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An Autistic-Like Profile of Attention and Perception in Synaesthesia

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Synaesthesia and autism are two neurodevelopmental conditions that have been shown to co-occur more than expected by chance. The studies reported here test the hypothesis that increased sensory sensitivity and enhanced attention-to-detail are core cognitive features that are shared between them. In Study 1, we administer self-report measures of sensory sensitivity and autistic traits (the Autism Spectrum Quotient, AQ) to a large heterogeneous sample of synaesthetes. Both sensory sensitivity and the attention-to-detail subscale of the AQ show a “dose-like” relationship with synaesthesia: namely, more kinds of synaesthesia is related to a greater shift up the autistic spectrum. Study 2 uses two objective measures of visual perception/attention linked to autistic traits: change blindness and detection of local embedded figures. Both measures are shown here to be sensitive to the attention-to-detail subscale of the AQ, and synaesthetes outperformed controls on both tasks. Synaesthetes appear to occupy a specific cognitive niche of having autistic-like traits linked to enhanced perception and attention. Whilst these typically occur in the absence of the traditional impairments that define autism, they may carry the cost of increased vulnerability to clinical levels of autism (Odds Ratio=2.07).

Keywords: autism; sensory sensitivity; embedded figures; synaesthesia/synaesthesia; change blindness.

Introduction

Synaesthesia and autism are two relatively common neurodevelopmental conditions that emerge early in life (Baird et al., 2006; J. Simner, Harrold, Creed, Monro, & Foulkes, 2009) and have a genetic contribution (Ma et al., 2009; Tomson et al., 2011). Several recent studies have shown that they are related insofar as the two conditions co-occur more often than expected by chance (Baron-Cohen et al., 2013; Neufeld et al., 2013). Baron-Cohen et al. (2013) reported a prevalence of 18.9% for various kinds of synaesthesia in their high-functioning autism sample, relative to 7.2% in their controls (Odds ratio=2.997, 95% CI=1.265-7.101). Neufeld et al. (2013) reported a prevalence of 17.2% of grapheme-colour synaesthesia in their high-functioning autism sample (they didn't test a separate control group but relied on published norms of 1.1 to 2.0% for this kind of synaesthesia and 4.6% if including other kinds; (J. Simner et al., 2006)). This co-morbidity may reflect shared features of atypical brain development in these groups, for instance regarding brain connectivity. The present research tackles the issue as to how/why they are related from the perspective of whether the two conditions have a shared cognitive or perceptual profile.

Autism Spectrum Condition (ASC) has, historically, been defined in terms of a triad of impairments: namely problems in social interactions, communication (verbal and non-verbal), and a limited repertoire of interests (Wing & Gould, 1979). However, this early view of autism has been extended and refined to encompass a wider range of symptoms including those that would be considered strengths rather than impairments. This includes enhanced detection of local features (Shah & Frith, 1983), enhanced perceptual processing (Mottron et al., 2013), and an aptitude for rule-based systems (Baron-Cohen, Ashwin, Ashwin, Tavassoli, & Chakrabarti, 2009). More recently, the new diagnostic criteria for ASC added atypical sensory sensitivity as a defining feature of autism including hyper-sensitivities (e.g. aversion to certain lights,

sounds) and hypo-sensitivities (e.g. repetitively stimulating the senses) (Association, 2013). Although these sensory symptoms are in some cases undesirable, they might not necessarily constitute an impairment in cognitive terms and they could conceivably be linked to some of the known strengths (Baron-Cohen et al., 2009).

Synaesthesia is generally not considered to be linked to impairments and is often considered as a ‘gift’ (N. Rothen, Meier, & Ward, 2012). People with synaesthesia have unusual sensory-like experiences (termed “concurrents”) that are elicited by certain triggering stimuli (termed “inducers”). Thus for lexical-gustatory synaesthesia, words act as an inducer of unusual flavour concurrents (e.g. the name “Philip” may trigger the taste of sour oranges) and in another variant, grapheme-colour synaesthesia, letters and numbers act as an inducer of concurrent experiences of colour. There is also evidence that there is increased sensitivity for the processing of certain sensory stimuli in synaesthetes. Grapheme-colour synaesthetes have enhanced perceptual discriminations of colour and shape (Ward, Rothen, Chang, & Kanai, in press), show increased EEG visual-evoked potentials to certain achromatic gratings (Barnett et al., 2008), and show reduced TMS (transcranial magnetic stimulation) phosphene thresholds to occipital cortex suggesting greater intrinsic excitability in this region (Terhune, Tai, Cowey, Popescu, & Kadosh, 2011). Moreover, the latter is greater for ‘projector synaesthetes’ who experience their synaesthetic colours externally, as if they were veridical colours in the real-world (Terhune et al., 2015). Direct comparisons with autism on these measures are lacking but similar effects for EEG visual-evoked potentials are noted (Vlamings, Jonkman, van Daalen, van der Gaag, & Kemner, 2010) and the idea of an excitation/inhibition imbalance, favouring excitability, is a common one (e.g. Rubenstein & Merzenich, 2003). In other domains, the two conditions appear to be more different in their cognitive profile: synaesthesia has been linked to enhanced episodic memory (N. Rothen et al., 2012) but this finding does not extend to autism (Boucher & Bowler, 2008). Again, direct comparisons are generally lacking.

