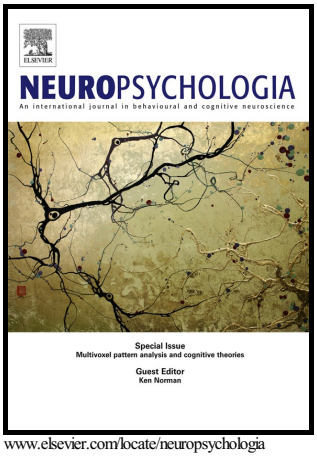
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Does Synaesthesia Age? Changes in the quality and consistency of synaesthetic associations

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Abstract

Developmental *grapheme-colour synaesthesia* is a rare condition in which colours become automatically paired with letters or digits in the minds of certain individuals during childhood, and remain paired into adulthood. Although synaesthesia is well understood in younger adults almost nothing is known about synaesthesia in aging. We present the first evidence that aging desaturates synaesthetic colours in the minds of older synaesthetes, and we show for the first time that aging affects the key diagnostic measure of synaesthesia (consistency of colours over time). We screened ~4000 members of the general population to identify grapheme-colour synaesthetes, targeting both younger and older adults. We found proportionally fewer older than younger synaesthetes, not only because fewer older people self-reported the condition, but because fewer also passed the objective diagnostic test. We examined the roots of this apparent decline in grapheme-colour synaesthesia, finding that the internal mental colours of synaesthetes become less saturated in older subjects, and importantly, that low-saturated colours are linked with test-failure. We discuss what these findings mean for a novel field of aging and synaesthesia research, in terms of the lifespan development of synaesthesia and how best to diagnose synaesthesia in later life.

Keywords: Grapheme-colour synaesthesia, synesthesia, ageing, chroma, consistency

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People with *grapheme-colour synaesthesia* experience automatic associations between graphemes (i.e., letters or digits) and colours. For example, synaesthete LB experiences the letter *m* as being a pale orange brown colour, and synaesthete KA experiences the letter *c* as dark grey (Ward, Simner, & Auyeung, 2005). The condition is associated with significant differences in the structure and function of synaesthetes' brains, and these differences are found (inter alia) in regions implicated in the perception of colour (Hubbard & Ramachandran, 2005; Rouw & Scholte, 2007). Although psychologists have come to understand a great deal about this condition in the last twenty years, one area that is particularly poorly understood is how grapheme-colour synaesthesia might develop across the lifespan. There have been only a small handful of studies looking at development in children (Green & Goswami, 2008; Simner & Bain, 2013; Simner, Harrold, Creed, Monro, & Foulkes, 2009) and virtually none looking at development in older age (but see Meier, Rothen, & Walter, 2014). Studies that have looked at synaesthesia in development might consider one feature of synaesthesia in particular – the consistency of synaesthesia over time (see below). In the current paper we will first briefly discuss why consistency is a central feature of synaesthesia research and then present the first empirical study showing that this feature changes in older synaesthetes. We also show age-related changes in other areas of synaesthetic experience, notably in the chroma of synaesthetes' mental colours, and we also show that chroma and consistency in synaesthesia are related. Our findings suggest a fundamental reconsideration not only of how permanent synaesthesia is as a mental trait, but also how the condition should be evaluated in younger and older people.

'Consistency' is arguably the most important characteristic of all types of synaesthesia because it is the definitional feature which is used most often in objective diagnostic tests of synaesthesia (Simner, 2012). The feature of consistency is, simply put, that synaesthetic associations such as the colours of letters, tend to stay the same for any given synaesthete.

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For example, if a synaesthete reports that the letter *a* is, say, synaesthetically red, it will typically continue to be red whenever the synaesthete is asked to state the colour of *a* (see Simner, 2012 for a review). This characteristic of consistency has been considered by many to be the key definitional criterion of synaesthesia (e.g. Cytowic, 1997) and it forms the basis of the most widely accepted diagnostic assessment for the condition (since Baron-Cohen, Wyke, & Binnie, 1987). In this diagnostic test (also known as the 'test of genuineness' or 'test of consistency') synaesthetes provide their synaesthetic associations (e.g., the colours for each letter of the alphabet) and are tested with the same stimuli more than once. The most widely used contemporary version of this test is the 'Synaesthesia Battery' (Eagleman, Kagan, Nelson, Sagaram, & Sarma, 2007) which measures consistency by presenting each grapheme three times in a random order within a single session. Synaesthetes are judged as those who are significantly more consistent in their colour choices (or other synaesthetic associations) compared to a group of controls. Controls are individuals who do not have synaesthesia but invent analogous associations and then try to recall these by memory alone. Only individuals who significantly outperform controls are considered 'genuine' synaesthetes.

The consistency measure used in tests such as the Synesthesia Battery is, in effect, a measure of the synaesthesia's stability at any given point in time. For typical synaesthetes, the synaesthesia is highly stable, meaning that the colour of each letter (or other trigger) remains consistent on repeated presentations. And because consistency is 'a fundamental characteristic of synaesthesia' within the synaesthesia research community (Simner, 2007, p. 696) the test of consistency has come to be considered the behavioural 'gold standard' for determining the genuineness of synaesthesia (Rich, Bradshaw, & Mattingley, 2005, p. 55). As such, well-conducted empirical studies will include synaesthetes in their testing cohort only after they have passed a consistency test, while those who fail this test are excluded.

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Consistency has therefore been verified in almost every synaesthesia paper in the contemporary literature to date (Baron-Cohen et al., 1987; Simon Baron-Cohen, Burt, Smith-Laittan, Harrison, & Bolton, 1996; Brang & Ramachandran, 2010; Palmeri, Blake, Marois, Flanery, & Whetsell, 2002; Rich et al., 2005; Simner, 2007; Ward, Jonas, Dienes, & Seth, 2010; Ward & Simner, 2003). In this article we evaluate this key feature of consistency and show with careful examination that it is susceptible to aging in grapheme-colour synaesthesia.

Adult synaesthetes tend to be highly consistent (e.g., up to 100%; Simner et al., 2006) but we believe consistency might decline in the latter parts of the lifespan, and this is for a number of reasons. First, synaesthesia has been linked to mental imagery (e.g. Havlik, Carmichael, & Simner, 2015; Spiller & Jansari, 2008; but see Simner, 2012) and imagery is known to decline in older people, in terms of both image-activation and image-maintenance (Dror & Kosslyn, 1994; Kemps & Newson, 2005). Other functions, too, show declines that may be relevant for synaesthetes: associative memory (Bastin et al., 2013) and chromatic discrimination (Kinnear & Sahraie, 2002) both decline, and both could theoretically be implicated in the synaesthetic pairing of graphemes with colours. Importantly, there is a large number of anecdotal reports from adults suggesting that while they had synaesthesia at a younger age, they no longer have synaesthesia now they are older (Simner & Bain, 2013; Simner et al., 2009). Finally two neurobiological features of synaesthesia are hyper-connectivity in white matter and increased grey matter volume, compared to non-synaesthetes (Rouw & Scholte, 2007; Weiss & Fink, 2009). Since both white and grey matter reduce in the elderly (e.g., Ziegler et al., 2012) this normal age-linked change may bring concurrent declines in synaesthesia.

The question of how synaesthesia develops and changes throughout the lifespan is hampered by a lack of randomly sampled populations to study. Synaesthesia is a rare condition,

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affecting small numbers in the population, making recruitment possible only by self-referral means (e.g., posting adverts) or by work-intensive screening of very large numbers of the general population in order to find the small numbers of synaesthetes among them. To date, only one study has explored the way in which synaesthesia develops in older individuals, and this study recruited a non-random population of self-referred synaesthetes. In this study, Meier et al. (2014) examined 439 grapheme-colour synaesthetes and found that older individuals had a smaller "bandwidth" to their synaesthesia (i.e., they had fewer graphemes with any synaesthetic colour at all) compared to younger synaesthetes. When bandwidth was accounted for however, their consistency was not inferior to the younger synaesthetes, although there were changes in the categories of colours found in younger versus older synaesthetes. Meier et al. reported that primary colours (such as red, green or blue) were relatively robust throughout adulthood and older age, whereas what they describe as more 'lurid' colours (e.g., Magenta, Violet; Meier et al., 2014, p. 5) became less prominent in the synaesthesia of older subjects. In contrast, other colours (e.g. brown, white and grey) were found to increase in synaesthesia with age.

