# Superior identification of component odours in a mixture is linked to autistic traits in children and adults.

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**Abstract:**

Most familiar odours are complex mixtures of volatile molecules which the olfactory system automatically synthesises into a perceptual whole. However, odours are rarely encountered in isolation, thus the brain must also separate distinct odour objects from complex and variable backgrounds. In vision, autistic traits are associated with superior performance in tasks that require focus on the local features of a perceptual scene. The aim of the present study was to determine whether the same advantage was observed in the analysis of olfactory scenes. To do this, we compared the ability of (i) Forty young adults (aged 16-35) with high (n=20) and low levels of autistic traits and, (ii) Twenty children (aged 7-11), with (n=10) and without an autism spectrum disorder diagnosis, to identify individual odour objects presented within odour mixtures. First, we used a 4-alternative forced choice task to confirm both adults and children were able to reliably identify eight blended fragrances, representing food related odours, when presented individually. We then used the same forced-choice format to test participants' ability to identify the odours when they were combined in either binary or ternary mixtures. Adults with high levels of autistic traits showed superior performance on binary but not ternary mixture trials. While children with an autism spectrum disorder diagnosis outperformed age matched neurotypical peers, irrespective of mixture complexity. These findings indicate, the local processing advantages associated with high levels of autistic traits in visual tasks are also apparent in a task requiring analytical processing of odour mixtures.

**Keywords:** Olfactory Perception, Odour Object, Autism Spectrum Disorder, Scene Analysis, Perceptual Style, Cognition

**Author Contributions:** SCW & DM conceived and designed the study, KW created and selected the fragrances, SCW & DM supervised test stimulus preparation & data collection. SCW analysed the data. SCW drafted the manuscript. All authors read, revised and approved the manuscript before submission.

**Abbreviations:** Alternative Forced Choice (AFC), Autism Spectrum Disorder (ASD), Autism Spectrum Quotient (AQ), The British Vocabulary Scale (BPVS).

## Introduction

Our ability to follow a conversation in a noisy restaurant or pick out a familiar face in a crowd attests to the brain's capacity for scene analysis, segmenting sensory inputs into coherent and meaningful component parts. This rapid, automatic process groups together information that emanates from the same source, allowing identification of specific objects against a complex background (Kondo, Van Loon, Kawahara, & Moore, 2017). While in vision and audition the processes underlying scene analysis have been widely studied from a range of disciplinary perspectives, the processes underlying olfactory scene analysis have received rather less attention (though see Gottfried, 2010; Rokni, Hemmelder, Kapoor, & Murthy, 2015; Sela & Sobel, 2010).

Real world odours, such as the aroma of coffee or the bouquet of a rose, are complex mixtures of volatile molecules that the olfactory system synthesises into a perceptual whole. From this perspective, olfactory perception is configural, forming a unitary percept, called an odour object, from volatile molecules emanating from a single source (Gottfried, 2010; Thomas-Danguin et al., 2014; Yeshurun & Sobel, 2010). This perceptual binding of stimulus features is so strong that, even with extensive training and experience, humans are poor at identifying the individual components of an odour mixture (Laing & Francis, 1989; Livermore & Laing, 1996). In order to identify and assess an odour object of interest, the olfactory system must also be able to segregate a target from surrounding odours emanating from other sources in the vicinity. Here, analytical processing is required to detect the presence or absence of a given odour object against complex and variable backgrounds (Wilson, 2016). Supportive of this capacity, Livermore and Laing (1998) reported that familiar odour objects were identified as if they were a single entity when presented in a mixture with other multicomponent items. As in other sensory systems, this process of pattern separation relies upon distinct neural representations for odour objects and their components, acquired through associative learning (Coureaud, Thomas-Danguin, Wilson, & Ferreira, 2014; Howard & Gottfried, 2014; Wilson & Stevenson, 2003).

However, whether stimuli are mixtures of multicomponent odour objects or of monomolecular odourants, human participants' capacity to identify component odours is very limited (Jinks & Laing, 1999; Laing & Francis, 1989; Laing & Glemarec, 1992a; Livermore & Laing, 1996, 1998). Participants' performance has been shown to decline rapidly with mixtures of more than three odours (Laing & Francis, 1989), even when attention is directly focused on finding a specific target (Jinks & Laing, 2001; Laing & Glemarec, 1992b). Indeed, humans' lack of ability to detect even a highly familiar target odour at above chance level, within a complex background, led to the suggestion such limitations on identification are physiological rather than cognitive (Jinks & Laing, 2001; Livermore & Laing, 1996). In support of this hypothesis, a calcium imaging study demonstrated the ability of mice to detect a target odour, against a variable multi-component background, was dependent on the degree of overlap between glomerular responses to target and background odours (Rokni et al., 2015). Thus demonstrating, olfactory scene analysis is constrained by limitations at the peripheral level.

However, scene analysis is not just a bottom-up process based on feature extraction and formation of perceptual objects, but is also dependent on top-down cognitive processes such as attention, expectation and memory (Kondo et al., 2017). Indeed, in both visual and auditory domains, individual differences in scene segmentation have been observed in the absence of any changes in low level stimulus processing, reflected by normal detection thresholds and acuity (Lin, Shirama, Kato, & Kashino, 2017; Pelofi, De Gardelle, Egré, & Pressnitzer, 2017; Takeuchi, Yoshimoto, Shimada, Kochiyama, & Kondo, 2017) . For example, individuals with Autism Spectrum Disorder (ASD) show superior performance on tasks that require focus on the local features of perceptual scenes, perhaps at the cost of making judgements about more global properties (Happé & Frith, 2006; Milne & Szczerbinski, 2009). In everyday tasks, such relative strengths and weaknesses are exemplified by the excellent ability of individuals with ASD to detect a target embedded in a complex visual scene, but also their difficulty listening selectively to speech in the presence of competing background noise (Lin et al., 2017; Mottron, Dawson, Soulières, Hubert, & Burack, 2006; Robertson & Baron-Cohen, 2017). Interestingly, preferences for local over global processing have also been observed in neurotypical individuals with high levels of autistic traits, suggesting they reflect a general difference in cognitive style rather than a specific clinical '*impairment*' (Cribb, Olaithe, Di Lorenzo, Dunlop, & Mayberry, 2016; Mottron, Burack, Iarocci, Belleville, & Enns, 2003; Turi, Burr, & Binda, 2018).