In a recent study, Ward et al. (2017) did directly contrast synaesthetes and people with a diagnosis of ASC on two standard self-report measures. The Glasgow Sensory Questionnaire (GSQ) asks about sensory hyper- and hypo-sensitivities across several modalities and is elevated in autism (Robertson & Simmons, 2013). The Autism Spectrum Quotient (AQ) asks about autistic-like traits with five subscales: four relate to impairments (social skills, communication, imagination, attention switching) and one relates to unusual abilities, attention-to-detail (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001). Synaesthetes reported elevated sensory sensitivity scores (intermediate in level between control and ASC samples) and they fell into the autistic range on one subscale of the AQ, namely attention-to-detail. Given that the effect was not significant for other subscales of the AQ, the conclusion was that synaesthesia and autism are related due to having similar sensory/attentional features (i.e. a putative strength rather than impairment).

The finding that synaesthesia and autism may be linked by traits conferring certain abilities is consistent with earlier claims that the co-occurrence of synaesthesia and autism may lead to savant abilities (Baron-Cohen et al., 2007; Julia Simner, Mayo, & Spiller, 2009). Savant abilities (e.g., Treffert, 2010) are instances of prodigious talent that co-occur with developmental difficulties such as ASC. The link between synaesthesia, autism and savant abilities has been tested directly in recent research. Hughes et al. (2017) examined the prevalence of grapheme-colour synaesthesia in people with a confirmed diagnosis of ASC but separated them into those who either did or did not report savant abilities. Only the ASC group with savant abilities had a higher prevalence of synaesthesia.

In summary, this previous research suggests a cognitive link between synaesthesia and autism centered (minimally) around increased sensory sensitivity and attention to detail. However, there are still many unanswered questions. Firstly, it is not clear whether this affects some kinds of synaesthesia more than others. The study of Ward et al. (2017) recruited

synaesthetes on the basis of having grapheme-colour synaesthesia (chosen because it is relatively simple to verify), but most of the sample also reported at least one other kind of synaesthesia. Among these were sequence-space synaesthesia, a particular focus here, in which sequential concepts (e.g. numbers, the calendar) are visualised as visuo-spatial configurations (Sagiv, Simner, Collins, Butterworth, & Ward, 2006). Secondly, most of the evidence to date is based on self-reported traits. Ward et al. (2017) used one measure to corroborate self-reports of sensory sensitivity namely a measure of ‘visual stress’ when viewing certain spatial frequencies (Wilkins et al., 1984). However, more typical measures from the literature on autism have not been used. The current research fills these important gaps. Our first study considered a more diverse sample of synaesthetes to extend the findings of Ward et al. (2017) using the GSQ and AQ. Our second study uses measures that have been shown to be cognitive strengths in people with autism, and that are good candidates for being related to enhanced attention-to-detail. These include a measure of visual change detection using a standard change blindness paradigm (Rensink, O'Regan, & Clark, 1997). Autistic adolescents are better at detecting changes in a related, continuity error paradigm (Smith & Milne, 2009). We also included a version of the Embedded Figures Test, which is regarded as a measure of local attentional processing and which people with autism tend to score higher on (e.g. Joliffe & Baron-Cohen, 1997)

Study 1: Self-reported Autistic-Like Attention and Perception Traits in Synaesthesia

Method

Participants

There were 182 synaesthetes (154 Female, 24 Male, 4 undisclosed; average age = 32.6 years, S.D. = 10.2) and 189 control participants (138 Female, 51 Male; average age = 29.4 years, S.D. = 13.2) in Study 1. Of these, 121 participants (76 controls, 35 synaesthetes) were

a reanalysis of those reported in Ward et al. (2017). The remainder were recruited specifically for this study as detailed below. Controls were selected opportunistically via personal communication and via social media, and the advert did not mention synaesthesia. It is to be noted that we did not ascertain the absence of synaesthesia in this group. Hence they are a normative control sample rather than a non-synaesthetic sample.

Synaesthetes were recruited from a database at the University of Sussex who had previously agreed to take part in our studies and had given information about the types of synaesthesia that they possessed. The new synaesthetic participants were selected on the basis of having grapheme-colour synaesthesia but not sequence-space synaesthesia (GCS, N=38) or the reverse: having sequence-space synaesthesia but not grapheme-colour synaesthesia (SSS, N=109). We subsequently also examined the effects of the presence of other kinds of synaesthesia beyond GCS and SSS. The additional types of synaesthesia considered were sound-to-colour (N=43 reported this), ‘tickertape’ synaesthesia in which people see visual spellings of words when listening to speech (N=48 reported this), and taste/smell concurrent experiences such as lexical-gustatory synaesthesia (N=30 reported this). We selected these types of synaesthesia on the basis of them involving senses other than vision and because they were relatively frequently reported. All participants with grapheme-colour synaesthesia had been verified as genuine using the standard diagnostic measure (i.e., as having high test-retest consistency on their colours for graphemes, with all achieving the accepted diagnostic (a score <1.43, Nicolas Rothen, Seth, Witzel, & Ward, 2013)).

For the grapheme-colour synaesthetes, 63 had previously completed the CLaN questionnaire (Nicolas Rothen, Tsakanikos, Meier, & Ward, 2013) which describes synaesthetic phenomenology on several dimensions. The two dimensions considered here are the Automaticity-Attention scale which describes the extent to which synaesthetic colours require effortful retrieval (an example item being “I experience the synaesthetic colours even

if I do not attend to them specifically; e.g., while reading a book”) and the Localisation scale which describes the extent to which synaesthetic colours are located externally (“I can point to the location of the synaesthetic colours”). Both of these dimensions affect neural and behavioural responses to graphemes in these synaesthetes (Nicolas Rothen, Tsakanikos, et al., 2013; van Praag, Garfinkel, Ward, Bor, & Seth, 2016).

