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Talent in autism: hyper-systemizing, hyper-attention to detail and sensory hypersensitivity

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We argue that *hyper-systemizing* predisposes individuals to show talent, and review evidence that hyper-systemizing is part of the cognitive style of people with autism spectrum conditions (ASC). We then clarify the hyper-systemizing theory, contrasting it to the weak central coherence (WCC) and executive dysfunction (ED) theories. The ED theory has difficulty explaining the existence of talent in ASC. While both hyper-systemizing and WCC theories postulate *excellent attention to detail*, by itself excellent attention to detail will not produce talent. By contrast, the hyper-systemizing theory argues that the excellent attention to detail is directed towards detecting 'if p, then q' rules (or [input–operation–output] reasoning). Such law-based pattern recognition systems can produce talent in systemizable domains. Finally, we argue that the excellent attention to detail in ASC is itself a consequence of *sensory hypersensitivity*. We review an experiment from our laboratory demonstrating sensory hypersensitivity detection thresholds in vision. We conclude that the origins of the association between autism and talent begin at the sensory level, include excellent attention to detail and end with hyper-systemizing.

Keywords: autism; Asperger syndrome; savant

1. INTRODUCTION

Savantism is found more commonly in autism spectrum conditions (ASC) than in any other neurological group (see Howlin in press), and the majority of those with savantism have an ASC (Hermelin 2002). This 'comorbidity' (or to use the more neutral term 'co-occurrence', since comorbidity is a strange term to use when one of the characteristics is not a disability) shows us that these two profiles are associated well above chance. This forces us to ask: why the link between talent and autism?

In this paper, we argue that while savantism (defined as prodigious talent) is only seen in a subgroup of people with ASC, a universal feature of the autistic brain is *excellent attention to detail* (Shah & Frith 1993; Jolliffe & Baron-Cohen 1997; O'Riordan *et al.* 2001). Furthermore, we argue that excellent attention to detail exists in ASC because of evolutionary forces positively selecting brains for *strong systemizing*, a highly adaptive human ability (Baron-Cohen 2008).

Strong systemizing requires excellent attention to detail, and in our view the latter is in the service for the former. Attention occurs at an early level of cognition, while systemizing is a fairly high-level aspect of cognition. Next, we argue that one can trace excellent attention to detail to its basis in *sensory hypersensitivity* in ASC. Finally, in this paper, we review an experiment from our laboratory in vision, which points to sensory hypersensitivity in ASC, and briefly describe our research programme exploring this in other modalities (olfaction, hearing and touch). But first, what is systemizing?

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One contribution of 18 to a Discussion Meeting Issue 'Autism and talent'.

2. SYSTEMIZING

Talent in autism comes in many forms, but a common characteristic is that the individual becomes an expert in *recognizing repeating patterns* in stimuli. We call this systemizing, defined as the drive to analyse or construct systems. These might be any kind of system. What defines a system is that it follows *rules*, and when we systemize we are trying to identify the rules that govern the system, in order to predict how that system will behave (Baron-Cohen 2006). These are some of the major kinds of system:

- —*collectible* systems (e.g. distinguishing between types of stones or wood);
- —*mechanical* systems (e.g. a video recorder or a window lock);
- —*numerical* systems (e.g. a train timetable or a calendar);
- —*abstract* systems (e.g. the syntax of a language or musical notation);
- —*natural* systems (e.g. the weather patterns or tidal wave patterns);
- —*social* systems (e.g. a management hierarchy or a dance routine with a dance partner); and
- —*motoric* systems (e.g. throwing a Frisbee or bouncing on a trampoline).

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In all these cases, one systemizes by noting regularities (or structure) and rules. The rules tend to be derived by noting if p and q are *associated* in a systematic way. The general formulation of what happens during systemizing is one looks for laws of the form 'if p, then q'. If it is Friday, then we eat fish. If we multiply 3 by itself, then we get 9. If we turn the switch to the down position, then the light comes on. When we think about the kinds of domains in which savants typically excel, it is those domains that are highly systemizable.