Atypical sensory processing is a core diagnostic feature of ASD with clinical estimates of the prevalence of sensory deficits in children and adults with autism ranging from 30-100% (Dawson & Watling, 2000; Tomchek & Dunn, 2007). Behaviourally, children with ASD show high levels of food refusal and selectivity (Bandini et al., 2010; Luisier et al., 2015). More broadly, in a neurotypical adult population, autistic traits were found to be positively associated with food neophobia (Stafford, Tsang, López, Severini, & Iacomini, 2017). Given the centrality of olfaction to ingestive behaviours, and the fact both clinical and parental reports frequently highlight atypical responses to tastes and smells (e.g. Rogers, Hepburn, & Wehner, 2003), several studies have specifically tested olfactory processing in ASD (see Schecklmann et al., 2013; Tonacci et al., 2017 for reviews). Though methodologies used are heterogenous and findings inconsistent (Addo, Wiens, Nord, & Larsson, 2017; Ashwin et al., 2014; Dudova et al., 2011; Koehler et al., 2018; Kumazaki et al., 2016; Tavassoli & Baron-Cohen, 2012), overall the literature indicates that while low-level processes such as detection and discrimination are intact, higher level functions such as odour identification may be impaired (Bennetto, Kuschner, & Hyman, 2007; Galle, Courchesne, Mottron, & Frasnelli, 2013; Koehler et al., 2018; Schecklmann et al., 2013; Suzuki, 2003; Tonacci et al., 2016; Wicker, Monfardini, & Royet, 2016).

While cognitive factors such as attention, learning and memory are acknowledged to influence chemosensory perception (Le Berre et al., 2008; Prescott, 2012; Sinding et al., 2015; Thomas-Danguin et al., 2014; White, Thomas-Danguin, Olofsson, Zucco, & Prescott, 2020), the vast majority of existing research on olfactory mixture perception focuses on bottom-up influences. To the best of our knowledge, whether the local processing advantages associated with high levels of autistic traits in visual scene analysis are also apparent in a task requiring analytical processing of odour mixtures, hasn't been addressed. To test this hypothesis, we first considered whether neuro-typical adults' ability to identify familiar, multi-component, food related odours presented in a mixture was associated with their levels of autistic-traits. We then compared the ability of children with a diagnosis of ASD to age and language matched peers in their performance on the same task.

## Experiment 1: Do young adults with high levels of autistic traits show enhanced capacity to identify multi-component food odours hidden in a mixture?

### Materials and Methods:

**Participants**

Forty-three participants (28 female), aged 16-35 (M = 20.09, S.D. +/- 5.00), free from current colds, respiratory infection or known olfactory dysfunction, took part in the study. Twenty-eight of the participants were recruited through a secondary school in the North West of England, the other 15 from the participant panel at Liverpool John Moores University, School of Natural Sciences & Psychology. Participants from the university panel received a £5 shopping voucher in return for completing the study. The study was approved by Liverpool John Moores Research Ethics committee and has been performed in accordance with the ethical standards laid down in the Declaration of Helsinki.

**Materials**

*Autism Spectrum Quotient (AQ)* (Baron-Cohen, Wheelwright, Skinner, Martin, & Clubley, 2001): The AQ measures autistic traits in the general population. The questionnaire consists of 50 statements and asks participants to indicate how much each one applies to them on a 4-point scale with descriptors: “Definitely agree”, “Slightly Agree”, “Slightly Disagree” and “Definitely Disagree.” For half the questions an “Agree” or “Slightly Agree” response indicates characteristics similar to those on the autistic spectrum and are scored as 1, whereas “Disagree” or “Slightly Disagree” responses are scored as 0. The other 50% of questions are reverse scored.

*Odour Stimuli:* Eight different food related fragrances were used, Blackcurrant, Chocolate Cake, Cola Bottles, Cucumber, Marzipan, Mint, Orange and Strawberry. 6 of the fragrances were blended by a professional perfumer (KW) and varied in complexity from 3 - 32 components. These fragrances were created for a previous project KW was involved in, aimed at supporting deafblind children to make food and drink choices (Murdoch, Gough, Boothroyd, & Williams, 2014). The remaining two

(Mint and Orange) were essential oils. All were diluted to 10% in ethanol, apart from mint which was diluted to 5% in ethanol. For testing, fragrances were pipetted onto individual quarters of filter paper (GE Healthcare Whatman™ 55mm diameter, Fisher Scientific), placed at the bottom of an Amber glass jar (Azpack™ 120ml, Fisher Scientific). The dose presented varied between 100 and 200 µl (2-4 drops from a Pasteur pipette) as follows: Mint (100 µl ), Chocolate Cake (150 µl), Cola Bottles (150 µl ), Marzipan (150 µl ), Orange (150 µl ), Strawberry (150 µl ), Blackcurrant (200 µl) and Cucumber (200 µl). These doses were determined based on iterative pilot testing with 9 naïve adults.

*Odour Identification Task:* Participants were asked to identify each of the 8 individual fragrances. Stimuli were presented in the same order shown in Table 1 or in reverse order. The aim was to establish that participants could reliably identify all the stimuli individually. On each trial, the participant was asked to smell the contents of the jar and to select which of 4 pictures shown best represented the fragrance presented (Figure 1A). In this phase only, where an incorrect answer was given, the participant was informed of the correct response. All participants completed this phase twice to ensure they could accurately identify all the individual stimuli on the second attempt.

