Numeracy Skills in Child Synaesthetes: Evidence from grapheme-colour synaesthesia

Abstract

Grapheme-colour synaesthesia is a neurological trait that causes lifelong colour associations for letter and numbers. Synaesthesia studies have demonstrated differences between synaesthetes and non-synaesthetes in ways that extend beyond synaesthesia itself (e.g., differences in their cognition, personality, and creativity). This research has focused almost exclusively on adult synaesthetes, and little is known about the profiles of synaesthetic children. By and large, findings suggest advantages for synaesthetes (e.g., Chun & Hupé, 2016; Havlik et al., 2015; Rothen et al., 2012; Rouw & Scholte, 2016; Simner & Bain, 2018) although differences in mathematical ability are unclear: some research indicates advantages (e.g., Green & Goswami, 2008) whilst others suggest difficulties (e.g., Rich et al., 2005). In the current study, we tested numerical cognition in a large group of children with grapheme-colour synaesthesia. Synaesthetes with coloured numbers showed advantages over their peers in their sense of numerosity, but not in their curriculum mathematics ability. We discuss how our findings speak to models for synaesthesia, to methodologies for assessing number cognition (e.g., dot numerosity tasks), and to the wider educational practice of using coloured number-tools in schools (e.g., *Numicon*; Oxford University Press, 2018).

Keywords: synaesthesia, children, mathematics, dot numerosity, dual-coding

Synaesthesia is an unusual neurological trait affecting at least 4.4% of the population (Simner et al., 2006). For people with synaesthesia, commonly encountered stimuli (e.g., words, music) trigger secondary experiences like colours or tastes (for review, see Simner & Hubbard, 2013). In the current study we focus on *grapheme-colour synaesthesia*, in which letters and numbers give rise to automatic colour sensations. For example, a grapheme-colour synaesthete might feel that *F* is blue, *6* is red, and so on (J. Simner, Glover, & Mowat, 2006; J. Simner & Holenstein, 2007). Grapheme-colour synaesthetes have recognised neurological differences; for example, differences in white matter connectivity in regions associated with colour processing (e.g., Rouw & Scholte, 2007) as well as differences in more distributed areas such as the superior parietal cortex (for review, see Rouw, Scholte, & Colizoli, 2011 and Hupé & Dojat, 2015). In our study we ask whether children with grapheme-colour synaesthesia show behavioural differences to their peers in ways that extend beyond the synaesthetic sensations themselves. We compared randomly sampled child synaesthetes aged 6-10 years, and matched controls, in terms of their abilities in numerical cognition.

In adults at least, there is growing evidence to suggest that synaesthetes have a particular cognitive profile in which they outperform non-synaesthetes in a number of ways. For example, adult grapheme-colour synaesthetes show better memory than non-synaesthetes for word lists (Gibson, Radvansky, Johnson, & McNerney, 2012), better memory for colour (Yaro & Ward, 2007), and more vivid visual mental imagery in self-report (Barnett & Newell, 2008). Rouw and Scholte (2016) found, too, that a group of synaesthetes also outperformed non-synaesthetes in a general intelligence test (and many of these synaesthetes had coloured graphemes). Also, Chun and Hupé (2016) found that a similar group of synaesthetes were significantly better than controls in a verbal comprehension task. Ward, Thompson-Lake, Ely and Kaminski (2008) also showed that synaesthetes outperformed non-synaesthetes in objective measures of creativity, such as a convergent creativity task (i.e., finding the missing link between three ostensibly unrelated words), and that synaesthetes engage more than controls in creative hobbies and employment (see also Rich et al., 2005; Rothen & Meier, 2010b). In summary, synaesthetes perform better than their peers in a number of measures, suggesting they have particular differences in domains outside synaesthesia itself.

Despite this large body of research on adult synaesthetes, very little attention has been paid to synaesthetic children. One recent study, Simner and Bain (2018), found that child grapheme-colour synaesthetes aged 10-11 years showed superiority in a speed-of-processing task (which required them to quickly discriminate between different objects in an array). Simner and Bain (2018) also re-analysed data from a sample of grapheme-colour synaesthetes studied by Green and Goswami (2008) which pointed towards a possible verbal comprehension benefit for child synaesthetes, and this was subsequently confirmed by Smees et al. (2019). Together, these small number of findings suggest that cognitive abilities may be potentially superior in synaesthetes from a young age. And certainly by the time they are adults, synaesthetes show a range of cognitive advantages over their peers.

In the current study we investigated whether differences in the cognitive profile of synaesthetes extends to numeracy skills, and in particular whether differences are found in synaesthetic children. It is important to understand whether synaesthetic children are difficult to their peers in numeracy and literacy since there are on average 2.2 grapheme-colour synaesthetes in every primary school in the UK, and (given different class sizes) there are 5.1 in the USA. But in previous research, results on numerical cognition have been somewhat conflicting – in both adults and children. Studies have suggested that synaesthetes may experience both advantages *and* disadvantages in mathematics, depending on the type of synaesthetes tested and the way numeracy was explored. Green and Goswami (2008) measured numeracy skills in children using the WISC arithmetic test (O'Donnell, 2009), and found that grapheme-colour synaesthetes were trending towards superior scores (see Simner and Bain, 2018, for a statistical analysis of the descriptive data presented by Green and Goswami). However, the child synaesthetes tested by Green and Goswami had not been randomly sampled, and Simner and Bain (2018) have described a number of ways in which these sampling methods may have encouraged superior performers, irrespective of whether children had synaesthesia or not.

Other studies have suggested that grapheme-colour synaesthesia might in fact hinder numerical cognition. Rich, Bradshaw, and Mattingly (2005) simply asked adult synaesthetes (the majority of whom experienced grapheme-colour synaesthesia) about their experiences of mathematics; 4.7% felt they had advantages in mathematics, while 16% felt they experienced difficulties. However, there were no baselines against which to compare these responses (e.g., no groups of non-synaesthetes). And in children, Green and Goswami (2008) tested whether child grapheme-colour synaesthetes aged 7-15 would experience difficulties if numbers were presented to them in incongruent colours (i.e. colours conflicting with each child's synaesthesia) compared to congruent colours (i.e. colours matching each child's synaesthesia). Synaesthetes performed a simple digit-recall task and showed worse memory for incongruent trials compared to a neutral baseline (black text; but see Simner & Bain, 2018, who did not replicate this finding). A similar study by Mills, Metzger, Foster, Valentine-Gresk and Ricketts (2009) looked at a case study of adult grapheme-colour synaesthesia and showed that arithmetic, too, was slower when digits were presented in incongruent colours. These latter studies suggest that grapheme-colour synaesthetes may experience difficulties from conflicting colours, but does not speak to number cognition more generally.