Examples might be from numbers (e.g. spotting if a number is a prime number), calendrical calculation (e.g. telling which day of the week a given date will fall), drawing (e.g. analysing space into geometric shapes and the laws of perspective, and perfecting an artistic technique), music (e.g. analysing the sequence of notes in a melody, or the lawful regularities or structure in a piece), memory (e.g. recalling long sequences of digits or lists of information) or even learning foreign languages (e.g. learning vocabulary or the laws of grammar). In each of these domains, there is the opportunity to repeat behaviour in order to check if one gets the very same outcome every time. Multiplying 3 by itself *always* delivers 9, the key change in this specific musical piece always occurs in the 13th bar, throwing the ball at this particular angle and with this particular force always results in it landing in the hoop.

3. SYSTEMIZING THE RUBIK'S CUBE

Let us take a cardinal example of savantism: a non-conversational child with autism who can solve the Rubik's Cube 'problem' in 1 min and 7 s. This is a nice example because it illustrates several things. First, that the child's non-verbal ability with the Rubik's Cube is at a much higher level than either his communication or social skills, or indeed what one would expect of his age. Second, it prompts us to ask: what are the processes involved in solving the Rubik's Cube? At a minimum, it involves analysing or memorizing the sequence of moves to produce the correct outcome. It is a series of 'if p, then q' steps. This child with autism appeared to have 'discovered' the layer-by-layer method to solve the 3×3×3 Rubik's Cube problem, which at best takes a minimum of 22 moves. (Note that he was not as fast as the current 2008 World Champion Erik Akkersdijk who in the Czech Open championship solved the Rubik's Cube in 7.08 s!).

4. SYSTEMIZING IN AUTISM SPECTRUM CONDITIONS

What is the evidence for intact or even unusually strong systemizing in ASC? First, such children perform above the level that one would expect on a physics test (Baron-Cohen *et al.* 2001). Children with Asperger's syndrome (AS) as young as 8–11 years old scored higher than a comparison group who were older (typical teenagers). Second, using the systemizing quotient (SQ), people with high-functioning autism or AS score higher on the SQ compared with general population controls (Baron-Cohen *et al.* 2003). Third, children with classic autism perform better than controls on the picture-sequencing test where the stories can be sequenced using physical-causal concepts (Baron-Cohen *et al.* 1986). They also score above average on a test of how to figure out how a Polaroid camera works, even though they have difficulties figuring out people's thoughts and feelings (Baron-Cohen *et al.* 1985; Perner *et al.* 1989). The Polaroid camera test was used as a mechanical equivalent to the false belief test, since, in the former, all one has to do is infer what will be represented in a photograph given the 'line of sight' between the camera and an object, whereas, in the latter, one has to infer what belief (i.e. mental representation) a person will hold given what they saw and therefore know about.

Strong systemizing is a way of explaining the non-social features of autism: the narrow interests; repetitive behaviour; and resistance to change/need for sameness. This is because when one systemizes, it is best to keep everything constant, and to only vary one thing at a time. That way, one can see what might be causing what, and with repetition one can verify that one gets the very same pattern or sequence (if p, then q) every time, rendering the world predictable. One issue is whether hyper-systemizing only applies to the *high*-functioning individuals with ASC. While their obsessions (with computers or maths, for example) could be seen in terms of strong systemizing (Baron-Cohen *et al.* 1999), when we think of a child with *low*-functioning autism, many of the classic behaviours can be seen as a reflection of their strong systemizing. Some examples are listed in box 1.

5. SYSTEMIZING AND WEAK CENTRAL COHERENCE

As with the weak central coherence (WCC) theory (Frith 1989; and discussed in the paper in this volume by Happé), the hyper-systemizing theory is about a different cognitive style (Happé 1996). Similar to that theory, it also posits *excellent attention to detail* (in perception and memory), since when one systemizes one has to pay attention to the tiny details. This is because each tiny detail in a system might have a functional role leading to new information of the form 'if p, then q'. Excellent attention to detail in autism has been repeatedly demonstrated (Shah & Frith 1983, 1993; Jolliffe & Baron-Cohen 2001; O'Riordan *et al.* 2001; Mottron *et al.* 2003).