*Binary and Ternary Mixtures Task:* Participants were asked to identify component fragrances within binary and ternary mixtures (see Table 1). In both phases, trials were completed in the same order presented in Table 1 or in reverse order. For a binary mixture, on each trial, participants were presented with a jar containing two pieces of fragrance impregnated filter paper. The experimenter indicated one of the odours present in the jar (see Mixture Component Table 1) and the participant was asked to identify which one of four pictures represented another odour also "hidden" there (see Targets in Table 1). E.g. told jar contains Chocolate Cake and must identify the smell of Strawberry is also present from four options (Figure 1B). For ternary mixtures the jars each contained three pieces of fragrance impregnated filter paper. The experimenter indicated two of the odours present in the jar and participants were asked to identify which one of 4 pictures represented another odour also "hidden" there. E.g. told jar contains Marzipan and Chocolate Cake and they had to identify the smell of Mint is also present from four options.

On all trials, the 4 response options were a subset of the 8 test fragrances. All participants used the same response card for a given trial and the incorrect options were a random selection of the possible alternatives, see Figure 1A. A given image appeared across the whole set of response cards an approximately equal number of times.

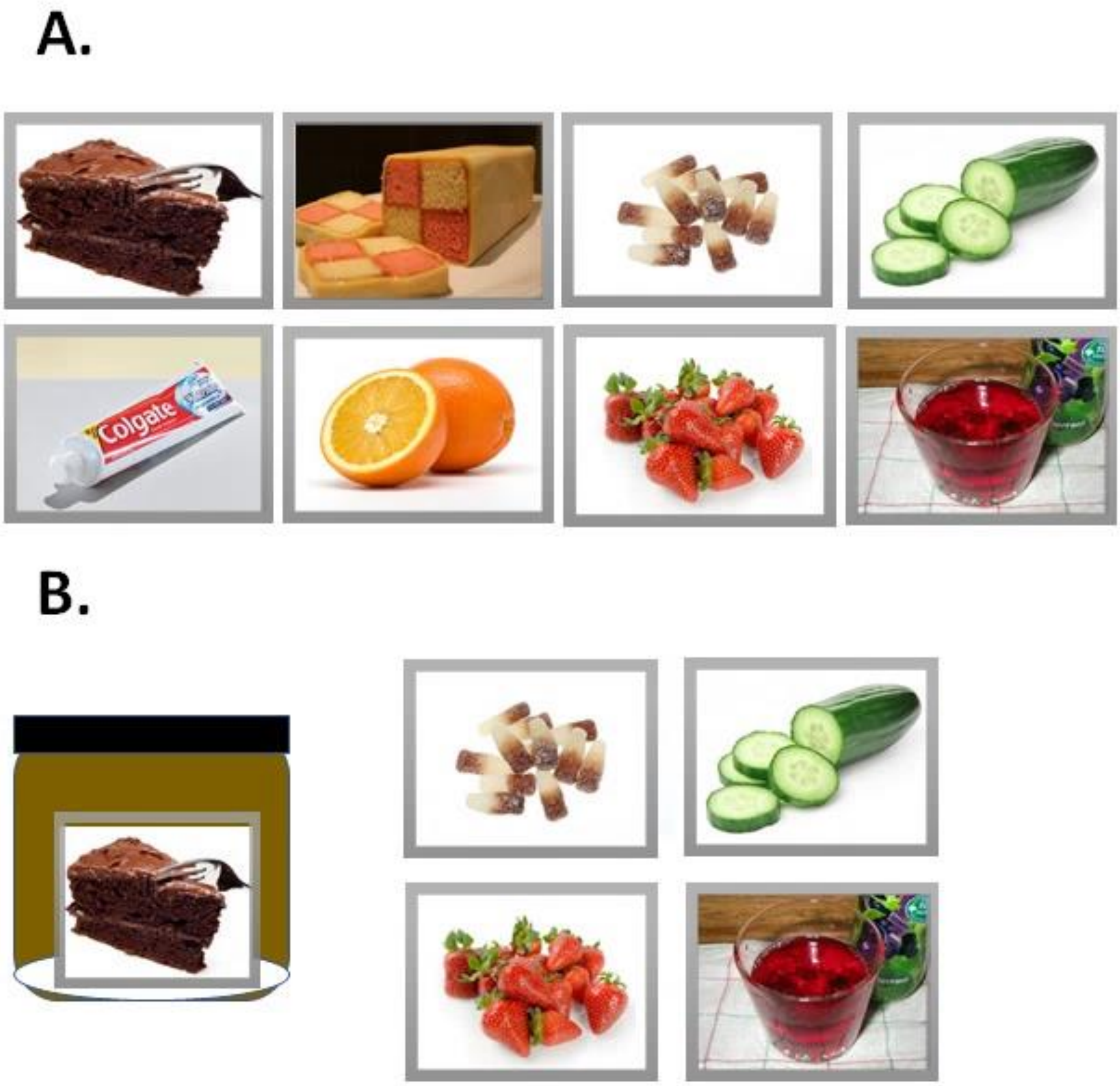


*Figure 1: A. Shows the images used to represent the eight odours in the study. B. Depicts an exemplar binary mixture trial. Here participants were told there was Chocolate Cake in the jar and had to identify which one of the 4 options presented was also "hidden" in there.*