Finally, Ward, Sagiv, and Butterworth (2009) looked at numeracy in another type of synaesthesia altogether. *Sequence-space synaesthetes* experience sequences such as numbers as being arranged in specific spatial patterns (e.g., they may feel that numbers unfold in lines across the visual field, or wrap around the body). Sequence-space synaesthetes were slower in mental calculation for functions such as multiplication, suggesting they might 'over-rely' on their visuo-spatial mental number line for numerical tasks that would usually involve verbal recall (e.g., multiplication; see Dehaene & Cohen, 1995, 1997; Lee & Kang, 2002). Other studies have shown that sequence-space synaesthetes show differences in their spatial-numerical mapping (e.g., differences in their mental number line; e.g., Toomarian, Gosavi & Hubbard 2019). In summary, this body of research suggests that some adult grapheme-colour synaesthetes self-report difficulties in maths, that adult sequence-space synaesthetes are slower in some domains of arithmetic, and that children and adults may struggle if using coloured numbers that clash with their synaesthesia. At the same time, the adult self-report was somewhat mixed, with self-reports of both advantages and disadvantages in maths, and no baseline to compare against. Additionally, the child finding did not replicate using improved recruitment methods (see Simner & Bain, 2018), so it remains unclear exactly whether and how children with synaesthesia might show differences in their numerical skills. We therefore present the first systematic study of this topic using randomised sampling and large group sizes.

Here, we tested children with synaesthesia, and measured numeracy in two ways: using a curriculum mathematics test, and a numerosity task. Numerosity is our intuitive "number sense" which allows us to understand magnitudes without counting the exact amount. Our sense of numerosity relies on an *approximate number system* (ANS) which comprises a set of mental processes that approximately encode magnitudes (Dehaene, 2001). Numerosity is often measured by asking individuals to make quantity judgements without enough time to physically count objects (Dehaene, 2001). For example, in the *Dot Numerosity* task used here (Halberda Mozzocco & Feigenson, 2008), children view a cluster of black dots adjacent to a cluster of white dots. Both appear on the screen simultaneously for a short period of time.

Children must then decide which array contained more dots. Adults are typically able to perform this task successfully, and can differentiate between dot arrays with a ratio of 1:1.15 (Barth, Kanwisher, & Spelke, 2003). In children, Lipton and Spelke (2004) found that even 6-months-olds discriminate at a ratio of 1:2, and that by 9 months, infants had improved this to somewhere between 1:1.5 and 1:1.25. The ANS therefore develops over time but is already established in young babies (see also Feigenson, Dehaene, & Spelke, 2004; Xu & Spelke, 2000).

In our study we look at how synaesthetes perform in this test of numerosity, as well as a traditional curriculum maths test. Evidence suggests there is some interaction between both types of numerical cognition, since better numerosity performance is linked with higher maths scores (Anobile, Stievano, & Burr, 2013; Chen & Li, 2014; Halberda et al., 2008). For example, Halberda et al. (2008) investigated children's numerosity ability and maths, and showed that differences in numerosity at age 14 is correlated to mathematics performance as far back as kindergarten. Wong, Ho, and Tang (2016) used structural equation modelling to suggest a causal directionality, in that better numerosity leads to improved numeral mapping, which consequently leads to improved mathematical skills. In the present analyses we investigate both numerosity and maths performance, asking first whether synaesthetes have superior performance in numerosity (ANS acuity), and then whether they also show superior performance in maths. We predict that child synaesthetes may perform differently to controls in tests of numerosity and/or mathematics compared to non-synaesthetic controls, and we review the basis of this hypothesis below.

One recent study has suggested that pairing colour with numbers could be tied to advantages in numerosity, even for non-synaesthetes. Rinaldi, Smees, Alvarez, and Simner (2019) looked at the pairing of colour with number in educational maths tools such as *Numicon* (Oxford University Press, 2018). *Numicon* is a learning tool which comprises ten colour-coded plastic shapes, corresponding to the numbers 1-10 (e.g., the shape for number 5 has five holes and is coloured red). Rinaldi et al. looked at how colour-coding in this tool aided children's learning. They tested a large cohort of children from the general population who had been taught with *Numicon* at school, and divided children into two groups: those who had naturally memorised the colour-coding of *Numicon*, versus those who had not. Rinaldi et al. found that children who had internalised *Numicon* colours (e.g., *5* is red) performed better in a dot numerosity task compared to their peers who had not internalised these colours. Rinaldi et al. suggested that the 'dual coding' of colours to numbers may have strengthened children's numerical encoding, leading to a stronger ANS and therefore improved numerosity skills. This type of dual-coding model was originally proposed by Paivio (1969), but has since been offered within models of synaesthesia (e.g., Gibson et al., 2012). Children who encoded *Numicon* colours in this earlier study were not synaesthetes, but they show synaesthesia-like associations[1] suggesting that genuine grapheme-colour synaesthetes, too, might benefit from coloured numbers in a similar way.

If applied to synaesthetes, the *Numicon* findings of Rinaldi et al. would predict that children with grapheme-colour synaesthesia might show benefits in numerosity, but no benefits in mathematics. This is because children who internalised *Numicon* colours were better than controls in numerosity, but not in a curriculum maths test. We therefore present both numerical tasks to our grapheme-colour synaesthetes. Importantly, we will compare synaesthetes with colours only for letters, to synaesthetes with colours for numbers, because the dual-coding model of Rinaldi et al. (2019) predicts numerical benefits for synaesthetes with coloured numbers but not coloured letters. However, if synaesthetes score well for reasons *unrelated to* dual-coding (e.g., from some broader type of enhanced perceptual or structural organisation (see Hänggi, Wotruba, & Jäncke, 2011; Ramachandran & Azoulai, 2006; Simner & Bain, 2018), we might find higher numerosity (and potentially even, better curriculum maths scores) irrespective of whether synaesthetes have colours from letters or from numbers.