One difference between these two theories is that the WCC theory sees people with ASC as drawn to detailed information (sometimes called a local processing bias) either for *negative* reasons (an inability to integrate was postulated in the original version of this theory) or because of stronger local processing (in the later version of this theory). By contrast, the hyper-systemizing theory sees this same quality (excellent attention to detail) as being highly purposeful: it exists in order to understand a system. Attention to detail is occurring for *positive* reasons: in the service of achieving an ultimate understanding of a system (however small and specific that system might be).

We can return to the Rubik's Cube problem to see the difference between these two theories more clearly. At one level, the Rubik's Cube is a three-dimensional block design test but where the cubes are all connected.

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Box 1. Systemizing in classic autism and/or Asperger's syndrome

type of systemizing	classic autism	Asperger's syndrome
sensory systemizing	tapping surfaces or letting sand run through one's fingers	insisting on the same foods each day
motoric systemizing	spinning round and round, or rocking back and forth	learning knitting patterns or a tennis technique
collectible systemizing	collecting leaves or football stickers	making lists and catalogues
numerical systemizing	obsessions with calendars or train timetables	solving maths problems
motion systemizing	watching washing machines spin round and round	analysing exactly when a specific event occurs in a repeating cycle
spatial systemizing	obsessions with routes	developing drawing techniques
environmental systemizing	insisting on toy bricks being lined up in an invariant order	insisting that nothing is moved from its usual position in the room
social systemizing	saying the first half of a phrase or sentence and waiting for the other person to complete it	insisting on playing the same game whenever a child comes to play
natural systemizing	asking over and over again what the weather will be today	learning the Latin names of every plant and their optimal growing conditions
mechanical systemizing	learning to operate the VCR	fixing bicycles or taking apart gadgets and reassembling them
vocal/auditory/verbal systemizing	echoing sounds	collecting words and word meanings
systemizing action sequences	watching the same video over and over again	analysing dance techniques

Recall that the block design test is the subtest on Weschler IQ tests on which people with autism perform at their best (Shah & Frith 1993; Happé 1996). The Rubik's Cube contains 21 movable connected cubes (since the five central cubes do not move) with different coloured faces in the 3×3×3 version. According to the WCC theory, the reason why people with autism show superior performance on the block design test is that their good local processing enables them to 'see' each individual cube even if the design to be copied is not 'pre-segmented' (Shah & Frith 1983). It is clear how good local processing would lead to faster 'analysis' of the whole (design) into constituent parts (the individual cubes), but to solve the Rubik's Cube (or the block design problem), more than just good local processing is needed. A strength in 'if p, then q'-type reasoning is also required. On the classic block design subtest, one needs to *mentally or manually rotate* the cube to produce the relevant output. That is, one needs to *perform an operation* on the input to produce the relevant output. The same is true (but with more cubes and therefore more complexity) in the Rubik's Cube problem: 'If the red cube with the green side is positioned on the top layer on the right side and I rotate the top layer anticlockwise by 90 degrees, then this will complete the top layer as all one colour'.

In earlier formulations of systemizing, the key cognitive process was held to be in terms of [input–operation–output] processing (Baron-Cohen 2002, 2006). In mathematics, if the input = 3, and the operation = cubing, then the output = 27. In the Rubik's Cube notional example above, the input = [the red cube with the green side is positioned on the top layer on the right side], the operation = [rotate the top layer anticlockwise by 90 degrees] and the output = [complete the top layer as all one colour]. Note that WCC makes no mention of the key part of this that is *noting the consequences of an operation*. Simply seeing the parts in greater detail would not by itself lead to *understand the operations* (the moves) needed to solve the Rubik's Cube.

Another difference between the WCC theory and the hyper-systemizing theory is that the latter (but not the former) predicts that over time, the person may achieve an excellent understanding of a whole system, given the opportunity to observe and control all the variables (all the 'if p, then q' rules) in that system. WCC would predict that even given all the time in the world, the individual will be forever lost in the detail. The existence of talented mathematicians with AS such as Richard Borcherds is proof that such individuals can *integrate* the details into a true understanding of the system (Baron-Cohen 2003). In the rule 'if *p*, then *q*', the terms 'if' and 'then' are how the details become integrated, albeit one small step at a time. The idea at the neurological level that ASC involves an abundance of local short-range connectivity (Belmonte *et al.* 2004) may explain this cognitive style of identifying one specific link between two details.