The study was approved by the University of Sussex Science and Technology Research Ethics Committee.

Materials

The GSQ measures sensory sensitivity across seven different modalities (visual, auditory, olfactory, gustatory, tactile, vestibular and proprioceptive) and each modality includes three hyper-sensitivity and three hypo-sensitivity questions, giving 42 items in total (Robertson & Simmons, 2013). Items are answered using a 5 point Likert scale (Never, Rarely, Sometimes, Often, Always), and include questions such as “Do you ever feel ill just from smelling a certain odour?” or “Do you react very strongly when you hear an unexpected sound?”. All items have been shown to load on to a single factor (Robertson & Simmons, 2013) and, hence, it is conventional to assign a single score to participants. Responses are scored from 0 (Never) to 4 (Always) with total scores ranging from 0-168. The reliability of the GSQ was excellent (Cronbach’s $\alpha=0.914$).

The AQ is a questionnaire designed to measure autistic-type traits in people with average intelligence (Baron-Cohen et al., 2001). It uses 50 items measuring five different subscales; social skills, attention switching, attention to detail, communication and imagination, with each subscale contributing 10 items. Responses are given on a four point Likert scale (Definitely Disagree, Slightly Disagree, Slightly Agree, Definitely Agree). Examples of these items include “I am often the last to understand the point of a joke”, “I am not very good at remembering phone numbers” and “I find it difficult to work out people’s

intentions". Each item is given a score of 1 or 0 depending on whether it reflects an autistic-like trait or not (i.e. irrespective of level of agreement) thus total scores range from 0-50. A score of 32 and above is considered to be comparable to clinically diagnosed levels of autism (Baron-Cohen et al., 2001). Many studies, particularly those looking at sub-clinical levels of autism, also consider different subscale scores and this is the approach taken here given our a priori interest in the attention-to-detail component. The reliability of the AQ, based on binary scoring, was good (Cronbach's $\alpha=0.865$) although it was more variable at the level of subscales (social skills=.803, attention switching=.676, attention to detail=.613, communication=.931, imagination=.549).

Procedure

Participants completed the study online using Qualtrics. After providing informed consent, participants supplied demographic details. The GSQ was completed first followed by the AQ and the survey lasted approximately 20 minutes in total. It is to be noted that the survey itself did not ask about types of synaesthesia as this information had previously been supplied. Hence the synaesthetes were not primed to think about the particular characteristics of their synaesthesia (e.g. the variety of types that they have) when completing the test.

Results and Discussion

To explore the effects of different sub-types of synaesthesia, the data were analysed in two ways. Firstly we considered if there is a main effect of synaesthesia (i.e. comparing all synaesthetes against all controls). Secondly, we considered if there is an effect of the number of types of synaesthesia amongst the synaesthetes alone - i.e. a 'dose effect' of synaesthesia. For the types of synaesthesia considered here, a synaesthete can have a 'dose' between 1 and 5 types. The 5 types of synaesthesia are GCS, SSS, tickertape, sound-to-colour, and synaesthesias with taste/smell concurrents (e.g. lexical-gustatory).

The results for sensory sensitivity (GSQ) are displayed in Figure 1. The group differences were analysed adding age and gender as covariates. There was a main effect of group (i.e. synaesthete > control) on sensory sensitivity ($F(1,362)=25.105$, $p<.001$, $\eta^2=.065$; Cohen's $d=0.45$). Age was a significant covariate (older people having lower scores; $F(1,362)=21.216$, $p<.001$, $\eta^2=.055$) but not gender ($F(1,362)=1.210$, $p=.272$, $\eta^2=.003$). With regards to a 'dose effect' there was a significant correlation (within the synaesthetes) between number of types of synaesthesia and the GSQ score ($r=.444$, $p<.001$). The figure shows the data grouped for the most common combinations of synaesthesia. This illustrates the fact that the effect does not depend strongly on the types of synaesthesia experienced, but it is to be noted that the analyses were conducted on ungrouped synaesthetes. We can also conclude that the effect is not simply due to more sensory modalities being engaged in synaesthetes with multiple varieties. For instance, all of our synaesthetes have visual synaesthetic experiences but yet there is still a dose effect when one considers the visual questions alone ($r=.425$, $p<.001$) or when one considers those modalities that were not counted in terms of types of synaesthesia ($r=.359$, $p<.001$ for the combined touch, proprioception and vestibular questions). That is, increased sensory sensitivity appears to be related to the number of types of synaesthesia but is not strongly related to the type of synaesthesia experienced.

INSERT FIGURE 1 HERE

The AQ was broken down into the Attention-to-detail subscale and the remaining four subscales ('AQ-Other'). This was done primarily because it was motivated by our hypothesis that attention-to-detail would be more affected, although other research has shown that this separation is supported by factor analysis of the AQ (Ujie & Wakabayashi, 2015). These results are summarised in Figure 2, and the full data across all subscales are shown in the Supplementary Results. A 2x2 ANOVA contrasting AQ-other and Attention-to-detail in synaesthetes and controls, with gender and age as covariates, showed a main effect of

synaesthesia ($F(1,350)=48.95$, $p<.001$, $\eta^2=.123$), a main effect of subscale ($F(1,350)=4.337$, $p=.038$, $\eta^2=.012$), and – crucially – an interaction between group and subscale ($F(1,350)=8.729$, $p=.003$, $\eta^2=.024$). Synaesthetes had higher scores for both Attention-to-detail ($t(357)=6.737$, $p<.001$) and AQ-other ($t(357)=3.164$, $p<.001$). The effect size was medium for Attention-to-detail (Cohen’s $d=0.71$) and small for AQ-other (Cohen’s $d=0.33$). This is consistent with previous research suggesting that synaesthesia is more strongly linked to some autistic traits more than others (Ward et al., 2017). Of the covariates, only gender was significant as a main effect (males having higher AQ scores; $F(1,350)=8.187$, $p=.004$, $\eta^2=.023$) and there were no interactions with age and gender covariates (all p 's $>.10$). With regards to ‘dose effects’, there were significant correlations (within the synaesthetes) between number of types of synaesthesia and Attention-to-detail ($r=.237$, $p=.001$) but not for AQ-other ($r=.072$, $p=.339$), although the difference between the correlations did not reach significance ($t(175)=1.82$, $p=.070$).