With these findings, Meier et al., have taken an important first look at grapheme-colour synaesthesia in younger and older people but we argue that the fundamental properties of later-life synaesthesia are as yet unknown: namely whether consistency changes, how such changes might be linked to drifts in the quality of colours, and what implications this has for diagnosing older synaesthetes. Meier et al reported no change in consistency in older participants but their synaesthetes were given a palette of only 13 colours from which to select their synaesthetic colour (red, orange, yellow, light green, dark green, light blue, dark blue, pink, purple, brown, grey, black, white). This small palette is useful for the rapid testing of large numbers (e.g. Simner et al., 2006) but can provide relatively limited information about how colours change subtly over time. In the current study we present subjects with a

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palette of over 16 million colours, with fine-grained gradations in hue, saturation and luminance, in the expectation this might be more sensitive to changes occurring in aging. Secondly, Meier et al. recruited subjects by self-referral, although it is possible that this method may inadvertently recruit participants not reflective of 'typical synaesthetes'. Simner (2012) has suggested that the particular type of synaesthete who self-refers for study is likely to be in some way different from average synaesthetes simply because a decision to self-refer might rest on a number of factors, including one's strength of synaesthesia for example (i.e., only those with relatively strong synaesthesia might persuade themselves that they are worthy of study). This is especially important when considering aging because individuals with declining synaesthesia might be precisely those who decide not to self-refer -- creating an inherent confound in recruitment. To address this we took an alternative approach in testing a random sample of synaesthetes, recruited by screening a very large sample of the general population (N ≈ 4000) to identify approximately 100 randomly-sampled grapheme-colour synaesthetes among them. In our sampling we specifically targeted both younger and older adults, so that age-related differences could be examined.

In our study we assessed features of grapheme-colour synaesthesia across age groups and hypothesise that if synaesthesia declines in older age (e.g., in its consistency, or in the very presence of synaesthesia in older people) we may find proportionally fewer synaesthetes in older age groups, and/or synaesthesia that is less consistent over time. We point out that these measures are linked in our study since our 'gold standard' diagnosis for synaesthesia is one that measures consistency. We will therefore evaluate our results both in terms of how consistency changes with age, and, methodologically speaking, how this alters the number of people diagnosed as grapheme-colour synaesthetes in conventional genuineness testing. To anticipate our findings, we will show that synaesthetes become less consistent in their colours

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in aging and that this is linked to a separate effect of synaesthetic colours becoming less saturated (i.e., having lower chroma) in aging.

Methods

Participants

We tested 3893 participants (55% female; mean age = 28.34, range = 16.05 - 92.68, SD = 14.26). We also tested, but subsequently removed, an additional 48 subjects who provided an obviously incorrect date of birth (e.g., 2013). Participants were recruited by approximately 470 student research assistants as part of their undergraduate degree requirements. Each were given uniform instructions to recruit 8 adult participants (4 females) and to target both young and older age-groups where possible (see Simner & Carmichael, 2015 for more description of these methods). We took a number of steps to ensure as random a sample as possible including the fact that RAs were required to pre-select their sample, and then approach participants in a targeted way, rather than sending out an advert for self-referrals. They were instructed not to deliberately seek out, nor to avoid, people they knew to be synesthetes and not to inform participants in advance that the study investigated synaesthesia. Full details of this recruitment method are given in Simner and Carmichael (2015).

We screened our participants for grapheme-colour synaesthesia using the methods described below. This screening categorised our subjects as 95 grapheme-colour synaesthetes (58% female; mean age = 21.70, range = 16.45 - 70.75, SD = 7.01) and 3647 non-synaesthetes (55% female; mean age = 28.66, range = 16.05-90.46, S.D. 14.4) [1]. A further 122 participants were categorised as "malingerers" (64% female; mean age 24.70, range 17.13-92.68, S.D.

[1] This objective test, which is the foundation for modern synaesthesia studies, presents an objective test to people who self-declare synaesthesia but not to those who do not. This is due to the asymmetry in confidence in the self-declaration question: those who say 'no' are almost always non-synaesthetes but those who say yes are a mixture of non-synaesthetes and synaesthetes (see Simner et al., 2006) which the objective tests can then discriminate between.

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11.76) in that they self-reported grapheme-colour synaesthesia but did not pass our objective test of genuineness[2], as described further below. A final 29 participants were removed because they encountered an equipment failure. Our studies were approved by the University of Edinburgh Psychology Research Ethics Committee and the study was conducted in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki. The task took approximately 10-25 minutes.

Materials and Procedure

Participants completed an online screening test for grapheme-colour synaesthesia, which they accessed via a web page address which was sent to them electronically. At the start of the test, participants entered demographic information including date of birth and sex, and then completed a short health questionnaire (the full results of which will be reported elsewhere, but which included one question that will become relevant below: "Have you ever been diagnosed with depression?"). Participants then advanced to the screening test for synaesthesia. We used the *Synesthesia Battery* online testing interface (Eagleman et al., 2007) which contains perhaps the most widely used test for grapheme-colour synaesthesia based on the 'gold standard' method of consistency (see above), and we cloned that site with permission from the authors (see Carmichael et al., 2015 for details of our cloning). This test has two components for the purposes of our study here. First, participants were asked whether they experience grapheme-colour synaesthesia with the question "*Do numbers or letters cause you to have a colour experience?*" This was accompanied by an example and an option to reply separately for numbers and/or digits. If participants indicated that they saw neither

[2] Note that we use the term 'malingerer' following convention and only for clarity but are in fact agnostic about the nature of these 122 individuals. We assume they are likely to be a mixture of genuine synaesthetes with low consistency (Simner, 2012) and non-synaesthetes falsely-claiming synaesthesia (Simner et al., 2006), and as such they represent a different make-up to confirmed synaesthetes and non-synaesthetes. Future consistency data from self-declared non-synaesthetes might be a useful comparison to the data of 'malingerers' to determine the exact makeup of the 'malingerer' group, although this is outside the scope of the present study.

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letters nor numbers in colour, they advanced to an exit page and were categorised as non-synaesthetes. Participants who responded 'yes' to (either or both) letters and digits progressed to an objective test for grapheme-colour synaesthesia, described below.

In the objective test, participants were shown the letters A-Z and/or digits 0–9 (according to their self-report in the earlier question). Each grapheme was shown individually on-screen, three times in a fully randomised order. On each trial, participants selected their synaesthetic colour from an on-screen palette of approximately 16 million colours. These three colour choices were then compared for each grapheme (e.g., three colours for the letter *a*) to establish how far away they lie in colour space. This distance is normalised and averaged across all graphemes to produce one score. A small score reflects consistent colours (i.e., that colours for the same grapheme were close in colour-space) and in particular, a score less than 1.43 indicates the level of consistency diagnostic of synaesthesia (Carmichael et al., 2015; Rothen, Seth, Witzel, & Ward, 2013). Using this protocol, participants can be categorised as either (a) *non-synaesthetes* (who respond 'no' when asked whether they have grapheme-colour synaesthesia) (b) *grapheme-colour synaesthetes* (who respond 'yes' and also pass the objective consistency test; *henceforth referred to as synaesthetes for conciseness*) or (c) *malingerers* (who respond 'yes' but fail the objective test). For full details on this synaesthesia diagnostic test (see Eagleman et al., 2007; Meier & Rothen, 2013).