*Table 1 shows the contents of each jar during the 3 experimental phases. Identification was the only phase where feedback was given and was performed twice before completion of the Binary and then the Ternary phase. For approximately half the participants, the stimuli within each phase were presented in the same order shown here, the other half received them in reverse order. Target refers to the odour participants were required to identify for successful completion of each trial. Mixture Components are the additional fragrances participants were told were present on a given trial.*

| Trial Number | Mixture Components | Mixture Components | Target |
|---|---|---|---|
| **Phase 1: Identification** | | | |
| 1 | | | Chocolate Cake |
| 2 | | | Cola Bottles |
| 3 | | | Blackcurrant |
| 4 | | | Mint |
| 5 | | | Cucumber |
| 6 | | | Marzipan |
| 7 | | | Orange |
| 8 | | | Strawberry |
| **Phase 2: Binary Mixtures** | | | |
| 9 | | Marzipan | Blackcurrant |
| 10 | | Cucumber | Marzipan |
| 11 | | Chocolate Cake | Strawberry |
| 12 | | Orange | Chocolate Cake |
| 13 | | Mint | Cola Bottles |
| 14 | | Cola Bottles | Orange |
| **Phase 3: Ternary Mixtures** | | | |
| 15 | Cucumber | Mint | Strawberry |
| 16 | Mint | Strawberry | Marzipan |
| 17 | Cola Bottles | Blackcurrant | Cucumber |
| 18 | Orange | Strawberry | Blackcurrant |
| 19 | Marzipan | Chocolate Cake | Mint |
| 20 | Cola Bottles | Chocolate Cake | Orange |

**Procedure**

Testing took place on a 1:1 basis in a quiet room. Participants sat opposite the experimenter at a table and first completed the Odour Identification Task. Jars were presented individually. On each trial, the lid was unscrewed and held away from the participant for approx. 5 seconds while the experimenter gave them instructions, the jar was then placed under the participant's nose, around 5 cm away. Participants were instructed to smell the contents of the jar and asked to indicate which of the four pictures presented best represented the odour they smelled in the jar. For the Mixtures

Task, participants were told one (binary mixtures) or two (ternary mixtures) of the odours in the jar and asked to identify which of 4 images presented best represented the other odour that was present. To avoid olfactory fatigue, there was a 30 second interval between trials and a two-minute break between each phase of testing. Participants were then asked to complete the AQ questionnaire, before being thanked for their time and debriefed.

**Data Analysis**

On a participant by participant basis, the proportion of correct answers given for the Identification phase as well as in Binary and Ternary Mixtures phases were calculated. Participants were separated into two groups according to their score on the AQ, using a median split (Iacobucci, Posavac, Kardes, Schneider, & Popovich, 2015). The median score of the sample was 19. All participants scoring 18 or under made up the Low AQ group (N=20, Mean AQ= 13.35, Range 5-18), while all participants scoring 20 or over made up the High AQ group (N=20, Mean 24.4, Range 20-35). There were 7 females in the low AQ and 13 females in the high AQ group. The mean age of the Low AQ group was 20.9 (S.D. = 3.66) and of the High AQ group was 19.1 (S.D.4.99) The was no significant difference in the age of the two groups ($t(38)=1.19$, $p=0.24$). The three participants scoring 19 on the AQ (1 Male) were excluded from further analysis, though their addition to either the Low or High AQ group does not materially change the results reported. Data were analysed using SPSS (version 26). The Identification and Mixture Phases were analysed separately using a Generalized Linear Model to conduct binomial logistic regression on proportion of correct responses, participant was entered as a random factor.

## Results

*Odour Identification*

As shown in Figure 2, both groups performed near ceiling on the initial Identification Task, indicating that, even before feedback, participants found the odours used familiar and recognisable. There was no significant difference in the performance of the two groups (Wald $\chi^2$ (1) = 2.15, p=.143).

*Odour Mixtures*

A two-predictor logistic model was fitted to the data to test the hypotheses that Complexity and AQ Group would predict proportion of olfactory stimuli correctly identified and that these factors would interact (See Table 2). This revealed there was a significant Group x Mixture Complexity interaction (p=.028). As shown in Figure 2, this reflects the fact that while the High AQ group performed better than the Low AQ group on binary trials (p=.003), there was no significant difference in their performance on ternary trails (p=.53).

When examining the performance of the Hi AQ Group alone, there was a significant effect of Mixture Complexity (Wald's $\chi^2$ (1) = 5.54, p=.02), reflecting poorer performance on the ternary than the binary mixtures (see Figure 2).

Single sample t-tests confirmed that performance by both groups, at both phases, was significantly above chance (all ps $\leq$ 0.002).

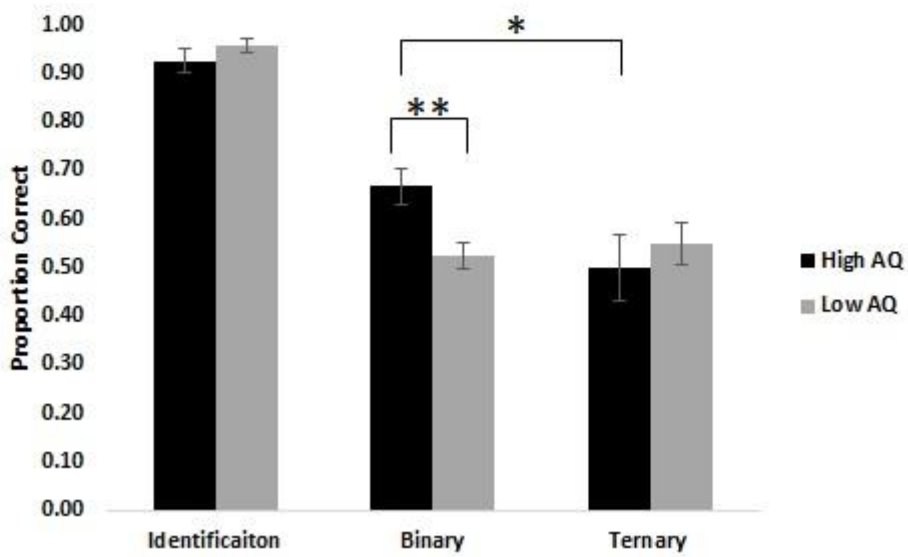


*Figure 2: Shows the mean proportion (+/- S.E.) of correct responses made by the High and Low AQ Groups in each of the 3 phases of the experiment. There was no difference between the Groups in the Identification phase. In the Mixtures phase, the High AQ group performed significantly better on the Binary trials than the Low AQ group (**p=0.003), but there was no difference in the two groups' performance on the more complex Ternary mixtures. Only the High AQ group showed a significant effect of mixture complexity, performing significantly worse on the Ternary than the Binary trials (*p=0.02).*