Although both sensory sensitivity and Attention-to-detail show dose effects, there were differences. Whereas having a single type of synaesthesia (i.e. comparing those with 1 form of synaesthesia to controls) is linked to increased Attention-to-detail ($t(257)=3.929$, $p<.001$), this was not the case for sensory sensitivity ($t(257)=0.055$, $p=.957$) where differences emerged only for multiple kinds of synaesthesia (i.e. 2+).

INSERT FIGURE 2 HERE

Next we considered the proportion of people with an $AQ \geq 32$, which is a commonly used cut-off for clinical levels of autism. Figure 3 shows that there is a strong association between the number of types of synaesthesia and the number of people lying above this cut-off ($\chi^2(4)=13.991$, $p=.007$). Thus, the more types of synaesthesia a person has the greater the vulnerability to more extreme autistic tendencies. The odds ratio (OR) of having high levels of autistic-traits (defined as $AQ \geq 32$) given the presence of 1 or more of these types of synaesthesia was $OR=2.07$ (95% $CI=.98-4.21$). Given that our sample of synaesthetes was not

random (we deliberately selected synaesthetes having fewer types, i.e. SSS or GCS but not both) this is a conservative estimate. The OR of having $AQ \geq 32$ if a person has 3 or more of these types of synaesthesia is $OR=4.76$ (95% $CI=1.89-11.96$). It is to be noted that synaesthetes with an $AQ \geq 32$ don't achieve these high scores solely through an inflated Attention-to-detail score but are reporting a range of autistic symptoms including socio-communicative impairments (see Supplementary Results for a full summary).

INSERT FIGURE 3 HERE

Finally, for the grapheme-colour synaesthetes we considered how the specific phenomenology of their synaesthesia, as assessed via the CLaN (Nicolas Rothen, Tsakanikos, et al., 2013), is linked to the GSQ and AQ. The results are summarised in Table 1. There was only one significant correlation: namely between the Automaticity-Attention subscale of the CLaN and the Attention-to-detail subscale of the AQ. This suggests a relationship between real-world attentional traits and the attentional characteristics of the synaesthesia. As the questionnaires were done separately (up to several years apart), the association is unlikely to be a trivial bias in responding. Although projecting synaesthetic colours externally has been linked to visual cortical excitability (Terhune et al., 2015), the CLaN Localisation scores (which are very similar to the notion of 'Projector'; (Anderson & Ward, 2015) were unrelated to sensory sensitivity as indexed by the GSQ.

INSERT TABLE 1 HERE

In summary, Study 1 showed that the relationship between synaesthesia and autistic-traits depends strongly on the amount of synaesthesia rather than the specific type of synaesthesia that is possessed. This is true for both sensory sensitivity and the Attention-to-detail subscale of the AQ. This was not the case for other subscales of the AQ that cover the traditional triad-of-impairments in autism. Whilst the AQ-other score was significantly enhanced in synaesthesia the effect size was small and did not show a significant dose effect.

We conclude that there is a close relationship between synaesthesia and the attention/sensory traits of autism, probably reflecting a common neurobiological mechanism. Synaesthetes appear to occupy an important cognitive niche: they gain many of the benefits linked to autism without necessarily incurring the impairments (but with an elevated risk of doing so). The potential cognitive advantages are explored in Study 2.

Study 2: Objective Evidence of Autistic-Like Attention and Perception Tendencies in Synaesthesia

Method

Participants

All of the synaesthetes from Study 1 were invited to participate in Study 2, and a total of 56 of them took part (mean age = 33.8, SD= 10.9 years; 47 females, 9 males). Of this sample 54 completed both tasks of Study 2, 1 completed only the Embedded Figures Task and 1 completed only the Change Blindness task.

A separate control group was recruited for the purposes of this study using Amazon's Mechanical Turk, which has been shown to produce a more representative sample than opportunistic sampling (Buhrmester, Kwang, & Gosling, 2011; Hauser & Schwarz, 2016). There were 90 control participants (mean age = 41.2, SD= 10.5 years; 33 females, 13 males, 3 undisclosed and the remainder did not complete the question due to technical error). Of this sample 66 completed both tasks, 13 completed only the Embedded Figures Task and 12 completed only the Change Blindness task.

The study was approved by the University of Sussex Science and Technology Research Ethics Committee.

Materials

The Embedded Figures Test assesses the ability to extract information from context by spotting a simple ‘local shape’ within a more complex figure. For the Embedded Figures Test, there were 30 target stimuli (i.e., local shapes) and, for each target stimuli, there were four more complex stimuli only one of which contained the target. All stimuli were black-and-white line figures taken from a website testing for cognitive abilities (<http://www.allindiaexams.in>). None of the target stimuli required rotation to match with the response. The target stimulus was presented above the four response options, which were smaller in size, by three-quarters.