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Results

In total, 3647 participants reported they did not have grapheme-colour synaesthesia (so were classified as *non-synaesthetes*). A further, 95 reported they did experience grapheme-colour synaesthesia and also passed the consistency test (and so were classified as *synaesthetes*). A further 122 reported having grapheme-colour synaesthesia but did not score the legitimate <1.43 required to pass the objective test, and for this reason they were classified as

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malingerers. (This 122 comprised 98 participants who scored 1.43 or higher; 23 subjects who failed to enter enough coloured graphemes to generate a valid average test score; and one whose low score was the result of entering all achromatic responses).

Our analyses below fall into three distinct parts. The first part considers how aging affects the diagnostic criterion of synaesthesia (i.e., consistency). We look across the three diagnostic groups (non-synaesthetes N = 3647, synaesthetes N = 95, and malingerers N = 122) and compare their ages. We also divide our sample into younger participants (N = 2977) and older participants (N = 887; see below) to directly compare the proportion of synaesthetes diagnosed within each age-group and the overall consistency of younger and older individuals who self-reported as having synaesthetic experiences. In the second part of our analyses we look at the luminance and chroma of colours for all participants who gave chromatic colours irrespective of their diagnostic status (N = 193; see below); we ask whether colours change in quality across age. In the third part of our *Results* we look to see whether these effects of aging, colour-quality, and colour consistency are related.

Part 1: How does aging affect the diagnostic criterion of synaesthesia (consistency)?

Our test for grapheme-colour synaesthesia diagnosed three types of participant and Figure 1 shows the mean age for each group (synaesthete, malingerer, and non-synaesthete). We found that synaesthetes were the youngest at 21.70 years (SD = 7.01), followed by the malingerers (M = 24.70 years, SD = 11.76), then the non-synaesthetes, who were the oldest with a mean age of 28.66 years (SD = 14.26). This main effect of age had a small effect size but was highly statistically significant Welch's $F(2,163.83) = 46.48$, $p < .001$, *est.* w^3=0.03). In pairwise Games-Howell corrected comparisons, non-synaesthetes were older than both malingerers ($p < .01$) and synaesthetes ($p < .001$), and malingerers were older than synaesthetes ($p = .05$).

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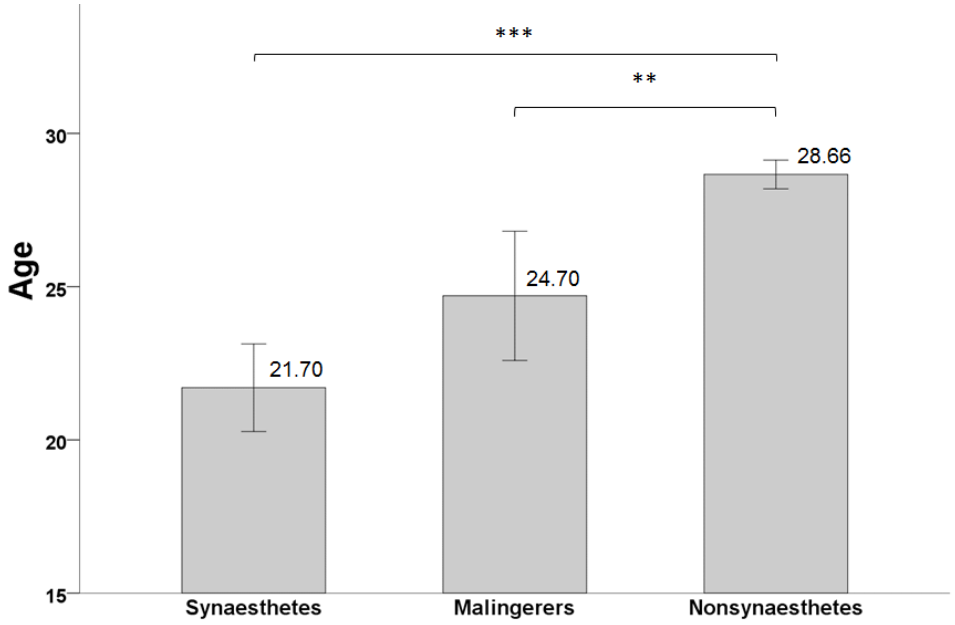


Figure 1: *Mean age in years of participants across three groups: synaesthetes (N = 95), malingerers (N =122) and non-synaesthetes (N = 3647). Error bars represent 95% CI. ** p = .001, *** p < .001.*

These initial results suggest prima facie that older people may be less synaesthetic and so we explored this further by splitting participants into two groups of younger versus older participants. This required careful consideration of where to place the age cut-off between "young" and "old" participants because although it is incontrovertible that cognitive and perceptual functions decline in aging there is uncertainty about the age at which that decline begins. Aging research was traditionally framed in terms of participants aged over 50, although there is now evidence that functions begin to decline during the 20s and 30s (Salthouse, 2009). Given this, we took a data-led approach and created our split around a cut-off of 35 years because age was bimodally distributed within our population around approximately this value (see Figure 2). It is highly plausible that age-related changes may indeed occur across these age bands, because a number of neurobiological variables that could influence synaesthesia show declines beginning as young as the 20s (e.g., declines in

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regional brain volume, Fotenos, Snyder, Girton, Morris, & Buckner, 2005; cortical thickness, Salat et al., 2004, and myelin integrity related to white-matter cohesion, Hsu et al., 2008).

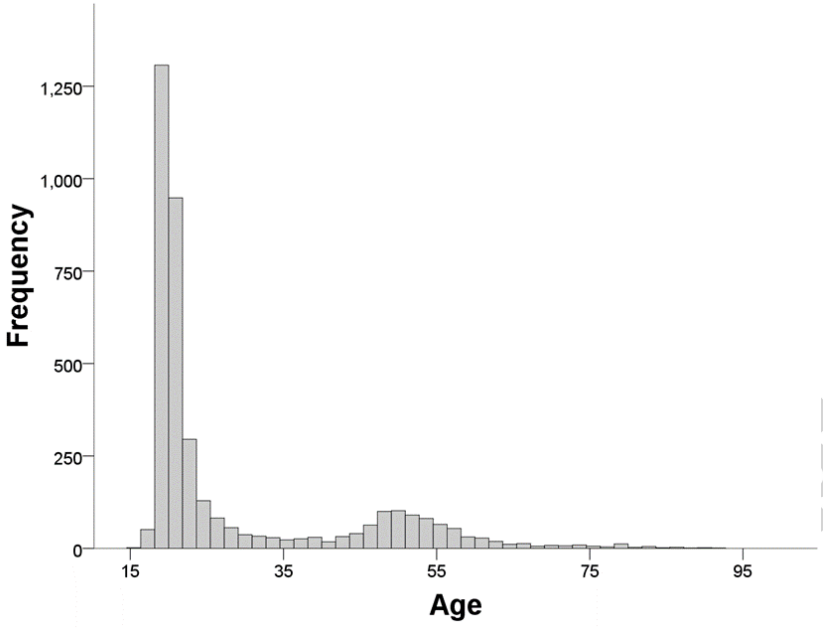


Figure 2: *Bimodal distribution of age (in years) within our total sample of participants, separated at around the age of ≃35 years (N = 3864).*

The younger age group (<35 years) contained 2977 participants and had a mean of 21.13 years (range = 16.05 - 34.95, SD = 2.89) while the older age group (≥ 35 years) contained 887 participants and had a mean age of 52.65 years (range = 35.05 - 92.68, SD = 9.68). After dividing subjects into these two age groups, we found just 3 synaesthetes among the nearly 900 individuals aged 35+ years. In clear contrast, there were 92 synaesthetes in the under-35 group, even though this latter group was just three times larger in total. In other words, 3.1% of all subjects under the age of 35 were diagnosed as synaesthetes compared to only 0.3% of subjects over 35 years. Indeed, the significant odds of participants under the age of 35 being identified as synaesthete were 9.4 times higher than respondents 35 years or older, $\chi^2(1) = 20.45$, $p < .001$ (*Yates corrected*), odds ratio = 9.40.