Finally, this comparison between synaesthetes with numbers versus letters-only also allows us to address a recent methodological debate surrounding dot-numerosity tasks. Some have suggested dot-numerosity may not be tapping numerical processing at all, but rather visual processing (Gebuis, Gevers, & Cohen Kadosh, 2014). If this this the case, there would be no reason to expect number synaesthetes to be different from letter-only synaesthetes. However, if we find instead that number synaesthetes are indeed better than letter-only synaesthetes, this

[1] Rinaldi et al. tested children from the same population as our study here, but their target population (children internalising *Numicon*) were very different to our targets here (children with synaesthesia). Synaesthetes have largely idiosyncratic colours, while *Numicon-internalizers* have a fixed set of colours, following the maths tool. And synaesthetes are identified very differently: they must consistently report their colours in retests across periods as long as approximately 7 months (see *Methods*), while *Numicon-internalisers* simply state their colours once (and match to *Numicon* at rates higher than chance). When comparing children from both target groups (i.e., current study vs. Rinaldi et al., 2019), only two in 41 synaesthetes we test here appeared in both groups. These two children cannot be ruled out as legitimate synaesthetes, since children with synaesthesia can, on rare occasions, “imprint” their colours from the environment (Witthoft & Winawer, 2006). However, for clarity we point out that removing these two children from our current study does not alter the pattern of results reported below in any way.

would provide innovative evidence that the numerosity dot task does indeed tap into numerical processing -- at least to some extent (see also Schneider et al., 2017).

We also tested two types of non-synaesthetes as controls: non-synaesthetes with *average-performance* for multisensory stimuli, and non-synaesthetes with *superior-performance* for multisensory stimuli (see *Methods*). These latter can recall coloured-graphemes in short-term memory tests particularly well (i.e., they can invent colours for numbers/ letters, then recall these associations a few minutes later), but they do not have the life-long associations found in synaesthetes. By including both *high-* and *average-performing controls* in our study, we can unpack whether benefits for synaesthetes in numerical cognition relate in any way to having a good memory – in which case *high-performing controls* might perform as well as synaesthetes. Conversely, if synaesthetes have advantages unrelated to this type of memory ability, they should out-perform both groups of controls. In summary, we present a dot-numerosity task and a mathematics test to grapheme-colour synaesthetes, who have either coloured numbers or coloured letters only. We compare their performance against two types of controls: non-synaesthetes with superior- or average-performance in memorising coloured graphemes. We predict that synaesthetes with coloured numbers might out-perform all other groups if they have superior numbers skills, and we may see this effect in our maths test and/or our dot-numerosity task (assuming this latter taps numerical processing).

Methods

Participants

We tested 34 children with grapheme-colour synaesthesia who had been identified from an earlier screening program, and our sample size was determined by this earlier screening (Rinaldi, Smees, Carmichael, & Simner, 2019; Simner, Alvarez, Rinaldi, Smees, & Carmichael, 2019; J. Simner, Rinaldi, et al., 2019). This program identified child synaesthetes between the ages of 6 and 10 years, from the student bodies of 22 primary schools in the south of England, Years 2 through 5. Since opt-outs were minimal (only 1%), this sample represents an unbiased cohort of local child synaesthetes. The screening methodology is described fully within Rinaldi et al. (2019; see also; Simner, Alvarez, Rinaldi, et al., 2019; Simner, Rinaldi, et al., 2019) but essentially required each child to repeatedly pick colours for the letters A-Z and numbers 0-9 from an extensive colour-palette. Synaesthetes were identified by detecting the gold standard characteristic of 'consistency over time' (i.e., for a genuine synaesthete, associations tend to stay the same over time; e.g., if the letter *A* is red, it is *always* red). To be identified as a synaesthete, a child therefore had to be statistically more consistent than age-matched peers when reporting his/her grapheme-colour associations in three comparisons: within an initial consistency test (Session 1), *and* within a second consistency test (Session 2), *and* across the 7 months between these two sessions. In other words, these methods for identifying synaesthetes were highly conservative, and full details are given in Rinaldi et al. (2019; see also; Simner, Alvarez, Rinaldi, et al., 2019; Simner, Rinaldi, et al., 2019).

Once synaesthetes were identified, we divided them into two groups: synaesthetes with only coloured letters ($n = 14$), versus synaesthetes who had coloured numbers ($n = 20$, including 13 synaesthetes who had both letters and numbers). Henceforth we refer to these as *letter-only synaesthetes*, and *number-synaesthetes* respectively[2]. We identified and excluded an additional 7 children who has been identified with grapheme-colour synaesthesia but also had yet another type of synaesthesia (which triggered sensations *other* than colour). Since we were interested in colour specifically, we did not include these children within our study. Full demographic details of our final groups are given in Table 1.

In addition to synaesthetes, we also tested non-synaesthetic controls. These controls were children drawn from the same population as synaesthetes, but had failed the synaesthesia diagnostic. We divided our controls into two groups: both were non-synaesthetes but they differed in one element of the screening test. *Average-performing controls* performed within the average range within the Session 1 consistency test, whereas *high-performing controls* were superior performers in Session 1 (although they did not maintain consistency in Session 2 or across Sessions). High-performing controls therefore showed an increased ability to remember paired associations (e.g., colours for numbers within a single test session) but without having the long-term consistency characteristic of synaesthesia. Comparing both types of controls with synaesthetes will therefore allow us to distinguish features of synaesthesia from considerations of memory (see Simner & Bain, 2018; Simner et al., 2009).

Average-performing controls were matched pairwise to each synaesthete and to each *high-performing control* (in an approximate ratio of 2:1) in both age and sex, and also, where possible, within schools. Where school-matching was not possible, controls were matched from

[2] Our crucial focus is whether synaesthetes have coloured numbers or not. Due to limited numbers of synaesthetes, we collapsed two group of synaesthetes together: those with coloured numbers only, and those with coloured numbers and letters. These children all had coloured numbers, so formed the 'number-synaesthetes' group. Our comparison group of synaesthetes had *no* coloured numbers (i.e., 'letter-only synaesthetes').

a school sharing the same socio-economic status (i.e., using each school's percentage *Free School Meals*, as the UK school-wide benefit linked to low household income; see Taylor, 2018). All children (Years 2-5) completed our numerosity test, while only Years 3-5 completed our maths test (see *Methods* for details). An additional 15 participants were tested but subsequently excluded from our numerosity analysis: nine children experienced a technical failure and six children did not finish the task. Exclusion criteria were established prior to analysis.