For the change blindness test, 48 coloured image pairs were selected from a pre-existing database (Sareen, Ehinger, & Wolfe, 2015): one image was an original indoor scene and in the other image one of the objects (e.g., a vase) was removed. The image size was 1024 x 768 pixels and the software always displays at the true size rather than rescaling. Approximately half of the changes were on the left side and half on the right. Example of stimuli from the two tests is shown in Figure 4.

INSERT FIGURE 4 HERE

Procedure

All participants completed the tests online presented from Inquisit software (www.millisecond.com). The order of the Change Blindness and Embedded Figures Tests were counterbalanced across participants and both tests took around 30 minutes to complete. Controls also completed the AQ (as described in Study 1) and another measure that was separate from this study (the O-LIFE, Mason & Claridge, 2006).

For the Embedded Figures Test, participants were first given three practice trials with feedback as to the correct answer. The 30 test trials then followed presented in a random order. Participants were instructed to decide which of the four options contains exactly the local shape

without rotating or changing in any way. Participants were encouraged to be as accurate as possible but to press the response as soon as they had found it as response times would be recorded. Each trial started with a central fixation cross presented for one second followed by the stimulus which remained on the screen until a response was received. Participants responded by pressing one of four response keys (1, 2, 3, 4). No feedback was given on the test trials.

For the Change Blindness test, participants were given one practice example followed by the main trials presented in a random order. Each trial began with a central fixation (3 seconds) followed by a blank black screen (1 second). The pre-change scene was presented (240 msec) followed by a blank black screen (80msec) followed by the post-change scene (240msec) and another blank (80msec). This cycle of scenes and blanks continued until the participant responded or until a 30 second time-out. Participants were instructed to use a mouse controller to click on the object that kept appearing and disappearing. The next trial began immediately afterwards and no feedback was given. For each scene, the changed object was defined a priori by a circular region of interest (x,y coordinate of centre and radius) and responses within this region were classified as correct. The ability to detect changes is largely unrelated to the size of the changed object (in our stimulus set, the correlation between object radius and detection rate was $r=.086$).

Results and Discussion

We first examined the AQ self-report scores, which were gathered from Synaesthetes in Study 1, and from our new controls in Study 2. Here, synaesthetes again had significantly higher AQ Attention-to-detail than this group of controls (synaesthetes=7.01, SD=1.88; controls=5.61, SD=2.45; $t(141)=3.627$, $p<.001$) but they did not differ significantly on AQ-Other (synaesthetes=15.58, SD=7.76; controls=13.22, SD=7.46; $t(141)=1.816$, $p=.071$).

Although we did not test an autistic group, there were six controls who reported clinical levels of autistic traits ($AQ \geq 32$; mean = 37.8, S.D.=5.0). This provides an opportunity to test our synaesthetes against this high-AQ group (noting that the mean AQ of our synaesthetes is far lower at 21.2), as well as providing further evidence that these particular tests are related to autistic traits rather than, for instance, synaesthetes being more motivated.

In the two main tests, all participants scoring < two standard deviations from the mean on accuracy were excluded. This led to 6 exclusions from the Change Blindness test and 1 exclusion for the Embedded Figures Test. Response times were averaged only for correct trials. The results for the two tasks are summarised in Figure 5.

INSERT FIGURE 5 HERE

For the Change Blindness test, synaesthetes were significantly more accurate than controls ($t(125)=3.16$, $p=.002$, Cohen's $d=0.56$) but they did not differ in response times ($t(125)=-0.74$, $p=.459$, Cohen's $d=0.13$). The test is a reliably related to the AQ Attention-to-detail subscale, correlating both with RT (faster change detection linked to greater attention-to-detail; $r=-.256$, $p=.004$) and accuracy ($r=.240$, $p=.007$). The test was not related to AQ-Other (RT $r=-.121$, $p=.177$; accuracy $r=.105$, $p=.242$). The difference in correlations between AQ-other and Attention-to-detail were not significant ($p's > .10$).

For the Embedded Figures Test, synaesthetes were significantly more accurate than controls ($t(130)=4.23$, $p<.001$, Cohen's $d=0.74$) but they did not differ in response times ($t(130)=-0.43$, $p=.669$, Cohen's $d=0.07$). The test is a reliable measure of the AQ attention-to-detail subscale: the latter correlated with accuracy ($r=.289$, $p=.001$) but not RT ($r=-.011$, $p=.904$). Accuracy in this test was also related to AQ-other (accuracy $r=.285$, $p=.001$; RT $r=.061$, $p=.489$).

When synaesthetes were compared against the high-AQ subset of controls, these two groups did not differ significantly on either change blindness (accuracy: $t(59)=.449$, $p=.655$;

RT: $t(59)=.830$, $p=.410$) or embedded figures (accuracy: $t(58)=-.293$, $p=.881$; RT: $t(58)=.447$, $p=.657$). Thus, synaesthetes share the cognitive advantages of people with clinically high levels of autistic traits ($AQ \geq 32$) despite having a mean AQ score that is substantially lower (~16 points or ~2 standard deviations).

In summary, Study 2 used objective measures of attention and visual cognition that have been linked to enhanced abilities in autism. We confirm that these tests are indeed related to variations in autistic tendencies in neurotypicals and synaesthetes insofar as better performance on these tests correlated positively with the Attention-to-detail subscale of the AQ. Moreover, we demonstrate that participants with synaesthesia outperform controls on these tests, consistent with their self-reported attentional characteristics.