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We considered two possibilities for this significant age effect: that older people are less likely to self-report synaesthesia (i.e., fewer of them advance to the objective consistency test) and/or that older people who self-report synaesthesia are less likely to pass the objective consistency test. Hence we first asked whether older people were less likely to self-report synaesthesia by looking at the proportion of people in each age group who responded 'yes' to our self-report question ("*Do numbers or letters cause you to have a colour experience?*"). In total 5.7% of our sample (N = 3864) self-reported grapheme-colour synaesthesia, and within this, the proportion was higher among younger people (6.7% of those < 35 years, *N = 200*) compared to older people (1.9% of those ≥35 years; *N = 17*; see Figure 3). The odds of participants under the age of 35 identifying themselves as synaesthetes were 3.7 times higher than respondents who were 35 years or older and this was highly significant, $\chi^2(1) = 29.73$, $p < 0.001$, odds ratio = 3.69.

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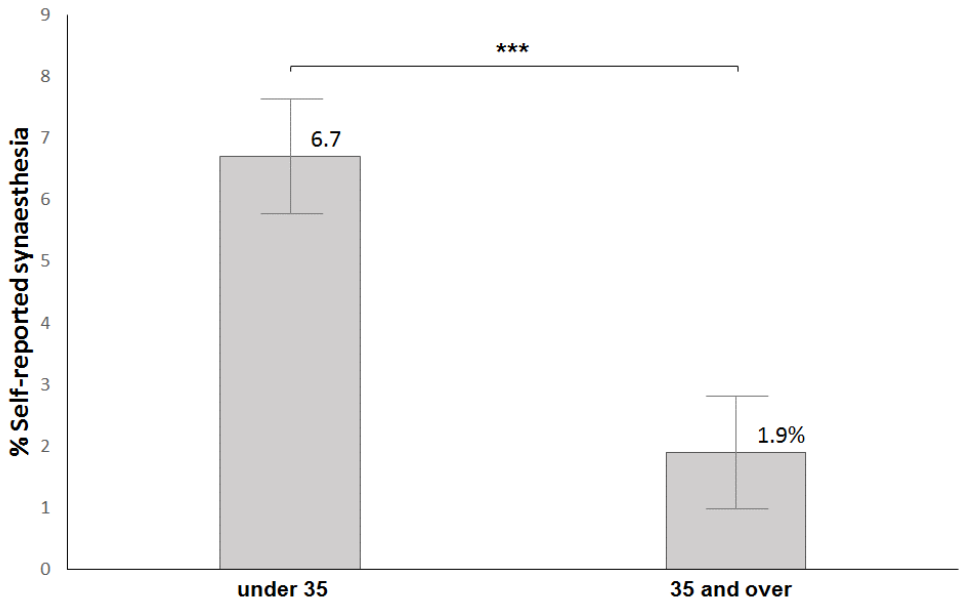


Figure 3: *The percentage of younger ($N_{Total\ <35}$ = 2977) and older ($N_{Total\geq\ 35}$ = 887) people who self-reported having synaesthesia ($N_{<35}$ = 200, $N_{\geq\ 35}$ = 17, respectively). Error bars represent 95% CI. *** p < .0001*

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Next we also found an age effect in terms of passing the objective test, i.e., when considering only those who self-reported synaesthesia (N = 217). We asked whether younger people were more likely to pass the test of consistency, and this was indeed the case. Those under the age of 35 were 4.0 times more likely to be identified by the *Synesthesia Battery* as synaesthetes (test pass, <1.43 score) than older respondents, $\chi^2(1) = 4.03$, $p = .045$, (*Yates' corrected*), odds ratio = 3.98, and this can be seen in Figure 4.

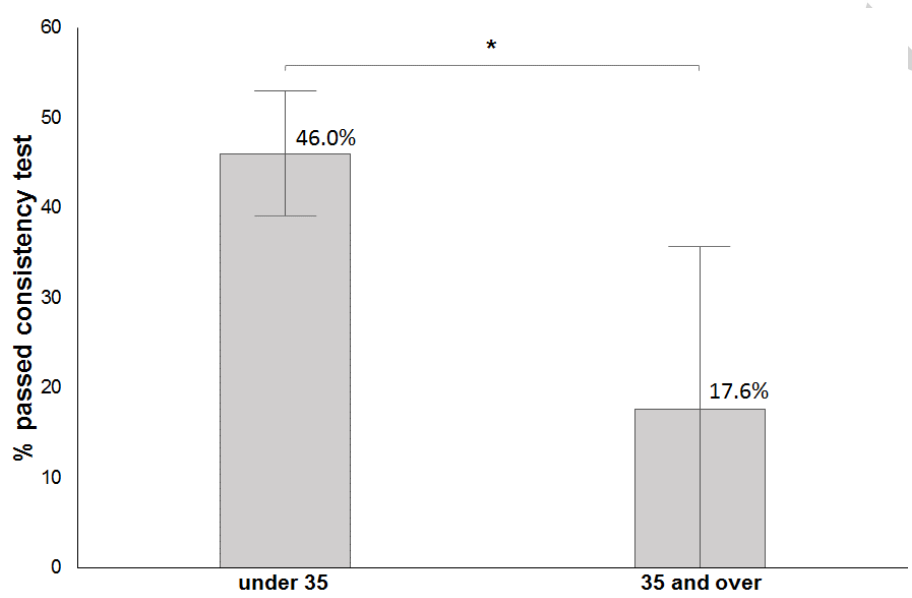


Figure 4: *The percentage of self-reported synaesthetes within each age group ($N_{Self\text{-}Report\ <35} = 200$, $N_{Self\text{-}Report\geq 35} = 17$), passing the objective consistency test ($N_{<35\ Passed} = 92$ vs $N_{\geq 35\ Passed} = 3$). Error bars represent 95% CI. * p < .05.*

Since consistency scores are essentially a normalised average distance in colour space, they are incremental values across a range (from 0 to 6) and so can be analysed across a continuum irrespective of whether the individual passed the 1.43 threshold for synaesthesia. We therefore ended our examination of the relationship between age and consistency scores by ignoring synaesthetic status, and considering instead all 193 respondents who had a valid

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test score (i.e., excluding achromatic and single grapheme respondents; see above). Since there were uneven numbers in younger and older groups (N_{Total} = 193 of which $N_{<35}$ = 176, $N_{\geq 35}$ = 17) and the distribution of the younger group data was non-normal, we used a non-parametric independent-sample test to analyse the data. This analysis showed that scores were higher (i.e., there was less consistency) in older participants (*Mdn* = 43.71; N = 17) compared to younger participants (*Mdn* = *61.92*; N = 176) and this difference was significant, U = 803.00, p = .002. In line with Meier et al., (2014), we also found a negative correlation between age and number of coloured graphemes for people self-reporting grapheme-colour synaesthesia irrespective of their objective score; *rho* (191) = -.144, p = .046, *two tailed*).

In summary, our analyses shows that age influences consistency scores not only in determining the final diagnostic status of participants (synaesthetes vs. malingerers vs. non-synaesthetes) but also in rates of self-diagnosis, rates of test-confirmation, and also when considering test scores and number of coloured graphemes on a continuum, irrespective of diagnostic status.

Part 2a: How does aging affect the quality (chroma and luminance) of colours?