Table 1

Number (N) of participants by group and gender, mean age and standard deviation (SD). For each analysis, we compare each type of *synaesthete* to *high- memory controls* and their respective *average-performing controls* (e.g., the analysis for *letter-only synaesthetes* will compare participants in row 2, row 5, and 8).

Group	Total N	N Female	N Male	Mean age	SD age
Synaesthete:					
Letter-only synaesthetes	14	9	5	8.64	1.30
Number synaesthetes	20	10	10	8.88	1.15
High-performing control:					
high-performing control for letters-only	80	48	32	8.26	1.31
high-performing control for numbers	161	77	84	8.30	1.16
Average-performing control:					
matched to letter-only synaesthetes and high-performing controls	172	102	70	8.19	1.27
matched to number synaesthetes and high-performing controls	372	180	192	8.36	1.16

Materials and Procedure

Our study received ethical approval by the Sussex University Science and Technology Research Committee. Children completed two tests of numerical cognition, described below. Testing took place between October 2016 and April 2017. Neither children nor experimenters knew the synaesthetic status of children at the point of their testing for numerosity and mathematics.

Numerical Cognition: Curriculum Maths.

Our in-house maths test came from Rinaldi, Smees, Alvarez et al. (2019), and assessed key components from the UK primary school mathematics curriculum ("The national curriculum in England: Key stages 1 and 2 framework document," 2013). This pencil-and-paper test had 47 questions in total, which represented one question for each of the 7-9 topics per year – across six school years (Years 1-6). These topics covered a range of subjects including arithmetic, fractions, graphs, timetables, percentages, geometry and so on (see Figure 1 for examples from the test). Children started the test with questions two years below their current school year (e.g., Year 3 students start with Year 1 questions). Since there is no set UK math curriculum prior to Year 1, students in Year 2 could not complete an equivalent test so were excluded from mathematics testing. The test presented one question per line, and children were given five minutes to answer as many questions as possible. Children were not expected to go beyond their current year-group material in the allocated time, although all correct questions were scored. This pencil and paper task is available from the corresponding author on request.

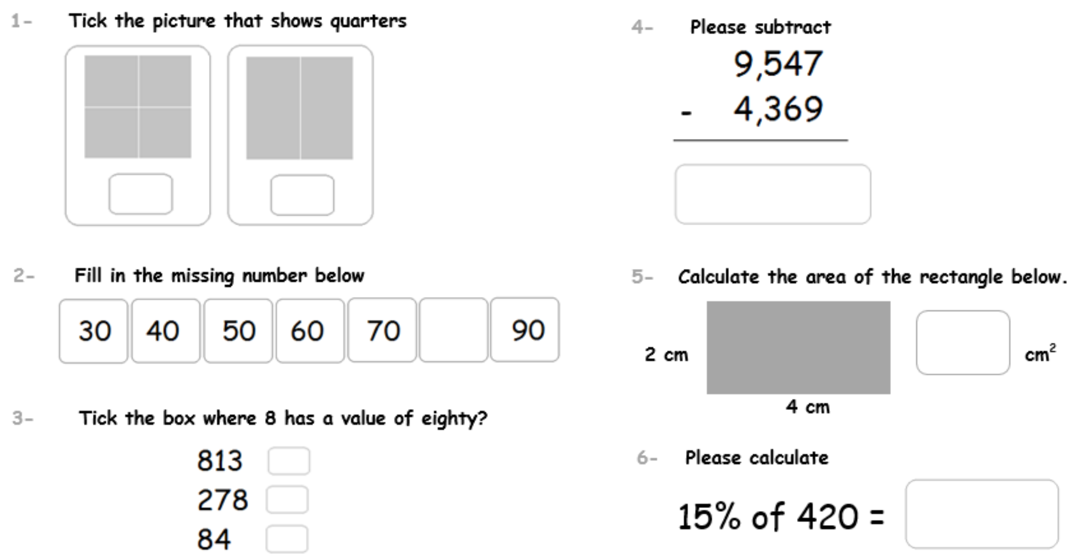

Figure 1. Example questions from each year of the curriculum maths test (curriculum year shown in grey).

Numerical Cognition: Dot Numerosity.

Our numerosity task was presented on electronic tablets. Children were each given a touch screen Acer Aspire SW3-016 or Acer One 10 tablet, which ran on Intel® Atom TM x5-Z8300 Processors, with Windows 10 and had 10.1" LED backlight touchscreens (1280 x 800 pixels).

As in Rinaldi, Smees, Alvarez et al. (2019), our task was the Panamath dot numerosity task (Halberda et al., 2008) available from http://panamath.org/, which we presented with a task-time of 2 minutes, and default settings which generate an adjusted level of difficulty based on each child's age (entered in whole years). This test briefly presents a cluster of white dots adjacent to a cluster of black dots (1382 – 1951ms dependent on age; see Figure 2 for screen-shot). Children were required to press one of two buttons (marked with a white or black sticker) to indicate whether there had been more white dots or black dots. Children were told they would play a short game in which they would not have time to count the dots, but should make their best guess as quickly as possible.

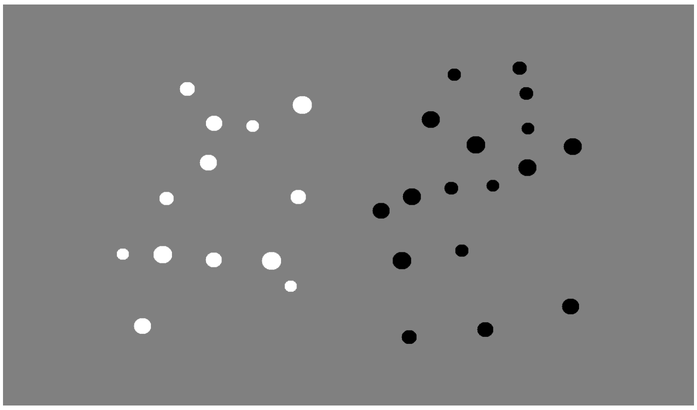

Figure 2. A screenshot of the Panamath dot numerosity test.