***Table 2: Logistic Regression statistics for the mixtures phase of the task with the dependent variable Proportion Correct and the independent variables AQ Group and Mixture Complexity.***

| **Predictor** | **β** | **SE β** | **Wald's $\chi^2$** | **df** | **p** |
|---|---|---|---|---|---|
| Constant | <.001 | .267 | <.001 | 1 | 1.00 |
| Mixture Complexity | .693 | .294 | 5.54 | 1 | .019 |
| AQ Group | .201 | .318 | .40 | 1 | .527 |
| AQ group * Mixture Complexity | -.794 | .361 | 4.84 | 1 | .028 |
| **For Binary mixtures** | | | | | |
| Constant | .693 | .168 | 17.08 | 1 | <.001 |
| AQ Group | -.593 | .200 | 8.81 | 1 | .003 |
| **For Ternary mixtures** | | | | | |
| Constant | <.001 | .267 | <.001 | 1 | 1.00 |

| | | | | | |
|---|---|---|---|---|---|
| AQ group | .201 | .318 | .399 | 1 | .527 |

## Discussion

Using a 4-alternative forced choice (AFC) task, we found that adults were able to identify which of 8 familiar food related odours were the "hidden" components of binary and ternary mixtures at above chance level. Those participants who reported above average levels of autistic traits performed differently on the task than the group reporting average or below average levels of autistic traits. That is, while the Low AQ group performed similarly on both binary and ternary mixture trials, the High AQ Group showed a superior level of performance on the binary mixtures trials that declined to the same level as the Low AQ group on the ternary trials.

This differential effect of mixture complexity on the performance of the two groups suggests they approached the task differently, perhaps employing different perceptual or attentional strategies. While performance on mixtures tasks is reliably reported to decline with increasing complexity, a significant decline in performance from binary to ternary mixtures is not always apparent, with variation probably reflecting differences in task design and difficulty (Jinks & Laing, 2001; Laing & Francis, 1989; Laing & Glemarec, 1992a; Livermore & Laing, 1998). Thus, it isn't clear whether our current findings reflect the fact the High AQ group's strategy was only beneficial on binary mixture trials or whether, in the Low AQ group, increasing familiarity with the odour stimuli or adoption of a response strategy eliminated any effect of complexity on performance.

However, the superior performance of the High AQ group on the binary mixtures trials provides some support for our hypothesis that the local processing style, associated with high levels of autistic traits, confers an advantage in olfactory scene analysis, just as it does in visual and auditory domains (Cribb et al., 2016; Lin et al., 2017). To address this question further, we repeated our initial study with children, comparing aged matched groups with and without a diagnosis of ASD. In order to ensure differences in language and comprehension ability did not confound our findings, we used the same non-verbal, 4-AFC procedure as in the present study. In addition, we tested the two groups' receptive vocabulary.

## Experiment 2: Do children with ASD show enhanced ability to identify multi-component food odours hidden in a mixture compared to neurotypical peers matched for age and verbal ability?

### Materials & Methods

#### Participants

Twenty children aged 7 -11 years, free from current colds, respiratory infection or known olfactory dysfunction, were recruited from a primary school in North West England. Ten (8 Male, Mean Age=9.9, S.D. +/- 0.99) were recruited from a Special Educational Needs unit and had received a diagnosis of ASD by a trained clinician based on DSM IV-TR (American Psychiatric Association, 2000) criteria. In addition, ten typically developing children (4 Male, Mean Age=9.4, S.D. +/- 1.17) were recruited from mainstream classes in the same school. The study was approved by Liverpool John Moores University's Psychology Research Ethics Committee and has been performed in accordance with the ethical standards laid down in the Declaration of Helsinki. Parents / Guardians gave written informed consent for their child to participate.

#### Measures

*The British Picture Vocabulary Scale – Second Edition (BPVS-II):* is an untimed test of a child's receptive vocabulary level for Standard English. On each trial the examiner reads a word and the child is asked to select which of 4 pictures best illustrates the word's meaning. Participants are first introduced to the test and then, based on their age, their basal set of stimuli (one on which they make one or no errors) is established. The test continues with word sets of increasing difficulty until a ceiling set (a set of stimuli on which they make eight or more errors) is reached (Dunn, Dunn, Whetton, & Burley, 1997; Mahon & Crutchley, 2006). A total of 14 sets of 12 items is available.

*Odour Stimuli:* 7 of the 8 fragrances, prepared and presented as in experiment 1, were used in this study (see Table 2). The Cucumber fragrance was omitted as initial testing indicated children did not reliably identify it when presented individually, even after feedback. The Odour Identification and Odour Mixture Tasks were presented as described in experiment 1. Table 2 shows the mixture compositions presented.