We have found above that the colours of older participants are less consistent in a synaesthesia test. In this section we consider what might be at the root of this change in consistency with aging. The colour responses of synaesthetes were captured in a colour palette that allows them to be broken down into the linear colour dimensions of chroma and luminance. In this section we inspect these values within CIEL*C*h space along both linear dimensions to see whether chroma and/or luminance plays a role in levels of consistency within the testing battery. We follow this line of investigation because if we were to find that

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older people had less chromatic colours, say, this could have implications for their consistency (in a way described fully at the end of this section)

Hence we first ask whether the chroma/ luminance of colours is related to consistency at all, irrespective of age. We considered all 193 individuals with a valid test score and compared the mean chroma selected by those who had passed the test (i.e. scored <1.43; N = 95) versus those who had failed the test (N = 98; see Figure 5). This analysis showed that those failing the objective test (i.e., *malingerers*) have significantly lower chroma than those who passed (i.e., *synaesthetes*) $t(191) = 4.77$, $p < .001$, *Cohen's d = 0.69*). In an analysis considering luminance (see Figure 6) we found a similar effect: those failing the test had significantly lower luminance than those who passed $t(191) = 3.55$, $p < .001$, *Cohen's d=0.41*; see Figure 6).

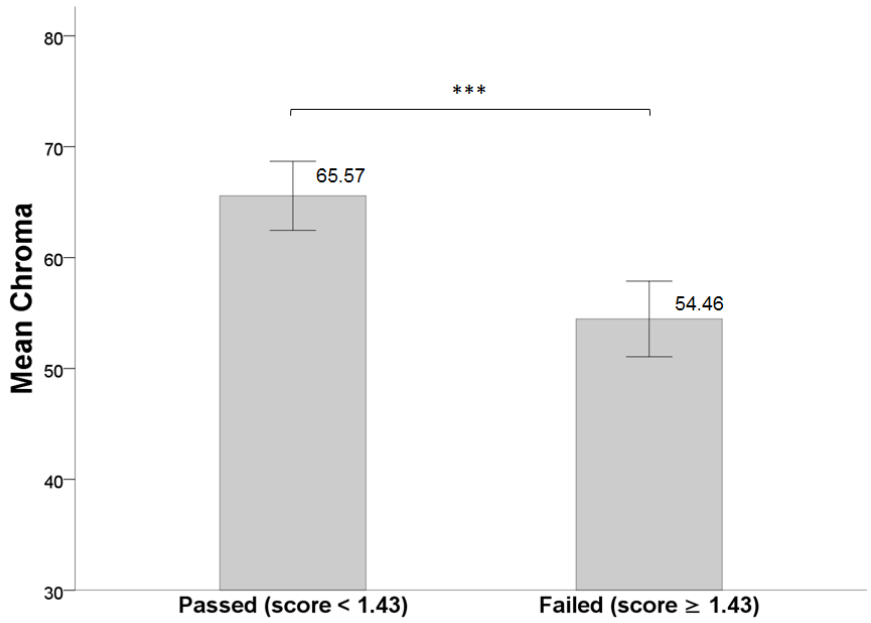


Figure 5: *Figure shows that those failing the objective consistency test (scoring ≥1.43; i.e., malingerers) have lower chroma colours than those who pass (synaesthetes). ***p < .001. Error bars represent 95% CI.*

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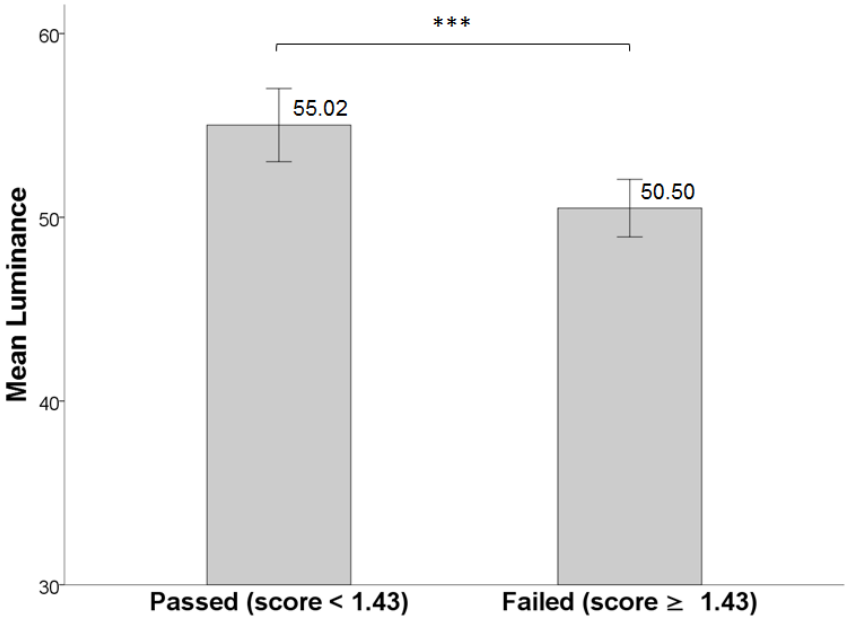


Figure 6: *Figure shows that those failing the objective consistency test (scoring ≥1.43; i.e., malingerers) have lower luminance colours than those who pass (synaesthetes). ***p < .001. Error bars represent 95% CI.*

In summary thus far, our data show a relationship between the chroma and luminance of colours on the one hand, and the ability to pass the consistency test on the other hand: low chroma/luminance give poor consistency scores. So we next explored whether either influence might be responsible for the aging effects found in the previous section. For example, given that both low-saturated colours, and older participants, tend to fail the test, we asked whether older participants tend to have low-saturated synaesthetic colours (and likewise for luminance).

We therefore compared the mean chroma of colours for 193 participants across our two different age groups (< 35 years vs. ≥ 35 years). Do older participants have lower chroma colours? We used independent sample t-tests because sample sizes were different in each group, but were normally distributed. We found that older participants did indeed have colours with lower chroma than younger participants (older M = 44.26, SD = 16.72, N = 17; younger M = 61.44, SD = 16.37, N = 176), and this was highly significant $t(191) = 4.13$, $p <$

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.001, *Cohen's d = 0.73*. In an analysis considering luminance we found no similar effects. In other words, age did not influence the luminance of colours, when considering all 193 participants who took the objective test $t(191) = 1.2$, $p > .05$.

Thus far we have found that older people were less likely to pass the behavioural 'gold standard' test for grapheme-colour synaesthesia. We then found that scores on this test are influenced by how bright and chromatic synaesthetes' colours are (e.g., less chromatic/luminant colours are less likely to pass). Finally we found that older people have less chromatic colours. The natural question is therefore to ask whether older people are failing the test only because their colours are less chromatic, or whether some other residual influence remains beyond that. Before proceeding however we first rule out an alternative interpretation of our data: that older people appear less consistent only due to possible confounds in the widely used synaesthesia diagnostic tool.

Part 2b: Do older people appear less consistent due to tool confounds?

We describe below two natural confounds within our choice of diagnostic tool for grapheme-colour synaesthesia (*The Synesthesia Battery*; Eagleman et al., 2007). This is arguably the most widely-used tool in this area of research but could artificially alter test scores for people with low chroma colours, for two reasons. Hence we first rule these out as a possible contributing factors as to why older people (with low chroma colours) appear less synaesthetic.

Our choice of diagnostic tool (Eagleman et al., 2007) calculates consistency scores based on distances in RGB space. In other words, synaesthetes score <1.43 because their colours for the same letter are close together within an RGB representation of colour. However, one

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feature of RGB space is that low saturated colours take up greater distances which could artificially exaggerate the distance between low chroma colours when calculating a consistency score. Put differently, synaesthetes with low chroma colours may appear less consistent simply by virtue of calculating their distance in RGB space. To address this we recalculated the consistency scores of all our 193 participants using an alternative 'perceptually real' colour space which attempts to control for this unwanted feature, by first converting the RGB values from the diagnostic tool into CIELAB space (with Illuminant D65 as white point, and converting to xyY assuming sRGB presentation on the users' monitors according to IEC standard). We then calculated distance using the standard measure of colour distance known as Delta E, using the CIEDE2000 specification (Sharma, Wu, & Dalal, 2005). To produce a final score, we took the average sum of Delta E, for each three colour-pairs, in each grapheme that had a full set of three colours, then we transformed it by taking it away from the maximum possible score for a grapheme (77.24), and normalising it to 0-100. For clarity we point out that our revised consistency score is higher when individuals are more consistent.