Results

We examined differences in numeracy skills, and first compare *letter-only synaesthetes* to controls (i.e., we compare *letter-only synaesthetes*, *high-performing controls, and their average-performing controls*), then repeat the process for *number synaesthetes*. We include age as a covariate in our models given that synaesthetes and *high-performing controls* were not age-matched to each other, and there is a known limitation in this regard for 6-year old synaesthetes[3]. Where appropriate we present mixed effects models, which are widely used with

[3] The diagnostic used in this study to identify synaesthetes has a known limitation for 6-year olds. Six year old synaesthetes have only very nascent synaesthesia (J. Simner et al., 2009) and the diagnostic can detect only those synaesthetes with most synaesthetic colours (typically the older of the 6 year olds). This weights 6 year olds away from being diagnosed as synaesthetes, and towards being diagnosed as high-performing non-synaesthetes (see Simner, Alvarez, Rinaldi, et al., 2019; Simner, Rinaldi, Alvarez, et al., 2019). No age effects are found at other ages, where the test performs better. Given this age effect in 6 year olds, we included age in our model as a co-

nested data (see Field, Miles, & Field, 2012) to capture random effects caused by different classes within different schools. We ran our Linear Mixed Effects models in R version 3.5.0 (R Core Team, 2016) using *lme4* (Bates, Maechler, Bolker, & Walker, 2015) and using *lmerTest* to obtain *p*-values (Kuznetsova, Brockhoff, & Christensen, 2017). Unless otherwise stated, we set our largest cohort as the reference group (i.e. *average-performing controls*, but see *Supplementary Information* (SI) at the end of the chapter for parallel models switching reference group to *high-performing controls*).[4]

Do synaesthetes show differences in numerosity?

Following Rinaldi, Smees, Alvarez et al. (2019), we analysed percent correct responses on the numerosity task. Scores notably lower than chance (<45%) were removed because this suggested confusion with key-bindings. We therefore removed 2 *high-performing controls* and 1 *average-performing controls* in our letter-only analysis (leaving 14 *synaesthetes*, 78 *high-performing controls* and 171 *average-performing controls*). In our analysis for *number synaesthetes* we removed 1 *high-performing controls* and 3 *average-performing controls* (leaving 20 *synaesthetes*, 160 *high-performing controls* and 369 *average-performing controls*)[5].Our percent correct variable was skewed with most children performing well on our task. We consequently used bootstrapped models. In an initial test we found no random effects of class or school (i.e., Linear Mixed Effects analysis not required), so we report bootstrapped linear regression models with a covariate of age (i.e., age at test, in years and decimals).

<u>Letter-only Synaesthetes</u>

We first looked at whether there were any significant differences between *letter-only synaesthetes* and controls. We found a significant age effect, but no significant difference between *letter-only synaesthetes* and our *average-performing controls* in their number of correct responses, and no significant differences between *high-performing* and *average-*

variate. Finally, we point out that this age-influence in our diagnostic makes our comparisons here more conservative (i.e., some 6 year old synaesthetes are pushed into the high-performing group, making group-wise differences harder, not easier, to detect).

[4] We note for transparency here that no part of our procedures or analyses were preregistered and due to ethical concerns relating to anonymity we are unable to make our data publically accessible, but our analysis code for all subsequent analyses are provided in Supplementary Information.

[5] We also identified statistical outliers with standardized residuals scores of lower than -3. We found that these outliers did not affect our pattern of results (i.e., same pattern whether these outliers were included or excluded). We therefore retained these children because they represented valid data-points (i.e., they were children who had carried out the test as instructed).

performing controls (Table 2). We switched our reference to *high-performing controls* and found the same; no differences between *letter-only synaesthetes* and *high-performing controls* (Table 1 in SI).

To explore our null result, we produced a Bayes Factor to determine whether we have enough evidence to accept the null hypothesis (Dienes, 2014). We used an uninformative prior using the *BayesFactor* package in R (Morey, Rouder, & Jamil, 2015). Bayes Factors lie on a continuum, where scores of less than 0.33 provide moderate evidence for the null hypothesis and scores above 3 provide moderate evidence for the experimental hypothesis, values of 1 being inconclusive, and values between 1 and 0.33/3 being anecdotal evidence only (Dienes, 2014; Raftery, 1995). Here we found a JZS Bayes Factor of 0.98 suggesting almost inconclusive evidence for the null hypothesis[6].

Table 2

Group status *(letter-only-synaesthetes, high-performing controls)* as a predictor of numerosity with *average-performing controls* as reference and based on 1000 bootstrapped samples. Chronological age is age in decimals.

	Estimate(B)	SE (B)	*p*	*95% CI*	
Step One					
Constant	78.94	3.90	.001	71.29	86.65
Age	1.05	0.44	.020	0.18	1.94
Step Two					
Constant	79.19	3.89	.001	71.55	86.79
Age	1.05	0.44	.017	0.20	1.95
Letter-only-synaesthetes (vs. average-performing controls)	0.67	2.34	.829	-4.28	5.03
High-performing Controls (vs. average-performing controls)	-1.00	1.40	.482	-3.85	1.65

Note: $R^2 = .018$ for step 1; $R^2 = .021$ for step 2

<u>*Number Synaesthetes*</u>

We repeated our analysis with *number synaesthetes*. Here, we found a different pattern of reults: *number synaesthetes* significantly out-performed *average-performing controls* (*p* = .003; see Table 3), and *high-performing controls* (*p* = .036; see Table 2 SI) with *number*

[6] We point out that Bayes factors should be interpreted in a qualitative way with benchmarks only as a guide, and we return to this issue in our Discussion.

synaesthetes on average scoring 4.2% higher in percent correct numerosity scores than *average-performing controls* and 3.1% higher than *high-performing controls*; this data is shown in Figure 3.

Table 3
Group status *(number-synaesthetes, high-performing controls)* as a predictor of numerosity with *average-performing controls* as reference and based on 1000 bootstrapped samples. Chronological age is age in decimals.

