., Molholm, S., Kelly, S. P., Shalgi, S., Mitchell, K. J., & Newell, F. N. (2008). Differences in early sensory-perceptual processing in synesthesia: A visual evoked potential study. *NeuroImage*, *43*, 605–613.

Brang, D., & Ramachandran, V. S. (2010). Visual field heterogeneity, laterality and eidetic imagery in synesthesia. *Neurocase*, *16*, 169–174.

Cytowic, R. E., & Eagleman, D. M. (2009). *Wednesday is Indigo Blue: Discovering the brain of synesthesia*. Cambridge, UK: MIT Press.

Dienes, Z. (2014). Using Bayes to get the most out of non-significant results. *Frontiers in Psychology*, *5*, 781.

Dixon, M. J., Smilek, D., Cudahy, C., & Merikle, P. M. (2000). Five plus two equals yellow. *Nature*, *406*, 365.

Dixon, M. J., Smilek, D., & Merikle, P. M. (2004). Not all synaesthetes are created equal: Projector versus Associator synaesthetes. *Cognitive, Affective and Behavioral Neuroscience*, *4*, 335–343.

Dovern, A., Fink, G. R., Fromme, A. C., Wohlschläger, A. M., Weiss, P. H., & Riedl, V. (2012). Intrinsic network connectivity reflects consistency of synesthetic experiences. *Journal of Neuroscience*, *32*, 7614–7621.

Dunn, L. M., Dunn, L. M., Whetton, C. W., & Burley, J. (1997). *The British picture vocabulary scales* (2nd ed.). Windsor, UK: NFER Nelson.

Dunn, L. M., Dunn, L. M., Whetton, C., & Pintilie, D. (1982). *The British picture vocabulary scale: Manual for the short and long forms*. Windsor, ON: NFER-Nelson.

Eagleman, D. M., Kagan, A. D., Nelson, S. S., Sagaram, D., & Sarma, A. K. (2007). A standardized test battery for the study of synesthesia. *Journal of Neuroscience Methods*, *159*, 130–145.

Gheri, C., Chopping, S., & Morgan, M. J. (2008). Synaesthetic colours do not camouflage form in visual search. *Proceedings of the Royal Society B*, *275*, 841–846.

Gibson, B. S., Radvansky, G. A., Johnson, A. C., & McNerney, M. W. (2012). Grapheme–color synesthesia can enhance immediate memory without disrupting the encoding of relational cues. *Psychonomic Bulletin and Review*, *19*, 1172–1177.

Green, J. A. K., & Goswami, U. (2008). Synaesthesia and number cognition in children. *Cognition*, *106*, 463–473.

Gross, V. C., Neargarder, S., Caldwell-Harris, C. L., & Cronin-Golomb, A. (2011). Superior encoding enhances recall in color-graphemic synesthesia. *Perception*, *40*, 196–208.

Hubbard, E. M., Arman, A. C., Ramachandran, V. S., & Boyton, G. M. (2005). Individual differences among grapheme-colour synaesthetes: Brain behavior correlations. *Neuron*, *45*, 975–985.

Jäncke, L., Beeli, G., Eulig, C., & Hänggi, J. (2009). The neuroanatomy of grapheme-color synesthesia. *European Journal of Neuroscience*, *29*, 1287–1293.

Jeffreys, H. (1961). *The theory of probability* (3rd ed.). Oxford, UK: Oxford University Press.

Luria, A. (1968). *The mind of a mnemonist*. New York, NY: Basic books.

Mills, C. B., Innis, J., Westendorf, T., Owsianiecki, L., & McDonald, A. (2006). Influences of a synesthete's photisms on name recall. *Cortex*, *42*, 155–163.

Pickering, S. J., & Gathercole, S. E. (2001). *Working memory test battery for children*. London, UK: Psychological Corporation Europe.

Pritchard, J., Rothen, N., Coolbear, D., & Ward, J. (2013). Enhanced associative memory for colour (but not shape or location) in synaesthesia. *Cognition*, *127*, 230–234.

Radvansky, G. A., Gibson, B. S., & McNerney, M. W. (2011). Synesthesia and memory: Color congruency, von Restorff and false memory effects. *Journal of Experimental Psychology: Learning, Memory and Cognition*, *37*, 219–229.