We then re-examined consistency across age but still found that scores were lower (i.e., that again there was less consistency) in older participants (*Mdn* = 58.21; N = 17; age ≥35 years) compared to younger participants (*Mdn* = 76.36; N = 176; age <35 years) and this difference was again significant, $U = 884.00$, $p = .005$. We therefore conclude that lower consistency in older subjects does not come as a result of any possible confound here (i.e., it does not result from differences in colour area for high and low chroma parts of RGB space).

We next tested a second possible confound, which is that people who are naturally lower in consistency (e.g., older people) might be recording artificially lower chroma colours due to a ceiling effect. The synaesthesia test uses a palette with chroma varying along one axis, and

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people selecting high chroma colours are selecting colours at the far edge of this axis. If variability is high, the mean chroma that is recorded will be lowered as a result of a ceiling effect: simply put, in cases of high chroma there are more available colours lower in chroma than higher. Since older adults are more variable (i.e., they have poorer consistency - see above) this could artificially lower what is recorded as their mean chroma. (The reverse is also true, that those with high variability choosing from low chroma would have their mean artificially elevated, but in general we find more high-chroma colours chosen by participants in our study.) To ensure that our results were not confounds from ceiling effects we matched a subset of the younger participants to every older participant on a measure of variability -- here, their mean consistency scores. In other words, for each older subject, we calculated the difference between their score and every younger subject's score. We then chose the younger subject with the smallest difference from the older subject's score (i.e. with the closest consistency score), and matched them to that older subject. When balancing variability in this way we continued to find a significant difference in the mean chroma between old participants (M = 44.36, SD = 16.72) and young participants (M = 59.59, SD = 20.97) just as before $t(32)=2.356$, $p = 0.025$. In summary, our analyses show that one of our age effects (older subjects are less consistent) is not confounded by calculating consistency in RGB space and that our other age effect (older subjects have lower chroma colours) is not confounded by age-differences in variability giving rise to ceiling effects.

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Part 3: How are aging, consistency and colour quality related?

After ruling out these confounds we are left with our earlier conclusions: that poorer consistency scores are linked to low chroma colours and to older people; and that older people have lower chroma colours (as well as lower luminant colours). In this section we compared the relative influence of these potentially-related effects. Our aim was to determine whether the consistency effect in aging is fully explained by the chroma effect alone: in other

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words, are older people less consistent simply because people with low-chroma colours are less consistent? Or is there an influence of aging that extends beyond differences in chroma?

We performed a mediation regression analysis to investigate the relationship between age, chroma, luminance and consistency on a continuous level. We took care to avoid confounds identified in 2b above by not using RGB space when calculating consistency and by not using the RGB-based scores anywhere this analysis. We again calculated consistency scores using the CIEDE2000 difference metric described above, and used the same CIELAB space to calculate chroma and luminance coordinates (CIELCh). Our model entered consistency as the dependent variable, age as the independent variable, chroma as the mediator (since chroma is correlated with age) and luminance as the co-variate (since luminance is not correlated with age, but consistency only). In our model we found that age was negatively associated with chroma (b = -0.360, p = .008), indicating that older subjects had less saturated graphemes. Chroma (i.e., grapheme saturation) was positively associated with consistency (b = .341, p < .001), indicating that subjects with more saturated graphemes had a higher consistency test-score (i.e., they were more consistent). When we looked at the relationship between age and consistency there was no direct relationship when chroma was taken into account (direct effect: b = -.116, p = .213) but instead, a small mediating effect of chroma on the relationship between age and consistency score (b = -0.123, where the bootstrapped 95% CI [-0.223, -0.058]). This supports the conclusion that the influence of aging on participants' consistency score is explained by changes in chroma (see Figure 7). In other words, older people are not inherently less consistent, but they have low chroma colours which itself influences consistency.

Finally, luminance was also independently related to consistency (b = 0.348, p = .039), indicating -- as before -- that individuals whose colours were less luminant was also likely to

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score poorer on the consistency test. These effects are captured in our model below (Figure 7). To ensure that the distribution of age in our sample did not lead to violations of the assumptions for regression analysis, we can confirm that the distribution of the residuals from both the age-chroma regression $D(193) = .056$, $p = .200$ and the chroma-consistency relationship controlling for age $D(193) = 0.43$, $p = .200$ are normally distributed.

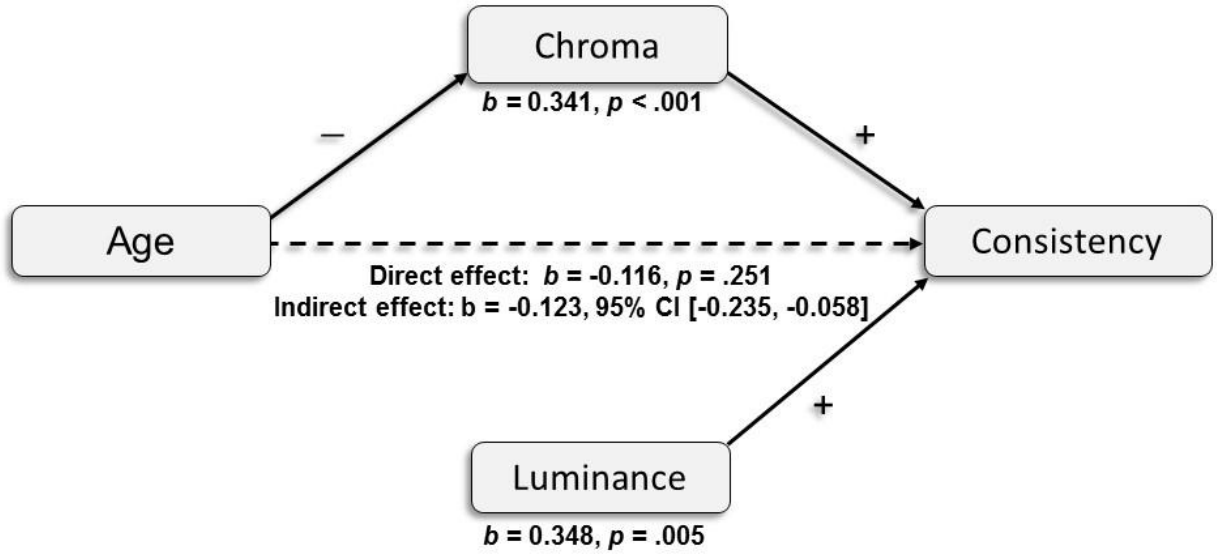


Figure 7: *Outcome of an analysis showing mediation effects predicting consistency score (i.e. higher score, more consistent). Results suggest a direct influence of chroma within the synaesthesia colour, but no direct effect of age.*

Discussion

We screened a large sample of the population for grapheme-colour synaesthesia, specifically targeting both younger and older people. Synaesthetes were verified by the 'gold standard' two-step process from the *Synesthesia Battery* (Eagleman et al., 2007) which requires them to first self-report having coloured graphemes, and then pass an objective test verifying their self-report. The objective test generates a consistency score, denoting on average how similar in colour was any given grapheme if presented repeatedly. (Since this consistency score

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represents colour distance, high consistency gives a low score, and a pass mark for synaesthesia is <1.43.) Using this 'gold standard' approach we classified individuals as either (a) *non-synaesthetes* (who respond 'no' when asked whether they have synaesthesia) (b) *synaesthetes* (who respond 'yes' and also passed the objective consistency test) or (c) *malingerers* (who respond 'yes' but failed the objective test). We found relationships between the groupings of participants, the age of the participants, the consistency of colours, and the chroma and luminance of those colours, which we summarise below.