*Table 3 shows the contents of each jar during the 3 experimental phases. Identification was the only phase where feedback was given and was performed twice before completion of the Binary and then the Ternary phase. The stimuli within each phase were presented in the same order shown here. Target refers to the odour participants were required to identify for successful completion of each trial. Mixture Components are the additional fragrances participants were told were present on a given trial.*

| Trial Number | Mixture Components | Mixture Components | Target |
|---|---|---|---|
| **Phase 1: Identification** | | | |
| 1 | | | Chocolate Cake |
| 2 | | | Cola Bottles |
| 3 | | | Blackcurrant |
| 4 | | | Mint |
| 5 | | | Marzipan |
| 6 | | | Orange |
| 7 | | | Strawberry |
| **Phase 2: Binary Mixtures** | | | |
| 8 | | Marzipan | Blackcurrant |
| 9 | | Chocolate Cake | Strawberry |
| 10 | | Orange | Chocolate Cake |
| 11 | | Mint | Cola Bottles |
| 12 | | Cola Bottles | Orange |
| 13 | | Blackcurrant | Marzipan |
| **Phase 3: Ternary Mixtures** | | | |
| 15 | Mint | Strawberry | Marzipan |
| 16 | Orange | Strawberry | Blackcurrant |
| 17 | Marzipan | Chocolate Cake | Mint |
| 18 | Cola Bottles | Chocolate Cake | Orange |
| 19 | Orange | Mint | Strawberry |
| 20 | Cola Bottles | Blackcurrant | Chocolate Cake |

**Procedure**

Testing took place on a 1:1 basis in a quiet room. Participants sat opposite the experimenter at a table and first completed the BPVS. Next, during the Odour Identification Task, the 7 jars were presented individually. On each trial, the lid was unscrewed and held away from the participant for approx. 5 seconds while the experimenter gave them instructions, the jar was then placed under the participant’s nose, around 5 cm away and participants were asked to indicate which of the four pictures presented best represented the odour they smelled in the jar. At this stage any errors were corrected by the experimenter. This identification phase was repeated twice with each of the test odourants to ensure all participants could identify all individual odours. For binary and ternary mixtures, participants were told one or two of the odours in the jar and asked to identify which of 4 images presented best represented the other odour that was present. To avoid olfactory fatigue, there was a 30 second interval between trials and a two-minute break between each phase of testing. In phases 2 & 3, no feedback was given.

**Data Analysis**

On a participant by participant basis, the proportion of correct answers given for the Identification Task, as well as in Binary and Ternary Mixtures phases, was calculated. Receptive vocabulary raw scores were calculated according to the BPVS-II scoring manual. Data were analysed using SPSS (version 26). Independent sample t-tests were used to compare the groups' performance on the BPVS. The Identification and Mixture Phases were analysed separately using a Generalized Linear Model to conduct binomial logistic regression on proportion of correct responses, participant was entered as a random factor.

## Results

*Receptive Vocabulary*

The mean receptive vocabulary score for the ASD group was 107.4 (S.D. 24.28) and for the Control group was 110.8 (S.D. 23.16). An independent samples t-test revealed there was no significant difference in receptive vocabulary of the two groups, $t(18)= 0.32$, $p=0.75$.

*Odour Identification*

As shown in Figure 3, both groups performed around ceiling level on the initial Identification Task, indicating that, even before feedback, the target odours were familiar and recognisable to the children. There was no significant difference in the performance of the two groups (Wald's $\chi^2$ (1) = 0.99, p=.321).

*Odour Mixtures*

A two-predictor logistic model was fitted to the data to test the hypotheses that Complexity and ASD Diagnosis would predict proportion of olfactory stimuli correctly identified and that these factors would interact (See Table 4). This revealed no significant effect of Complexity (p=.259) and no significant interaction between Complexity and Diagnosis (p=.791). There was however a significant effect of Diagnosis (p=.022), consistent with individuals with ASD showing superior performance on the olfactory task (Figure 3).

Single sample t-tests confirmed that performance by both groups, at both phases, was significantly above chance (all p's $\leq$ 0.002).

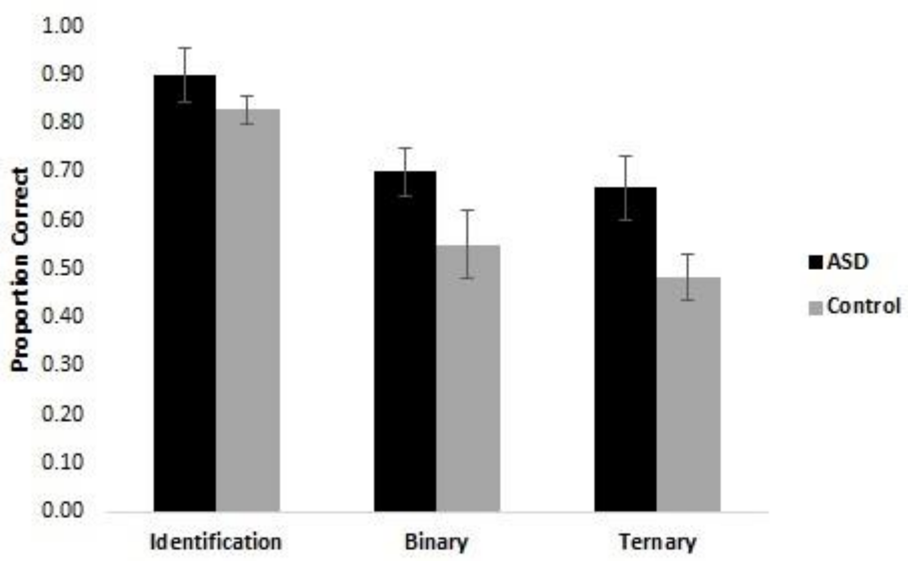


*Figure 3: Shows the mean proportion of correct responses given by the two groups over the 3 phases of the experiment (+/-S.E.). There was no difference in their performance on the initial Identification phase (p=0.32). However, the ASD Group performed significantly better than the Control Group on the Mixtures phases (p=0.02).*