6. HYPER-SYSTEMIZING: IMPLICATIONS FOR EDUCATION

Teachers, whether of children with autism or adults with AS, need to take into account that hyper-systemizing will affect not only how people with ASC learn but also how they should be assessed. IQ test items, essays and exam questions designed for individuals who are 'neurotypical' may lead to the person with

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ASC scoring zero when their knowledge is actually greater, deeper and more extensive than that of most people. What can appear as a slow processing style may be because of the massively greater quantity of information that is being processed.

A man with AS reported recently that 'I see all information in terms of links. All information has a link to something and I pay attention to these links. If I am asked a question in an exam I have great difficulty in completing my answer within the allocated 45 min for that essay, because every fact I include has thousands of links to other facts, and I feel my answer would be incorrect if I didn't report all of the linked facts. The examiner thinks he or she has set a nice circumscribed question to answer, but for someone with autism or AS, no topic is circumscribed. There is ever more detail with ever more interesting links between the details'.

When asked about the concept of apple, for example, he could not give a short summary answer such as 'an apple is a piece of fruit' (i.e. referring to the prototypical level 'apple' as linked to the superordinate level 'fruit') but had to continue by also trying to link it to the 7500 different species of apple (the subordinate-level concepts), listing many of each type and the differences in terms of the history of each species, how they are cultivated, what they taste and look like, etc. When asked about the concept of beetle, he could not just give a summary answer such as 'a beetle is an insect' but had to mention as many of the 350 000 species of beetle that he knew existed.

This cognitive style is understandable in terms of the hyper-systemizing theory because a concept is a system. A concept is a way of using an 'if p, then q' rule to define what to include as members of a category (e.g. if it has scales and gills, then it is a fish). Furthermore, concepts exist within a classification system, which are rules for how categories are related to one another. So, the question 'what is a beetle?' is trivial for a neurotypical individual who simply answers in terms of a crude, imprecise and fuzzy category: 'it is an insect'. It may, however, require a very long, exhaustive answer from someone with autism: beetles are members of the category of animal (kingdom), arthropods (phylum), insects (class), pterygota (subclass), neoptera (infra-class), endopterygota (superorder), coleoptera (order), and could be in one of four suborders (adephaga, archostemata, mycophaga and polyphaga), each of which has an infraorder, a superfamily and a family. Even the previous sentence would for this man with AS be a gross violation of the true answer to the question because so much important factual information has been left out. But for the hyper-systemizer, getting these details correct matters, because the concept—and the classification system linking concepts—is *a system for predicting* how this specific entity (this specific beetle) will behave or will differ from all other entities.

7. HYPER-SYSTEMIZING THEORY VERSUS EXECUTIVE DYSFUNCTION THEORY

The executive dysfunction (ED) theory (Rumsey & Q6 Hamberger 1988; Ozonoff *et al.* 1991; Russell 1997) is the other major theory that has attempted to explain the non-social features of ASC, and particularly the repetitive behaviour and narrow interests that characterize ASC. According to this theory, aspects of executive function (action control) involved in flexible switching of attention and planning are impaired, leading to perseveration. The ED theory, similar to the WCC theory, has difficulty in explaining instances of good understanding of a whole system, such as calendrical calculation, since within the well-defined system (calendar) attention can switch very flexibly. The ED theory also predicts perseveration (so-called 'obsessions') but does not explain why in autism and AS these should centre on systems (Baron-Cohen & Q7 Wheelwright 1994). Finally, the ED theory simply re-describes repetitive behaviour as an instance of ED without seeing what might be positive about the behaviour.