Ramachandran, V. S., & Azoulai, S. (2006). Synesthetically induced colors evoke apparent motion perception. *Perception*, *35*, I1557–I1560.

Rey, A. (1941). The psychological exam in cases of head trauma (The problems). *Archives de Psychologie*, *28*, 215–285.

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*, e5037.

Rothen, N., & Meier, B. (2010). Grapheme-colour synaesthesia yields an ordinary rather than extraordinary memory advantage: Evidence from a group study. *Memory*, *18*, 258–264.

Rothen, N., & Meier, B. (2013). *Synaesthesia and memory*. In J. Simner & E. M. Hubbard (Eds.), *The Oxford handbook of synesthesia* (pp. 692–706). Oxford, UK: Oxford University Press.

Rouder, J. N., Speckman, P. L., Sun, D., Morey, R. D., & Iverson, G. (2009). Bayesian t tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review*, *16*, 225–237.

Rouw, R., & Scholte, H. S. (2007). Increased structural connectivity in grapheme-colour synaesthesia. *Nature Neuroscience*, *10*, 792–797.

Rouw, R., & Scholte, H. S. (2010). Neural basis of individual differences in synesthetic experiences. *The Journal of Neuroscience*, *30*, 6205–6213.

Rouw, R., Scholte, H. S., & Colizoli, O. (2011). Brain areas involved in synaesthesia: A review. *Journal of Neuropsychology*, *5*, 214–242.

Simner, J. (2007). Beyond perception: Synaesthesia as a psycholinguistic phenomenon. *Trends in Cognitive Sciences*, *22*, 23–29.

Simner, J., & Bain, A. E. (2013). A longitudinal study of grapheme-color synesthesia in childhood: 6/7 years to 10/11 years. *Frontiers in Human Neuroscience*, 7, 603. doi:10.3389/fnhum.2013.00603

Simner, J., Glover, J., & Mowat, A. (2006). Linguistic determinants of word colouring in grapheme-colour synaesthesia. *Cortex*, *42*, 281–289.

Simner, J., Harrold, J., Creed, H., Monro, L., & Foulkes, L. (2009). Early detection markers for synaesthesia in childhood populations. *Brain*, *132*, 57–64.

Simner, J., & Hubbard, E. M. (2013). *The Oxford handbook of synesthesia*. Oxford, UK: Oxford University Press.

Simner, J., Mulvenna, C., Sagiv, N., Tsakanikos, E., Witherby, S. A., Fraser, C., Scott, K., & Ward, J. (2006). Synaesthesia: The prevalence of atypical cross-modal experiences. *Perception*, *35*, 1024–1033.

Simner, J., & Ward, J. (2006). The taste of words on the tip of the tongue. *Nature*, *444*, 438.

Smilek, D., Dixon, M. J., Cudahy, C., & Merikle, P. M. (2002). Synesthetic color experiences influence memory. *Psychological Science*, *13*, 548–552.

Spector, F., & Maurer, D. (2011). The colors of the alphabet: Naturally-biased associations between shape and color. *Journal of Experimental Psychology: Human Perception and Performance*, *37*, 484–495.

Taverna, A. S., & Peralta, A. O. (2013). Young children category learning: A training study. *European Journal of Psychology of Education*, *28*, 599–617.

Ward, J., Simner, J., & Auyeung, V. (2005). A comparison of lexical-gustatory and grapheme-colour synaesthesia. *Cognitive Neuropsychology*, *22*, 28–41.

Wechsler, D. (2003). *Wechsler intelligence scale for children* (4th ed.). San Antonio, TX: Harcourt Assessment.

Weiss, P. H., & Fink, G. R. (2009). Grapheme-colour synaesthetes show increased grey matter volumes of parietal and fusiform cortex. *Brain*, *132*, 65–70.

Yaro, C., & Ward, J. (2007). Searching for Shereshevskii: What is superior about memory in synaesthesia? *Quarterly Journal of Experimental Psychology*, *60*, 691–695.

Received 19 September 2016; revised version received 14 February 2017