General Discussion

This study had two aims. The first was to determine whether previously reported autistic traits in *grapheme-colour* synaesthesia are a characteristic of synaesthesia in general. The second aim was to provide evidence that these self-reported traits translate into real cognitive abilities. Both of these were confirmed. Synaesthetes report being higher on the autistic spectrum (using the AQ) and the effect is far greater for Attention-to-detail than the impairment-based symptoms of autism (although the latter is elevated too). Moreover, they report increased sensory sensitivity (a relatively new diagnostic feature of autism). Although we did not predict it *a priori*, both sensory sensitivity and attention-to-detail were related to the number of kinds of synaesthesia (a dose-like effect), this having been reported years earlier when our synaesthetes first volunteered for research. Neither sensory sensitivity nor attention-to-detail were strongly related to the type of synaesthesia. In the second study, we used two paradigms based on the previous literature on autism (change detection, embedded figures) that

we considered would be relevant specifically to the attention-to-detail trait. Synaesthetes outperformed controls on both measures, but did not differ in response times. Both tests were shown to be related to the AQ attention-to-detail score.

The exact nature of the cognitive mechanism that gives rise to differences in these traits and tasks is not clear. One possibility is that the mechanism lies at the level of attention. For example, Perceptual Load Theory states that the amount of sensory information that is processed post-attentively at any given time depends on the current demands of the task (the ‘load’) as well as an individual’s capacity (Lavie, 1995). It has been shown that people with autism appear to be able to process more sensory information even under conditions of high load (A. Remington, Swettenham, Campbell, & Coleman, 2009; A. M. Remington, Swettenham, & Lavie, 2012). That is, they appear to have a larger capacity and, hence, less attenuation of irrelevant sensory information. This could potentially explain performance on tasks such as change blindness (processing more sensory information in parallel enables better change detection) and the subjective symptoms (the sensory world feels very intense because there is less filtering of it).

Although this account has much to commend it, it fails to account for other data that suggests that, in both synaesthesia and autism, there are differences in perceptual processing that are not linked to attention. For example, both synaesthetes (Barnett et al., 2008) and people with autism (Vlamings et al., 2010) show enhanced visual-evoked potentials to high spatial frequency gratings that are known to be visually aversive for some people. There are also differences in basic perceptual abilities. There is a high rate of perfect pitch in autism (Heaton, 2003), and there is a genetic overlap between synaesthesia and perfect pitch (Gregersen et al., 2013). None of these observations fit with the idea of a wide attentional capacity. But they could perhaps be explained by theories such as ‘veridical mapping’ – a form of perceptual

pattern detection that has been argued to underpin both savant abilities in autism, as well as synaesthesia (Mottron et al., 2013).

Although we have emphasised the sensory/attentional symptoms (because they are statistically stronger), synaesthetes do have elevated scores on other aspects of the AQ and they have an increased vulnerability to clinically-relevant scores. As such, we are at pains to point out that this is a partial dissociation. Both synaesthesia and autism are likely to be complex genetic disorders (Geschwind, 2011) in that the affected genes may contribute to normal variation and aren't in themselves causal in the Mendelian sense. In this framework, genetic variations linked to increased sensory sensitivity would be a common source of vulnerability to both synaesthesia and autism, also explaining why the two tend to co-occur. The partial dissociation between the sensory/attentional features of autism (which are strongly implicated in synaesthesia) and the 'classic' symptoms of autism (which are less strongly implicated in synaesthesia) is important because it is not predicted by current models (e.g. Markram & Markram, 2010; Ramachandran & Oberman, 2006; Van de Cruys et al., 2014). It is possible that shifting upwards along the autistic spectrum (e.g. due to genetic differences) doesn't bring all the autistic traits upward at an equal rate but favours some over others. Another possibility is that the sensory/attentional symptoms and classic symptoms (e.g. poor social skills) have independent causes. If that is the case then there should be some neurodevelopmental condition that forms a double dissociation with synaesthesia; i.e. showing the social, communicative and imagination impairments of autism but little evidence of increased sensory sensitivity and increased attention-to-detail. Candidate disorders are anorexia nervosa (Westwood et al., 2016) and schizophrenia (Wouters & Spek, 2011) which are linked to an elevated AQ score, but not including attention-to-detail. Thus, although autistic traits are found in a wide variety of neurodevelopmental conditions there may be an important split, hitherto underappreciated, between the causes of sensory/attention and socio-cognitive

symptoms. Whatever the nature of the relationship, synaesthesia has the potential to become an important model for understanding the symptoms and neurodevelopment of autism.

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Table 1: The relationship between the phenomenology of grapheme-colour synaesthesia (automaticity-attention, and localisation), sensory sensitivity (GSQ) and AQ scores.

	Mean (SD)	Correlations, r (p)		
		GSQ	AQ Attention-to- Detail	AQ-Other
CLaN Automaticity-Attention	15.79 (3.65)	-.12 (.35)	.32 (.011*)	.05 (= .69)
CLaN Localisation	14.95 (6.46)	.09 (.46)	.19 (.13)	.18 (.15)

Figure 1: Sensory sensitivity, as measured by the Glasgow Sensory Questionnaire (GSQ), for controls and difference combinations of synaesthesia (mean and SEM). The numbers (0-5) denote the number of types of synaesthesia possessed, at least for those considered here. ASC = approximate level of performance of participants with a clinical diagnosis of autism (from Ward et al., 2017). GCS=grapheme-colour synaesthesia; SSS=sequence-space synaesthesia; lex_gus=lexical-gustatory synaesthesia and other taste/smell synaesthetic concurrents; mus_col = music-colour synaesthesia.