So, when the low-functioning person with classic autism has shaken a piece of string thousands of times close to his eyes, while the ED theory sees this as perseveration arising from some neural dysfunction which would normally enable the individual to shift attention, the hyper-systemizing theory sees the same behaviour as a sign that the individual 'understands' the physics (i.e. recognizes the patterns) behind the movement of that piece of string. He may be able to make it move in exactly the same way every time. Or to take another example, when he makes a long, rapid sequence of sounds, he may 'know' exactly that acoustic pattern, and get some pleasure from the confirmation that the sequence is the same every time. Much as a mathematician might feel an ultimate sense of pleasure that the 'golden ratio' (that $(a+b)/a = a/b$) and that this always comes out as 1.61803399, so the child—even with low-functioning autism—who produces the same outcome every time with their repetitive behaviour, appears to derive some emotional pleasure at the predictability of the world. This may be what is clinically described as 'stimming' (Wing 1997). Autism was originally described as involving 'resistance to change' and 'need for sameness' (Kanner 1943), and here we see that important clinical observation may be the hallmark of strong systemizing. Recent neuroimaging studies suggest that there might be aberrant processing of rewards in people with ASC Q8 (deMartino *et al.* 2008; Schmitz *et al.* 2008) and it will be important for future neuroimaging studies to test if the reward systems in the brain (e.g. the dopaminergic or cannabinoid systems) are active during such repetitive behaviour.

If we return to the Rubik's Cube example, an ED would predict that an inability to 'plan' should make solving a Rubik's Cube impossible for a savant with autism. By contrast, as we saw earlier, the hyper-systemizing theory has no difficulty in explaining such talent.

8. SENSORY HYPERSENSITIVITY

Rather than assuming that the strong systemizing in ASC is ultimately reducible to excellent attention to detail, in this section we pursue the idea that the excellent attention to detail is itself reducible to sensory hypersensitivity. Mottron & Burack (2001) postulated the 'enhanced perceptual functioning' model of ASC, characterized by

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superior low-level perceptual processing. To what extent is this a feature of basic sensory physiology?

Studies using questionnaires such as the sensory profile have revealed sensory abnormalities in over 90 per cent of children with ASC (Leekam *et al.* 2001; Kern *et al.* 2006; Tomchek & Dunn 2007). In *vision*, Bertone *et al.* (2003) found that individuals with ASC are more accurate at detecting the orientation of first-order gratings (simple, luminance-defined) but less accurate at identifying second-order gratings (complex, texture-defined). In the *auditory* modality, superior pitch processing has been found in ASC (Mottron *et al.* 1999; Bonnel *et al.* 2003; Heaton *et al.* 2008). In a case study, Mottron *et al.* (1999) reported exceptional absolute judgement and production of pitch. Bonnel *et al.* (2003) found superior pitch discrimination and processing abilities in individuals with high-functioning autism. O'Riordan & Passetti (2006) also reported superior auditory discrimination ability in children with ASC, and Jaervinen-Pasley *et al.* (2002) showed superior perceptual processing of speech in children with autism.

In the *tactile* modality, Blakemore *et al.* (2006) showed hypersensitivity to vibrotactile stimulation to a frequency of 200 Hz but not for 30 Hz. In addition, the ASC group rated suprathreshold tactile stimulation as significantly more tickly and intense than did the control group. Tommerdahl *et al.* (2007) reported participants with ASC outperformed controls in tactile acuity after short adaptation to a vibrotactile stimulus period of 0.5 s. (Note that this hypersensitivity is not always observed. On a tactile discrimination task, O'Riordan & Passetti (2006) found no differences in children with autism compared with controls.) Cascio *et al.* (2008) investigated tactile sensation and reported increased sensitivity to vibrations and thermal pain in ASC, while detection to light touch and warmth/cold was similar in both groups.

Only two previous studies have been reported investigating olfaction in ASC, and unlike the research into the other senses which consistently find hypersensitivity, both of these studies reported *deficits* in identifying odours despite intact odour detection (Suzuki *et al.* 2003; Bennetto *et al.* 2007). Looking more closely at the two previous studies into olfaction in ASC, both required participants to explicitly identify the odour from a choice of responses, and methodology likely to involve both executive function and memory. For example, the study by Bennetto and colleagues required participants to decide which of four possible responses an odour matched. A simpler task might provide a purer test of low-level olfactory discrimination in ASC.

In the final section of this paper, we summarize an experiment from our laboratory looking at vision in ASC, in terms of basic sensory detection thresholds (acuity). Ongoing studies from our laboratory are also testing sensory detection thresholds in other modalities (touch, audition and olfaction). Full details of these experiments are reported elsewhere (Ashwin *et al.* in press, submitted; Tavassoli *et al.* submitted).