	Estimate(B)	SE (B)	*p*	*95% CI*	
Step One					
Constant	75.21	3.32	.001	68.19	81.78
Age	1.48	0.37	.001	0.75	2.24
Step Two					
Constant	75.04	3.36	.001	68.36	81.54
Age	1.43	0.37	.001	0.71	2.17
Number-synaesthetes (vs average-performing controls)	3.49	1.07	.003	1.33	5.61
High-performing Controls (vs average-performing controls)	1.24	0.94	.189	-0.59	3.08

Note: $R^2 = .028$ for step 1; $R^2 = .035$ for step 2

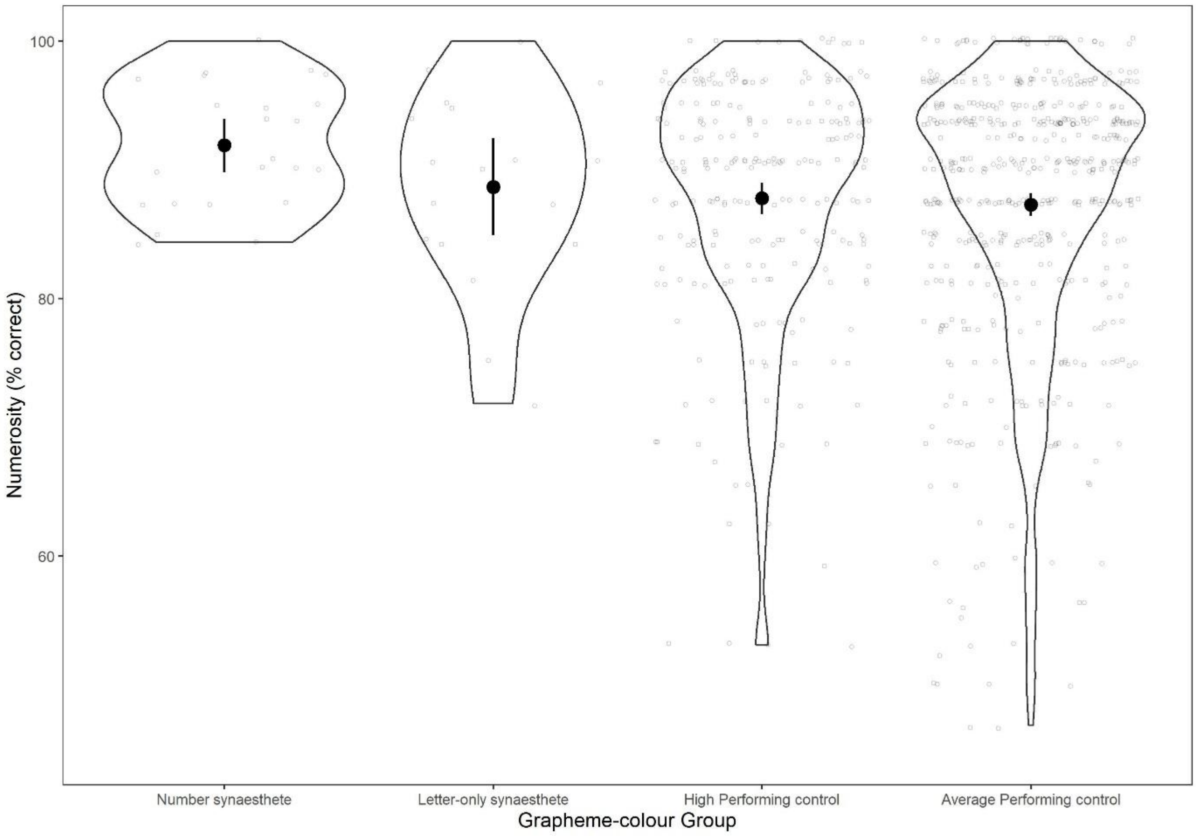

Figure 3. Violin plots illustrating the difference between grapheme-colour synaesthesia subtypes in correct numerosity responses. Error bars show 95% confidence intervals. For the purposes of illustration, all *high-performing controls* (high-performing for letters-only or high-performing for numbers) have been combined and all *average-performing controls* (matched to *number synaesthetes*, *letter-only synaesthetes*, and *high-performing synaesthetes*) have been combined.

Do Synaesthetes show differences in Curriculum Mathematics?

Only Years 3 to 5 took our maths test, so we examine differences between 10 *letter-only synaesthetes*, 51 *high-performing controls,* and 107 *average-performing controls*. In our *number synaesthete* groups we examine differences between 17 *number synaesthetes*, 121 *high-performing controls,* and 269 *average-performing controls*. Since different year groups saw different versions of the maths test (i.e. Year 3 started with Year 1 questions whereas Year 4 started with Year 2 questions) we first converted raw maths scores into z-scores standardized within year group. As with numerosity, we include age as a covariate, treating this as age-centred within year groups (since our test was based on school year rather than chronological age). Finally, we tested, and found, random effects of class and school, so report a linear mixed effects (LME) model including random intercepts for class and school (see Table 3).

<u>*Letter-only Synaesthetes*</u>

Taking *average-performing controls* as the reference group, we found no difference between *letter-only synaesthetes* and *average-performing controls* in maths score (p = .610) but we did find that *high-performing controls* were higher than *average-performing controls* (p = .041; See Table 4). We found a similar pattern when switching the reference group to *high-performing controls*; there was no difference between *letter-only synaesthetes* and *high-performing controls* (See Table 3 in SI). We again produced a Bayes Factor to confirm our null result of letter-only synaesthesia status. However, we found a JZS Bayes Factor of 0.44, suggesting anecdotal evidence for the null hypothesis.

Table 4

Group status *(letter-only synaesthetes, high-performing controls)* as a predictor of maths controlling for random effects of school and class with *average-performing controls* as reference. Chronological age is age within year group.