***Table 4: Logistic Regression statistics for the mixtures phase of the task with the dependent variable Proportion Correct and the independent variables Diagnosis and Mixture Complexity.***

| **Predictor** | **β** | **SE β** | **Wald's $\chi^2$** | **df** | **p** |
|---|---|---|---|---|---|
| Constant | -.067 | .175 | .145 | 1 | .704 |
| Diagnosis | .760 | .331 | 5.27 | 1 | .022 |
| Mixture Complexity | .267 | .237 | 1.27 | 1 | .259 |
| Diagnosis * Mixture Complexity | -.113 | .428 | .070 | 1 | .791 |

## Discussion

The findings of the present study show that using a 4AFC task children, like adults, were able to identify familiar food related odours hidden in binary and ternary mixtures, at above chance level. Furthermore, in line with our hypothesis, children with an ASD diagnosis were better at this task than neurotypical peers matched for age and language ability. This is consistent with the superior level of performance children with ASD have been reported to show on various scene analysis tasks in the visual domain (Cribb et al., 2016; Happé & Frith, 2006; Mottron et al., 2003). Thus, the finding suggests that cognitive factors are playing a role in olfactory scene analysis.

While the overall level of performance displayed by the children in our sample was similar to the adults in our previous study, here neither group showed any effect of mixture complexity on performance. This is not necessarily surprising given the mixtures used in the present study were relatively simple (Laing & Francis, 1989; Laing & Glemarec, 1992a). Limitations on identification of components within complex mixtures are thought to relate to the bottom-up constraints on odour coding (Jinks & Laing, 1999; Livermore & Laing, 1996). For example, neither training  nor-selective attention procedures improve humans' capacity to identify components in mixtures of 5-8 odourants (Jinks & Laing, 1999). Given our interest here was in identifying top-down cognitive factors that might also affect capacity to analyse odour mixtures, we wanted to ensure performance was not restricted by physiological limitations of the olfactory system. Thus, we used only simple binary and ternary mixtures within which, it was anticipated, participants would be able to identify components with some level of accuracy (Jinks & Laing, 1999, 2001).

While sensory sensitivities are a core diagnostic feature of ASD and known to affect all modalities, most research to date has focused on the visual, auditory and somatosensory domains, neglecting the chemical senses (Cascio, Moore, & McGlone, 2019; Haigh, 2018; Robertson & Baron-Cohen, 2017; Thye, Bednarz, Herringshaw, Sartin, & Kana, 2018 for recent reviews). Indeed, the current limited literature on olfactory processing in children with ASD is rather mixed, most likely reflecting the broad range of methodological approaches used, as well as some lack of control for potentially confounding factors like IQ and language ability (Schecklmann et al., 2013; Tonacci et al., 2016).

While the general consensus is that low level olfactory processing functions, like detection threshold and discrimination ability, are intact in this population (though see Koehler et al., 2018), the findings from the present study indicate that studying olfactory processing in the context of higher order perceptual functions, like object recognition and scene analysis, would be insightful. For example, given the importance of olfaction to our engagement with and enjoyment of food, further investigation into how perceptual differences relate to the high rates of restricted and atypical eating reported in ASD would be beneficial (Bennetto et al., 2007; Croy, Nordin, & Hummel, 2014; Luisier et al., 2015). Food neophobia is a common concern in ASD, and is associated with restrictive eating regimes (Jacobi, Schmitz, & Stewart Agras, 2008; Luisier et al., 2015; Stafford et al., 2017; Wallace, Llewellyn, Fildes, & Ronald, 2018). Perceived complexity is known to be an important contributor to hedonic ratings of foods and beverages (Palczak, Blumenthal, Rogeaux, & Delarue, 2019). Given individuals who report high levels of food neophobia rate complex foods as less acceptable than bland foods (Olabi et al., 2015), it seems possible that, in ASD, a locally focused processing style may result in higher levels of perceived odour and flavour complexity, resulting in decreased liking and greater food rejection.

## General Discussion & Conclusion

Taken together, the findings of the present studies indicate that individual differences exist in humans' capacity to identify familiar target odour objects from within simple binary and ternary mixtures. The superior performance of children with ASD, and adults with high levels of autistic traits, is hypothesised to reflect a local processing bias, which is well established in these groups within the visual domain (Cribb et al., 2016; Happé & Frith, 2006; Milne & Szczerbinski, 2009; Mottron et al., 2003; Turi et al., 2018).

Studying individual differences has been advocated as a useful approach to understanding cognitive functions. In particular, in identifying domain-general versus domain-specific processes. For example, the extent to which neurotypical adults show a bias for global over local processing was found to predict both object and face recognition performance (Gerlach & Starrfelt, 2018). An insightful future approach would be to determine whether global-precedence effects in vision are also predictive of odour object recognition. If perceptual style is domain-general, performance on established visual tests of perceptual style would be associated with ability to identify component odours in simple mixtures.

While a number of visual tasks have been widely used to measure preferences for global versus local processing, such as the Embedded Figures, Block Design, Navon's Hierarchical Figures and The Rod and Frame Task, several of these tests do not correlate strongly with each other, indicating they are measuring different constructs (Milne & Szczerbinski, 2009). For example, visual search tasks test the ability of participants to identify a target object within a background array. Whereas, in the Embedded Figures Test the target is a direct component of a larger meaningful whole. In neurotypical adults, performance on these two tasks was not correlated (Milne & Szczerbinski, 2009). The task used in the present study, similarly to previous tests of olfactory scene analysis, can be considered most analogous to a visual search task, where a target odour must be segmented from amongst a background (Rokni et al., 2015). For the task to be more analogous to the embedded figures task participants could be asked to identify components of a blended mixture which generates a separate, meaningful percept to that elicited by any of the constituent odorants alone. For example, when combined in the correct proportions, a caramel and a strawberry odour have been reported to smell like pineapple (Barkat, Le Berre, Coureaud, Sicard, & Thomas-Danguin, 2012; Le Berre et al., 2008). Since the brain has distinct configural and elemental representations of odour objects, analysis of the components of simple blends should be possible (Coureaud et al., 2014; Howard & Gottfried, 2014). Through the design and validation of tasks that tap specific aspects of perception and cognition, a greater understanding of the mechanisms underlying olfactory scene-analysis, and their relationship to processing in other sensory domains, can be gained.