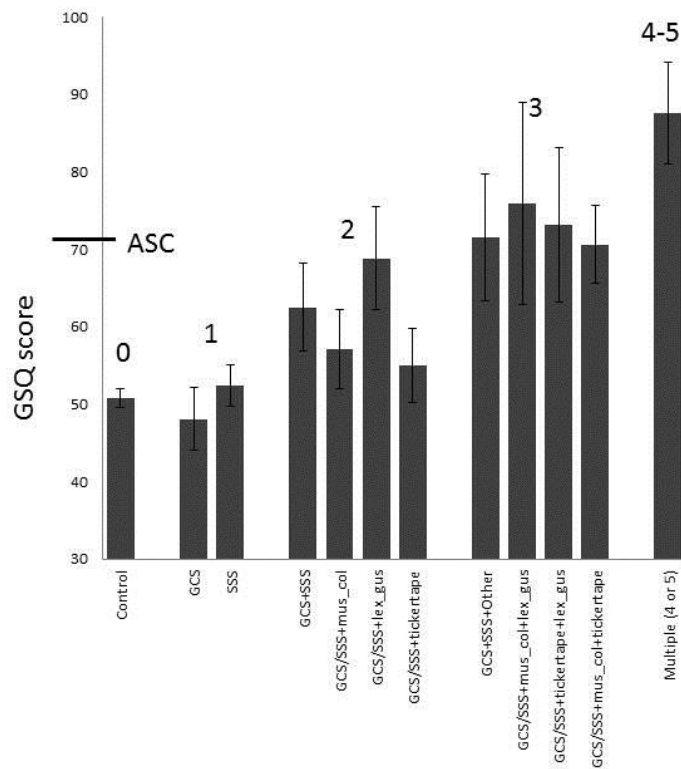


Figure 2. The Autism Spectrum Quotient (AQ) scores (on a 0-50 scale) divided into the Attention-to-detail subscale (average 10 items) and the remaining subscales (average of 40 items) for different kinds of synaesthetes and controls. The data is arranged in groups, from left to right, showing the number of kinds of synaesthesia (mean and SEM). The ASC sample reported by Ward et al. (2017) had a mean AQ of 40.2 comprised of 7.4 for Attention-to-detail and 32.8 for AQ-Other (indicated by the mark on the y-axis).

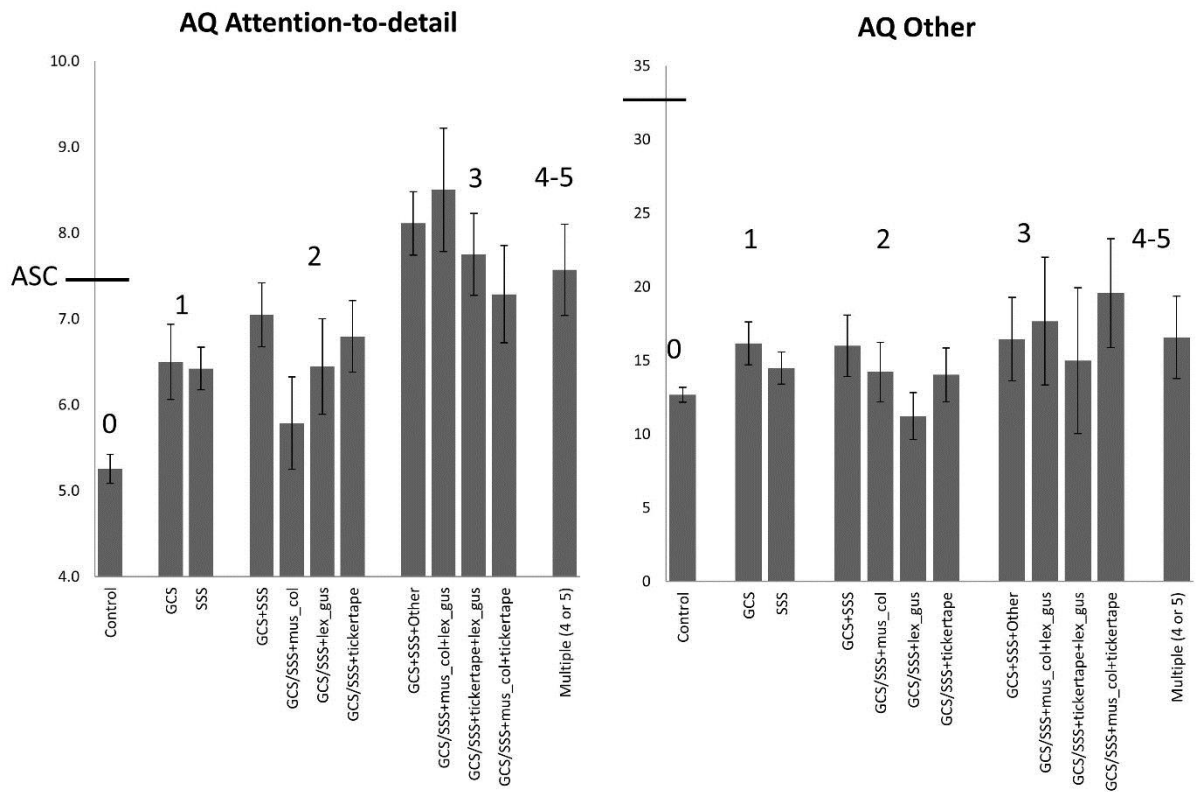


Figure 3: The proportion of participants with an AQ score ≥ 32 for controls (0 types of synaesthesia) and synaesthetes (1-5 kinds of synaesthesia).