We first found non-synaesthetes were older than malingerers and synaesthetes, not only because older people were less likely to self-report synaesthesia -- and therefore progress to the objective test -- but because they were also less likely to pass the objective test itself. We point out that in self-reporting, our participants did not have to declare "synaesthesia"; in other words, they did not have to be familiar with a term that might be more recognisable to younger than older subjects. They simply had to answer a question that would be equally understandable to both young and old ("Do numbers or letters cause you to have a colour experience? e.g., does the letter J "mean" yellow to you? Or does "5" make you perceive purple?"). The fact that proportionally fewer older adults reported this suggests that synaesthesia may in some way decline with age. Supporting this too, we found that fewer older than younger people were validated as synaesthetes by the objective test, even after self-report had been taken out of the equation (see below for the methodological implications of this).

Both our findings suggest, on the surface that some individuals who once had grapheme-colour synaesthesia when they were younger may no longer experience synaesthesia in older age (or they may no longer experience synaesthesia in the same way; see below). Our empirical finding is supported by several other lines of evidence. First our findings converge

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with a large number of anecdotal reports from people claiming to have lost synaesthesia as they aged (see Simner et al., 2009). Second, there is also comparable evidence of synaesthesia-loss in studies of childhood synaesthesia. When Simner and colleagues (Simner & Bain, 2013; Simner et al., 2009) tracked the development of synaesthesia in a group of children in real time between the ages of 6-10 years, there were two distinct patterns of results. Most synaesthetic children had grapheme-colour synaesthesia that grew stronger over time, as measured by a growth in the number of their consistently-coloured letters. However, a small number of individuals lost their synaesthesia over time: they were diagnosable as synaesthetes at age 6 or 7 but not at age 10. Hence, Simner & Bain (2013) provides empirical evidence to suggest another type of "synesthetic demise", this time in some children longitudinally, and their finding mirrors the evidence we have found in older people in our group-wise study here. Thirdly, a study by Meier and colleagues, too, showed that older people had changes in synaesthesia that might be equated to 'loss'. In their study, Meier et al. (2014) looked at synaesthesia in aging and found that older individuals had fewer graphemes with any synaesthetic colour at all compared to younger synaesthetes. In other words, Meier et al. found that the number of grapheme-colour associations decreased with age, i.e., the synaesthesia was "contracting" in older adults. Meier et al. did not however find a decline in consistency per se -- i.e., colours were not given inconsistently, as here; they were simply not given at all. Nonetheless, Meier et al.'s study differed from our own on a number of counts which may explain this difference in finding. Most importantly, we used a palette with 16 million possible colours, compared to the 13 used by Meier et al. Although the Meier palette was highly useful for testing large numbers, it might not have had the fine-grained ability to detect declines in consistency in the way we were able to do here. Finally, we point out that our data are similar to theirs when we use the same metric: we too find that the number of coloured graphemes declined in aging when considering the same type of

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population as Meier et al. (i.e., our data show a negative correlation between age and number of coloured graphemes for people self-reporting synaesthesia irrespective of their objective score). In summary, a number of lines of evidence now converge on the idea that synaesthesia changes with age in a way that might give rise to fewer synaesthetes in older age-groups using conventional testing.

In our study we also found that our objective test of consistency (Eagleman et al, 2007), used pervasively on synaesthetes, is sensitive to the *types of colours* reported: people whose colours were lower in chroma or luminance were less likely to pass the diagnostic for synaesthesia. Finally we found that older people are themselves likely to have lower chroma colours. We ruled out two possible confounds of the colour space used in the original testing tool, which could have artificially lowered chroma because of ceiling effects, and which could have exaggerated the distance between low chroma colours in RGB space. Finally, our modelling suggested our effects were linked: that older people were failing the test simply because their colours were low chroma, but that age was otherwise not a direct significant predictor of being diagnosed with grapheme-colour synaesthesia in this test. Had older people simply been less consistent as a direct consequence of aging, we might perhaps have considered this an instance of the higher inter-individual variance often found in older subject populations (i.e., older people are less consistent in responding across a range of tests; Nesselroade & Salthouse, 2004). But the fact that this effect is intimately tied with lowered chroma, and not with aging per se, leads us to look more closely at the possible reasons for this. Below we first consider why aging may be linked to lower saturated colours, and then consider why lower saturated colours might be tied to test-failure (i.e., poor test-retest consistency).

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In order to ask why older people have less chromatic synaesthetic colours, we must first rule out an alternative explanation. Our participants had to interact with an on-screen colour palette so we would want to first ask whether our results simply reflect changes in the perception of the physical world, rather than synaesthetic colours. We already know that a range of changes do occur in sensory colour perception during aging (Barbur & Rodriguez-Carmona, n.d.; Ben-David & Schneider, 2010; Hegde, 2011; Mateus et al., 2013) due to changes in the human lens (Ruddock, 1965; Said & Weale, 1959), foveal cone density (Salvi, Akhtar, & Currie, 2006) or changes in the chromatic visual pathways that lead to differences in electrophysiological responses (Fiorentini, Porciatti, Morrone, & Burr, 1996). One study in particular (Beke et al., 2008) suggests that changes in chromatic contrast sensitivity lead older people to perceive the world as less chromatic. In that study, older participants required more chroma relative to younger observers to achieve the same subjective appearance in a target display. Could the desaturated colour-choices in our data be explained simply by older participants perceiving the world (and hence the computer screen) in lower chroma? If so, our findings would be unrelated to changes in synaesthesia at all. However, the direction of our findings argues against this: the colours selected by our participants were lower in chroma for older people, but should have been higher if the screen simply appeared achromatic in a perceptual sense. In other words, if older participants' synaesthesia was unchanged but perception rendered the screen achromatic, subjects would have had to select higher (not lower) levels of chroma in order to compensate.

We therefore conclude that older participants indeed appear to experience less chromatic colours in their synaesthesia, in particular, and we therefore ask why this might be. One possibility is that the internal mental world is mirroring changes in external perception, given that experience and environment influence synaesthesia in important ways (Simner & Holenstein, 2007). Alternatively, it may be that changes are hedonically influenced, as found

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in other forms of synaesthesia (Russell, Stevenson, & Rich, 2015). At least one study (Dittmar, 2001) shows that older people have changes in their colour preferences, and we know elsewhere that colour-preferences can mirror changes in colour perception (Bubl, Tebartz Van Elst, Gondan, Ebert, & Greenlee, 2009; Carruthers, Morris, Tarrier, & Whorwell, 2010).

It might also be possible that synaesthetic changes in chroma are linked to other facets of aging, such as changes in levels of depression. Low mood/depression influences synaesthetic colours in ways similar to those found here: synaesthetes in negative or depressed mood states have lower luminance and saturation in their synaesthetic colours (Kay, Carmichael, Ruffell, & Simner, 2015). So might older people have lower saturated colours because they are more depressed? Lifespan changes in depression have been explored in the literature (e.g Fiske, Wetherell, & Gatz, 2009) but the results are mixed. Although certain traits of depression -- such as "loss of interest in living" -- are indeed elevated in older populations (Christensen et al., 1999) the overall prevalence of depressive episodes tend to decline in older age, especially in late aging (Bebbington et al., 1998). In our own sample, participants happen to have completed a health questionnaire (the full results of which will be reported elsewhere) which included the question "Have you ever been diagnosed with depression?" Those above 35 years did indeed report depression diagnoses significantly more often than younger subjects (14.3% of older subjects compared to 8.9% of younger, $\chi^2(1) = 22.0$, $p < .001$) although older people of course have more years of life in which a diagnosis could be made. But importantly, this metric of depression did not affect chroma in this particular cohort (i.e., when comparing those with and without a depression diagnosis: $M_{with\ depression} = 61.7$, $SD = 13.6$, N = 22; $M_{without\ depression} = 59.7$, $SD = 17.5$; N = 171; $t(191) = -.60$, $p = .500$) and nor did it affect luminance ($M_{with\ depression} = 54.0$; $SD = 8.0$; N = 22; $M_{without\ depression} = 52.5$, $SD = 9.2$, N = 171; $t(191) = -.70$, $p = .500$). Although we actually cannot say who may have

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been depressed at the moment of testing, unlike Kay et al. (2015), we suggest that the weight of evidence here and in the literature seems to point away from depression as the cause of differences in synaesthetic colour in older versus younger subjects. However, our ongoing studies are now investigating aging synaesthetes with more targeted depression measures.