In the present studies, the task instructions guided participants towards an analytical processing style, by directing them to identify a “hidden” component amongst known distractors. While selective attention procedures don’t necessarily improve adults’ analysis of complex odour mixtures (Laing & Glemarec, 1992b), studies of odour mixture and flavour processing have previously shown that such analytical instructions actively inhibit acquisition of configural flavour representations (Le Berre et al., 2008; Prescott, 2012; Prescott & Murphy, 2009). Given analytical processing has also been shown to inhibit liking (Prescott, 2012; Prescott, Lee, & Kim, 2011), further work is needed to determine whether the superior performance associated with high autistic traits reported here reflects a spontaneous perceptual processing bias, or simply greater ease adhering to the task requirements. A spontaneous bias, leading to a failure to form configural representations of odours and flavours, may offer some explanation for the heightened neophobia reported in ASD (Jacobi et al., 2008; Luisier et al., 2015; Stafford et al., 2017; Wallace et al., 2018).

By selecting stimuli and designing a study that was equally accessible to children and adults, there are some limitations to the present findings which warrant further investigation. For example, to keep testing times manageable, we did not consider every possible combination of stimuli from our set. Thus, we do not know whether, within a given mixture, some targets were more readily identified than others (Jinks & Laing, 1999; Laing & Francis, 1989; Laing & Glemarec, 1992b; Livermore & Laing, 1998). Studies systematically analysing perception of simple odour mixtures have determined that relative odour intensity is one of the most important predictors of the perceived quality of a mixture (Atanasova et al., 2005; Ferreira, 2012; Olsson, 1994). While the most common percept elicited by a binary mixture is an average of its components, even slight variations in intensity of component odours, as well as their quality and hedonics, can make some components more readily identified against the background than others (Ferreira, 2012; Olsson, 1994, 1998). Thus, further work is needed to confirm the generalisability of our findings to other odour stimuli and determine which specific properties of an odour mixture, and its components, are the strongest predictors of the observed result. Secondly, our fragrances were formulated in ethanol which, while producing a good quality stimulus, has a notable trigeminal effect (Carstens, Kuenzler, & Handwerker, 1998). It has previously been reported that, unlike their neurotypical peers, children with ASD fail to modulate their sniff response depending on the valence and intensity of an odour (Rozenkrantz et al., 2015). Since chemical activation of the trigeminal nerve also generates such reflexive motor responses (Ho & Kou, 2000), it is possible that that there were differences in the spontaneous sniff response of those with high and low autistic traits in the present studies. However, since this mechanistic difference was not predictive of odour perception (Rozenkrantz et al., 2015), it seems unlikely it is the main driver of our findings.

In conclusion, the studies reported here provide initial evidence that variation in cognitive style is associated with differential performance on a task requiring elemental analysis of an odour mixture.

This is consistent with previous findings in visual and auditory domains. Thus, future work investigating the mechanisms underlying olfactory scene analysis should further consider top-down in addition to bottom-up factors.

## Conflict of interests

KW is employed by Unilever, PLC. When the study was conducted, KW was employed by Seven Scent Ltd, Manchester. Neither Seven Scent nor Unilever had any role in the design and implementation of the study nor the decision to publish.

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## Figure legends

**Figure 1:** A. shows the images used to represent the eight odours used in the study. B. Depicts an exemplar binary mixture trial. Here participants were told there was Chocolate Cake in the jar and had to identify which one of the 4 options presented was also "hidden" in there.

**Figure 2:** Shows the mean proportion (+/- S.E.) of correct responses made by the High and Low AQ Groups in each of the 3 phases of the experiment. There was no difference between the Groups in the Identification phase. In the Mixtures phase, the High AQ group performed significantly better on the Binary trials than the Low AQ group (**p=0.003), but there was no difference in the two groups' performance on the more complex Ternary mixtures. Only the High AQ group showed a significant effect of mixture complexity, performing significantly worse on the Ternary than the Binary trials (*p=0.02).

**Figure 3:** Shows the mean proportion of correct responses given by the two groups over the 3 phases of the experiment (+/-S.E.). There was no difference in their performance on the initial Identification phase (p=0.32). However, the ASD Group performed significantly better than the Control Group on the Mixtures phases (p=0.02).

**Table Titles**

**Table 1:** Shows the contents of each jar during the 3 experimental phases. Identification was the only phase where feedback was given and was performed twice before completion of the Binary and then the Ternary phase. For approximately half the participants, the stimuli within each phase were presented in the same order shown here, the other half received them in reverse order. Target refers to the odour participants were required to identify for successful completion of each trial. Mixture Components are the additional fragrances participants were told were present on a given trial.

**Table 2:** Logistic Regression statistics for the mixtures phase of the task with the dependent variable Proportion Correct and the independent variables AQ Group and Mixture Complexity.

**Table 3**: Shows the contents of each jar during the 3 experimental phases. Identification was the only phase where feedback was given and was performed twice before completion of the Binary and then the Ternary phase. The stimuli within each phase were presented in the same order shown here. Target refers to the odour participants were required to identify for successful completion of each trial. Mixture Components are the additional fragrances participants were told were present on a given trial.

**Table 4:** Logistic Regression statistics for the mixtures phase of the task with the dependent variable Proportion Correct and the independent variables Diagnosis and Mixture Complexity.