Participants were administered the Freiburg visual acuity and contrast test, a standardized optometric test that uses the Landholt-C optotype (Bertone *et al.* 2003). The gaps in the C-shape range from 0.4 to 25 mm and appear in one of four positions: up; down; left; or right. Participants sat at a fixed distance of 60 cm from the computer screen and identified the location of the 'missing' part of the C-shaped stimulus by selecting one of four arrow keys on the keyboard. Participants had 3 s to respond on each of the 150 trials. The results generated a Snellen decimal, where a value of 1.0 represents 'normal' 20 : 20 vision (Heaton *et al.* 2008). A score of 20 : 10 is regarded as excellent vision, and means an object normally detected at 10 feet can be detected at 20 feet. Thus, Snellen values above 1.0 represent increasingly accurate vision, and values below 1.0 represent worse vision. The ASC group scored a mean acuity measure of 2.79 (s.d. $= \pm 0.37$), which was significantly better than the control group mean of 1.44 (s.d. $= \pm 0.26$), $t(40) = 4.63$; $p < 0.001$. The Snellen score of 2.79 for the ASC group represents acuity 2.79 times better than normal, and translates to vision of 20 : 7. This approaches the range reported for birds of prey.

Results from this and other experiments demonstrated greater sensory perception in ASC across multiple modalities. In the context of the earlier discussion of hyper-systemizing and excellent attention to detail, we surmise that these sensory differences in functioning may be affecting information processing at an early stage (in terms of both sensation/cognition and development) in ways that could both cause distress but also predispose to unusual talent. These results of hypersensitivity confirm previous findings and mirror anecdotal reports of individuals with ASC (Grandin 1996). For example, Temple Grandin writes that 'overly sensitive skin can be a big problem…Shampooing actually hurt my skin…To be lightly touched appeared to make my nervous system whimper, as if the nerve ends were curling up'. In terms of increased sensitivity to certain types of auditory stimuli (high frequencies), there are anecdotal reports that individuals with autism tend to avoid certain sounds. Grandin states 'I can shut out my hearing and withdraw from most noise, but certain frequencies cannot be shut out…High pitched, shrill noises are the worst'. Mottron *et al.* (1999) reported the case of a woman with autism who was hypersensitive to frequencies from 1 to 5 kHz at 13 years of age, and to 4 kHz at 18 years.

Enhanced sensitivity may be specific to certain stimuli in all modalities. In vision, Bertone *et al.* (2003) pointed out the importance of specific stimuli in investigating visual differences in ASC. In touch, Blakemore *et al.* (2006) reported hypersensitivity for higher frequency (200 Hz) vibrotactile stimulation, but not for lower (30 Hz). Pinpointing the precise stimuli in which enhanced sensitivity occur in ASC will be important for future research. To our knowledge, the highest frequency that has been used to investigate hearing in ASC is 8 kHz (Bonnel *et al.* 2003). Our ongoing study investigates very high frequencies, up to 18 kHz (Tavassoli *et al.* submitted). The reported hypersensitivity through frequencies above 16 kHz is especially important since some environmental sounds operate at or above this range of frequencies. Grandin reported 'Some of the sounds that are most disturbing to autistic children are the high-pitched, shrill noises made by electrical drills, blenders, saws, and vacuum cleaners'.

Hypersensitivity could result from a processing difference at various sensory levels including the density or sensitivity of sensory receptors, inhibitory and exhibitory neurotransmitter imbalance or speed of neural processing. Belmonte *et al.* (2004) suggested *local range neural overconnectivity* in posterior, sensory parts of the cerebral cortex is responsible for the sensory 'magnification' in people with ASC. While our laboratory and others have tested sensory profiles in ASC using fMRI (Gomot *et al.* 2006, 2008; Belmonte *et al.* in press), the combination of imaging and genetic approaches to study sensory perception in fMRI may lead towards a more complete picture. We conclude that the search for the association between autism and talent should start with the sensory hypersensitivity, which gives rise to the excellent attention to detail, and which is a prerequisite for hyper-systemizing.

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