Fixed Effects	Estimate(B)	SE (B)	*t*	*p(t)*
Intercept	-0.10	0.10	-1.06	.294
High-performing control (vs average-performing control)	0.32	0.16	2.06	.041

Letter-only synaesthetes (vs average-performing control)	-0.16	0.31	-0.51	.610
Age	0.34	0.23	1.46	0.15
Random Effects	Variance	SD	X^2	$p(X^2)$
Class	0.06	0.24	1.00	<.001***
Residual	0.82	0.91	-	-

Number Synaesthetes

Again taking *average-performing controls* as the reference, we found no difference between *synaesthetes* and *average-performing controls* in maths scores (p = .607), and no difference between *high-performing controls* and *average-performing controls* (p = .158; See Table 5), and we found a significant age effect. When we switched the reference to *high-performing controls* we found a similar pattern: no difference between *synaesthetes* and *high-performing controls* (See Table 4 in SI). This data is shown in Figure 4. We again produced a Bayes Factor to confirm our null result in *number synaesthetes*, again using the *BayesFactor* package in R. We found a JZS Bayes Factor of 0.11 suggesting moderate evidence to accept the null hypothesis.

Table 5
Group status *(number synaesthetes, high-performing controls)* as a predictor of maths controlling for random effects of school and class with *average-performing controls* as reference. Chronological age is age within year group.

Fixed Effects	Estimate(B)	SE (B)	*t*	*p(t)*
Intercept	-0.03	0.09	-0.32	.751
High-performing control (vs average-performing control)	0.14	0.10	1.41	.158
Number synaesthetes (vs average-performing control)	0.12	0.23	0.52	.607
Age	0.48	0.17	2.90	.004**
Random Effects	Variance	SD	X^2	$p(X^2)$
Class	0.16	0.39	27.75	<.001***
School	0.05	0.22	10.63	.001**
Residual	0.78	0.88	-	-

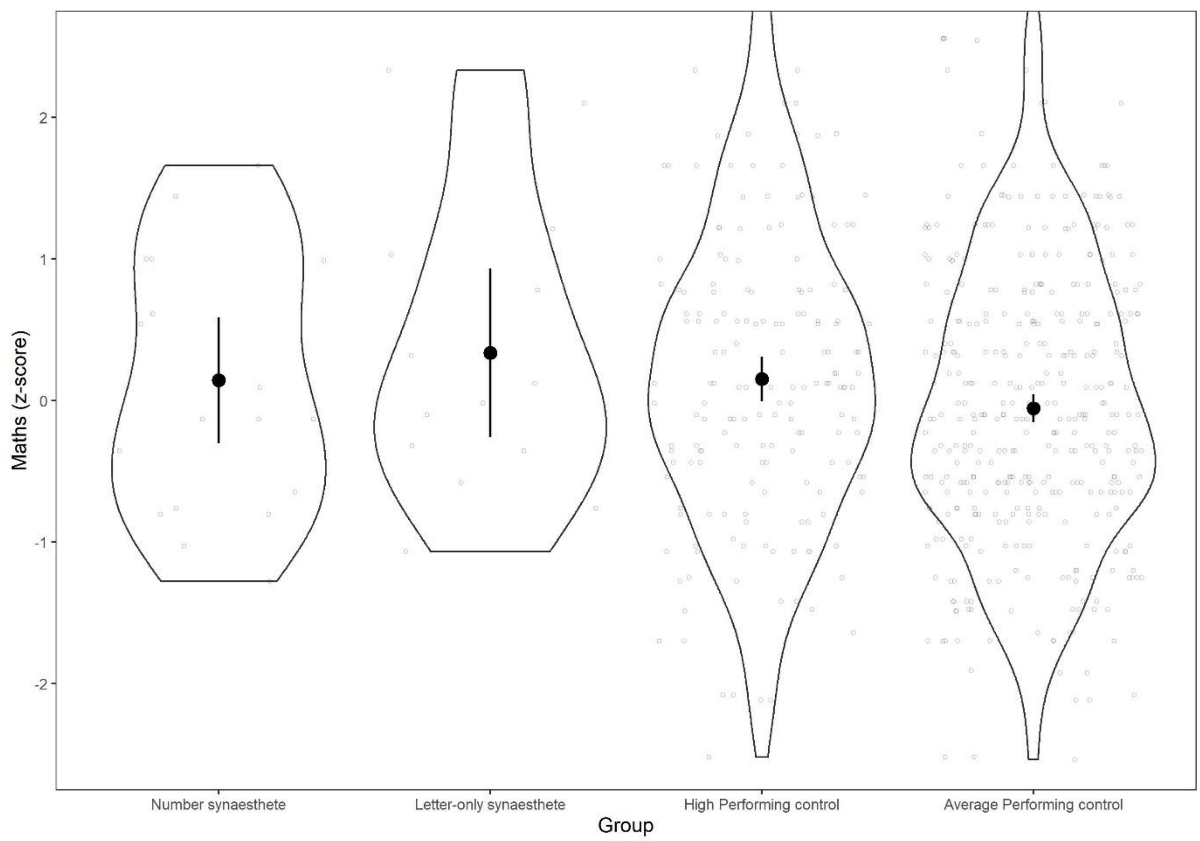

Figure 4. Violin plots illustrating the difference between grapheme-colour synaesthesia subtypes in mathematics. Error bars show 95% confidence intervals. For the purposes of illustration, all *high-performing controls* (high-performing for letters-only or high-performing for numbers) have been combined and all *average-performing controls* (matched to *number synaesthetes*, *letter-only synaesthetes*, and *high-performing synaesthetes*) have been combined.

Discussion

Here we examined the numerical cognition of children 6-10 years with grapheme-colour synaesthesia (i.e., lifelong associations of coloured letters or numbers). We compared synaesthetes with and without number associations (i.e. *number synaesthetes* and *letter-only synaesthetes*) to *high-performing controls* (i.e., children who can recall similar associations very well in the short-term, but are not synaesthetes) and *average-performing controls* (i.e., children with average recall in this domain). We found that *number synaesthetes* performed significantly better than both types of controls in a numerosity task (i.e., estimating which of two dot-clusters was more numerous, with only brief exposure). However, we found no differences between *letter-only synaesthetes* and controls in numerosity, and we found no difference between either type of synaesthete and controls in mathematics.