We point out that our study looked at aging across individuals, and this means that our aging effect (i.e., older people have less saturated colours) might have two possible causes: either it is related to biological aging, or it is related to aging as a cohort effect. This latter explanation would entail that our aging effect is due to environmental and social factors that differently influence younger and older people. This may indeed explain at least part of the relationship between lower saturation and higher age but it does not appear to provide a complete picture. For example, perhaps older synaesthetes pair graphemes with less saturated colours due to the quality of the colours in their environment growing up. Equally, perhaps the older cohort spent their developmental years supressing their associations due to low public understanding, making their colours duller and weaker. In contrast, younger cohorts might attend more to their synaesthetic associations because synaesthesia has become recognized in the public domain within the past 10 years, and this could reinforced their colours and make them brighter. However, such interpretations based on cohort influences we would have predicted two effects we did not find: that older cohorts had less robust (i.e., less consistent) colours per se, and that those colours would be not only less saturated but also less luminant. We found neither of these effects. So it is unclear how a cohort explanation would result in less saturated but not less luminant colours, and in colours that remained consistent in older people so long as chroma did not drop. It also does not explain anecdotal reports from individuals who claim they have lost synaesthesia as they grew older. Nevertheless, environmental/social factors and age-related effects on the quality of synaesthetic associations need to be teased apart in future longitudinal research.

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Above we have described several factors that might bring about changes in the saturation of synaesthetic colours in aging. These proposals also raise another intriguing possibility: if we consider synaesthesia as a form of (albeit unusual) mental imagery, we might ask whether *all* mental imagery becomes less saturated in older people. In other words, do the colours in the mind's eye desaturate in aging for all people? In our study we elicited colours only from those claiming to have synaesthesia, because this was our focus, and because the widely-used diagnostic is asymmetric (i.e., although people both with and without synaesthesia claim to have it, only those without synaesthesia claim not to)[3]. So standard synaesthesia testing – as performed here - does not elicit colours from self-declared non-synaesthetes. However, future studies might use the test in a non-standard way to elicit colours from non-synaesthetes: will *non*-synaesthetic imagery also follow the same trend, showing less saturated colours as the participant ages? This is a question currently being pursued in our lab for future publication.

We point out that our data concur with another finding in older synaesthetes, that they might show "a decline in the occurrence of lurid colors", as suggested previously by Meier et al. (2014, p1). Although Meier and colleagues not define 'lurid' it is certainly the case that lower saturated colours could be considered less lurid. Meier et al. also found fewer instances of yellow and orange and more instances of brown, which is again consistent with a desaturation effect of the type found here -- since desaturated yellow and orange arguably enter the colour-category of brown. We therefore conclude that the changes in colour-category found by Meier and colleagues are consistent with the underlying shift in the chroma of colours

[3] An anonymous reviewer has asked us to comment on whether people claiming *not* to have synaesthesia can also score well on the diagnostic test of consistency. A huge body of literature shows this not to be the case (see Simner, 2012, for an extensive review). Furthermore, two studies (Simner et al., 2009; Simner & Bain, 2013) show that a small number of non-synaesthetes who might perform well in very simple versions of this test (e.g., where graphemes are repeated two not three times, with an immediate retest across just 10 seconds, and with just 13 colours in the colour palette to choose from) cannot maintain their superior performance when the test becomes harder (e.g., with a longer test-retest interval).

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found here -- and that our reconsideration of their findings as a chroma-shift is a fundamental step in understanding how and why colour-changes occur in older synaesthetes.

We turn finally to the finding that consistency and chroma are related independently of age. We found that people with lower chroma colours are more likely to fail the consistency test, even when age is held constant. We offer two possible explanations, one related to methodology and veridical perception, and the other related to internal processing and synaesthetic perception. First, it is possible that low consistency arises due to difficulties with this (very widely used) type of testing interface at low saturation levels. Research in colour perception shows that hue and saturation are harder to discriminate at lower saturated levels for both younger and older individuals (Cooper, Ward, Gowland, & McIntosh, 1991). Given this, synaesthetes with low-chroma colours would find their colours harder to discriminate from neighbouring colours on screen, and may therefore make more errors than those picking from the saturated end of the scale. In other words, low-chroma colours may be inconsistent simply because they are harder to discriminate in the test. Alternatively, some studies have suggested that memory, too, for highly saturated focal colours is better than memory for non-focal unsaturated colours (e.g. Heider, 1972). Since is reasonable to assume that memory plays at least some role in grapheme-colour associations (see Witthoft & Winawer, 2013 for one type of example) they may be more difficult to remember in accurate detail when colours are low in chroma. This would again result in noisier estimates of synaesthetic colours and therefore poorer performance in the consistency test.

The standard test we used in our study did not gather information on whether our synaesthete participants were “projectors” or “associators”. Projector synaesthetes see their colours as if they were veridical qualities in external space (e.g. superimposed on graphemes when reading) whilst associators see them as mental images in the mind’s eye, or simply ‘know’

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what they are. An outstanding question that future research should address is whether this quality plays a role in the way that colour experience changes with age. We know that for example, projectors show increased grey matter in frontal and visual cortex, while associators show increased volume in hippocampus, amygdala and cerebellum (Rouw & Scholte, 2010). Normal age-related declines in grey matter in these latter three regions are known to be non-linear, with relatively stable volumes until age 50 followed by a more sudden decline thereafter, whilst declines within the frontal lobe are more linear (Ziegler et al., 2012). One might therefore predict that the trajectory and onset of change in synaesthetic experience might differ across associators and projectors. Another possibility is that projector synaesthetes might become more like associators later in life. Projector synaesthetes tend to score higher on self-reported object imagery compared to associators (Amsel, Kutas, & Coulson, 2017) and visual imagery tends to decline with age (Dror & Kosslyn, 1994; Kemps & Newson, 2005). As projector synaesthetes get older, they might therefore cease to project synaesthetic colour onto external space and instead experience colour in the mind's eye, as a result of general age related changes in visual imagery.

Further studies are required to pull apart the relative influences of methodology and memory, as well as external and internal perceptual processes, especially as we have used a gold standard, widely-accepted, extensively-used method for assessing synaesthesia in our study. Indeed, perhaps the key conclusion from our study is therefore a methodological one. If older people have desaturated colours, and if desaturated colours are a priori less likely to pass the gold standard test of consistency, then we suggest that this test might have an adjusted threshold for older subjects. The standard diagnostic cut-off in this test is <1 (Eagleman et al., 2007) or <1.43 (e.g., Rothen et al., 2013) but those studies did not specifically target older subjects within their cohorts. If their diagnostic thresholds were based on young participants it would make sense to set a higher threshold for older people.

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This is because older people have less saturated colours, and as we have seen, less saturated colours give rise to poorer consistency. In other words, we end our study with the methodological proposal that age-graded thresholds might be a useful way to adjust the diagnosis of synaesthesia for older subjects.

In summary, we found that older participants report synaesthetic colours that are less chromatic and are more likely to fail the consistency test, and that chroma explains the relationship between ageing and failing consistency. Our study emphasizes the need to gain a better understanding of how synaesthesia changes in later life, how different characteristics of a synaesthetic experience might influence performance on consistency tests, and how those tests should therefore be structured.

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Author Contributions

J.S. conceived the study and worked on all aspects. R.S. and J.A. contributed analyses and interpretations. A.I. contributed analyses and interpretations, and co-wrote the manuscript.

Competing financial interests

The authors declare no competing financial interests.

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Highlights

- Proportionally fewer older people report having grapheme-colour synaesthesia
- Proportionally fewer older people pass the objective synaesthesia consistency test
- Chroma of synaesthetic colours predicts consistency
- Older synaesthetes experience lower chroma colours, which lowers consistency

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