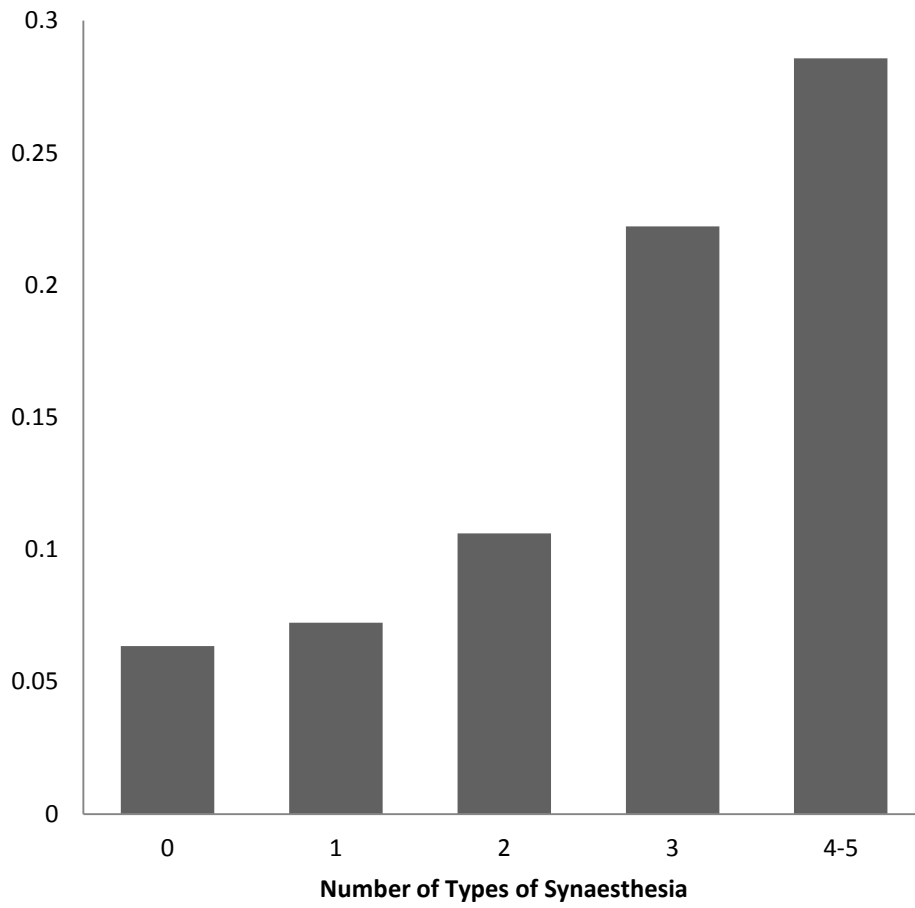


Figure 4: Examples of stimuli for the Embedded Figures Test (left; correct answer is 2) and Change Blindness test (right; changed object is the mirror on the left).

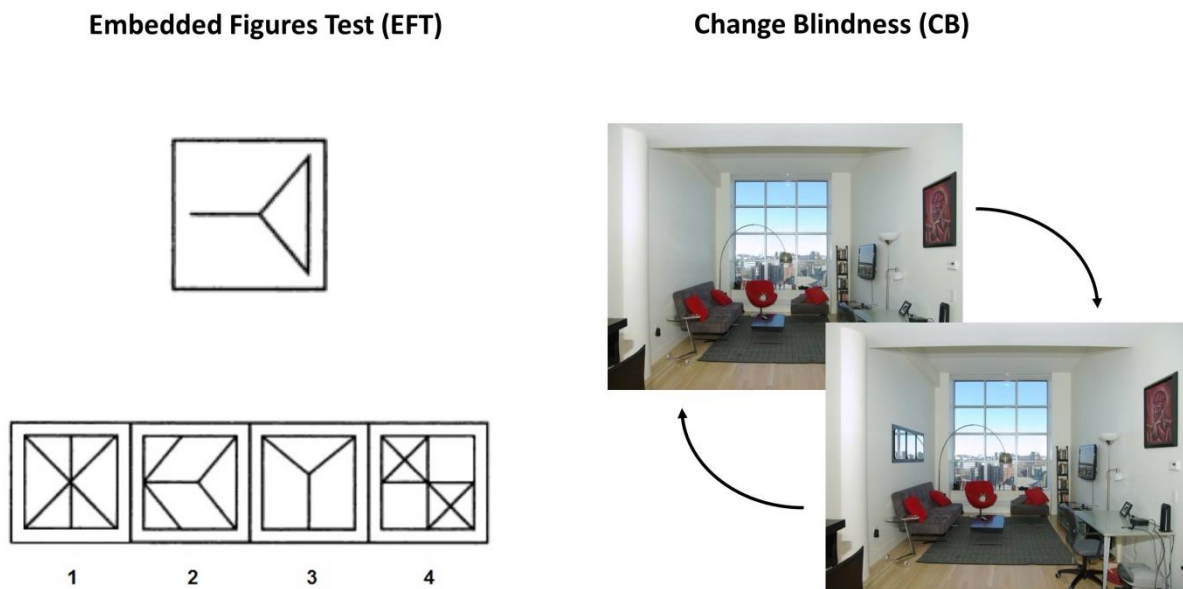


Figure 5: Performance on the Embedded Figures Test (left) and Change blindness (right). Synaesthetes outperform controls on both tasks: they are more accurate but have comparable response times.