Importantly, we highlight here that the numerosity advantage was found only in synaesthetes with coloured numbers, suggesting support for a dual-coding account (Paivio, 1969). In this type of model, colour-coding numbers (automatically, on a daily-basis, across the child's lifespan) could provide more robust number representations over time, and therefore strengthen numerical cognition in tests such as dot-numerosity (see below). It is important to note that this finding was limited to *synaesthetes* (with their lifelong colour associations) but was not found for *high-performing controls* (who can easily generate and remember similar associations, but only in the short-term). This suggests that improvements in numerosity come from colour associations that are robust and long-term.

A similar finding has emerged from a group of children who internalised long-term colours for numbers, but were not synaesthetes (Rinaldi, Smees, Alvarez, et al., 2019). As noted in our Introduction, these children learned coloured numbers from the educational tool *Numicon*, and showed advantages in the same test of numerosity over their peers who had not memorised colours (even though all children had been exposed to *Numicon*). Across both studies, we might therefore infer that dual-coding of numbers improves numerosity – whether synaesthetic or not. But how does this advantage in numerosity come about? One answer may lie in how colours encode into the mental number system. Rinaldi and colleagues concluded that the numerosity advantages they found (and indeed those here) require colours to be associated to magnitude, and not simply to Arabic numerals. They drew this conclusion by tracing their numerosity finding to number tools that colour-code magnitude in particular – such as *Numicon* (which pairs colours to plastic shapes with holes denoting magnitude; a comparison tool linking colours to the shapes of Arabic numerals did not show a similar effect). Importantly, colours target magnitude in synaesthesia, too. Berteletti, Hubbard and Zorzi (2010; also Gertner, Arend, & Henik, 2013; Kadosh et al., 2005) show that synaesthetes automatically activate colours not only when viewing numerals, but also when viewing dot clusters, suggesting that synaesthetic colours attach to magnitudes and not just to numerals[7]. In combination with Rinaldi, Smees, Alvarez et al. (2019), we therefore have evidence across two different groups (*synaesthetes* and *non-synaesthetes*) that internalising colours for numbers can associate with

[7] We do not suggest synaesthetes convert dot-patterns into exact numbers/ colours during the dot-numerosity task. Instead, we suggest that dual coding strengthens the ANS from a lifetime of pairing colours with numbers (numerals and magnitudes) and that this provides robust representations of magnitude – which can then be called upon during this task.

superior scores in numerosity – especially if those colours are encoded at the level of magnitude.

Our child synaesthetes show improved numerosity skills, but this did not translate into improved mathematics. Numerosity has a well-documented relationship with maths (Halberda et al., 2008; Wong et al., 2016) but synaesthetes benefiting at one level did not benefit at the other. This was true not only in our own data, but also in Rinaldi et al. (2019). This suggests that whatever colour-benefits are enjoyed by the Approximate Number System in numerosity, do not propagate through to processes governing mathematics. The reasons for this are unclear. It may be that improvements in numerosity were simply not strong enough resonate through to mathematics. Alternatively, it may simply be that our in-house mathematics test was not sensitive enough to detect them – a possible limitation of our study. It is important to note that our mathematics task involved additional non-numeric knowledge (how to read a graph, a pie-chart, a bus time-table, how to multiply fractions, compute angles via geometry etc.). Had our test been simply arithmetic, we may (possibly) have seen advantages, but even here, maths involves the application of rules that are not compatible with synaesthesia (e.g., 3 x 4 is 12, but purple x blue is not green). Synaesthetes sometimes describe these difficulties in anecdotal report, and it may be these unhelpful "conflicts" with synaesthetic colours that prevent magnitude benefits from propagating back into curriculum maths tests.

We point out finally that our results speak to methodological debates surrounding the dot numerosity task. Two key concerns have been that the task may tap inhibitory control (Clayton & Gilmore, 2015) and/or visual processing (Gebuis, Gevers, & Cohen Kadosh, 2014) rather than numerical cognition per se. Inhibitory control is the ability to suppress salient but task-irrelevant information (Merkley, Thompson, & Scerif, 2016), which is important in the dot task since dot-size is manipulated to compensate for surface area (which would otherwise change with fewer dots) but must be ignored (Clayton & Gilmore, 2015). Importantly however, our data argue against a mere visual/control explanation. If dot comparison did not tap numerical processing, there would be no reason to expect number synaesthetes to show advantages while letter-only synaesthetes did not. Instead our results provide innovative evidence that the dot task does indeed tap into numerical processing, at least to some extent. Our data therefore aligns with recent studies questioning inhibitory control in these tasks (Malone et al., 2019). It is important, however, to be cautious given that our Bayes Factors gave virtually "inconclusive" evidence for the null hypothesis in the case of letter-only synaesthetes. Nonetheless, Bayes factors should be interpreted in a qualitative way, and unlike p-values, they allow us to state that in the case of letter-only synaesthetes, the data support the null hypothesis more than for number synaesthetes (even though the former did not meet the <0.33 threshold; see (Wagenmakers et al., 2018).

In summary, we have shown that children with grapheme-colour synaesthesia have superior numerosity scores, tied to coloured numbers in particular. The nature of regression statistics do not allow us to infer the direction of causality but we have tacitly assumed that synaesthetic colours for numbers improve sense of magnitude. However, we acknowledge that the reverse might also be true: children with better numerosity may be better able to integrate colours into their magnitude schema and thereby develop synaesthesia. Our evidence supports a dual-coding account and joins a literature where synaesthetes benefit via a range of mechanisms (both dual-coding and otherwise). Hence although grapheme-colour synaesthetes have superior numerosity if their numbers are coloured (but not letters), they also show broader advantages for stimuli such as faces or scenes (Gross, Neargarder, Caldwell-Harris, & Cronin-Golomb, 2011; Pritchard, Rothen, Coolbear, & Ward, 2013; Rothen & Meier, 2010a; Ward, Hovard, Jones, & Rothen, 2013). Broad advantages do not negate dual-coding because more than one mechanism may work in parallel. These parallel mechanisms might perhaps be differences in "cognitive processing style" (Meier & Rothen, 2013), or "enhanced perceptual organisation" (Hänggi et al., 2011; Ramachandran & Azoulai, 2006; Simner & Bain, 2018) although future studies must better elaborate on the nature of these processes. In conclusion, our data join findings elsewhere in the literature, showing the range of cognitive benefits enjoyed by synaesthetes – which we can now extend to benefits in numerosity tasks.

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