

A case study of a multiply talented savant with an autism spectrum disorder: neuropsychological functioning and brain morphometry

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Neuropsychological functioning and brain morphometry in a savant (case GW) with an autism spectrum disorder (ASD) and both calendar calculation and artistic skills are quantified and compared with small groups of neurotypical controls. Good memory, mental calculation and visuospatial processing, as well as (implicit) knowledge of calendar structure and 'weak' central coherence characterized the cognitive profile of case GW. Possibly reflecting his savant skills, the superior parietal region of GW's cortex was the only area thicker (while areas such as the superior and medial prefrontal, middle temporal and motor cortices were thinner) than that of a neurotypical control group. Taken from the perspective of learning/practice-based models, skills in domains (e.g. calendars, art, music) that capitalize upon strengths often associated with ASD, such as detail-focused processing, are probably further enhanced through over-learning and massive exposure, and reflected in atypical brain structure.

Keywords: autism; savant; weak central coherence; implicit learning; neuroanatomy; magnetic resonance imaging

1. INTRODUCTION

Autism spectrum disorders (ASD) are associated with a remarkable combination of cognitive strengths and difficulties. The same individual may struggle to express or understand speech, while demonstrating amazingly good memory for routes, or fantastic understanding of mechanical systems. In some cases, special abilities are so pronounced that savant skills or 'islands of genius' may be considered to be present. Over the years, there have been many case, and some group, studies of savant skills (for review, see [Treffert 1989](#); [Hermelin 2001](#); [Heaton & Wallace 2004](#)). Although there have been reports of multiple skills possessed by a single individual (e.g. performance and memory skills for music; [Hermelin et al. 1989](#)), there have been limited reports of multiple skills across unrelated domains (e.g. music and maths). Furthermore, cognitive and neural mechanisms underlying savant skill development and expression remain elusive.

The case presented here, involving both neuropsychological assessment and structural neuroimaging, complements and adds to the extant literature, because this savant presents skills in two domains: art and calendar calculations. In addition to the assessment of IQ, calendar calculation, mental calculation, memory and general visuospatial abilities, we tested three broad neuropsychological domains hypothesized to be relevant to savant skill development ([Heaton & Wallace 2004](#)): (i) 'weak' central coherence, (ii) implicit learning, and

(iii) information processing speed (reviewed below). To assess potential neural correlates of his exceptional calculation and artistic abilities, we examined cortical thickness from a structural magnetic resonance image of his brain.

(a) *Weak central coherence*

A large body of evidence (for review, see [Happé & Frith 2006](#)) suggests that individuals with autism tend to favour local over global processing, opposite to the typical pattern. This bias, termed 'weak central coherence' (WCC), is reflected in, for example, relative strength on the block design subtest of the Wechsler Intelligence Scales, where ability to see a whole design in terms of its parts, and ability to resist the gestalt, is advantageous ([Happé, 1994](#)). Similarly, individuals with ASD often outperform controls on the embedded figures test (EFT; [Witkin et al. 1971](#)), in which a simple shape (e.g. a triangle) must be spotted within a more complex figure ([Shah & Frith 1983](#)).

This detail-focused cognitive style may relate to the expression and development of savant skills, including calendar calculation and artistic abilities. For calendar calculation, [Heavey et al. \(1999\)](#) suggest that the calendars can be broken down into 'fragments' of dates. Combining the natural tendency to segment large chunks of information with idiosyncratic interest in dates, calendar calculation skills may emerge. [Happé & Frith \(2006\)](#) suggest that stringing together calendar facts in the service of calendar calculation is indicative of 'local' coherence (analogous to processing grammar in language).

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

Artistic abilities also may rely upon good detail focus. [Mottron & Belleville \(1993\)](#) provided the example of a savant artist who approached his drawings in a piecemeal fashion, while a professional draughtsman who served as a control used outlines in his drawings initially, then progressed to more detailed elements. Furthermore, both savant artists with autism and typically developing artists obtain high scores on the block design task ([Pring *et al.* 1995](#)). This shared facility for segmenting patterns in both artists and those with autism suggests that WCC may contribute to the over-representation of savant skills in ASD.

(b) *Implicit learning*

'Implicit', or unintentional, learning has a number of definitions and associated theoretical accounts. What most share is the notion of an implicit knowledge base developed through non-conscious learning. The notion of implicit learning has particular appeal when explaining some savants' untrained abilities, and may help to explain savants' aptitude for learning relationships in a specific set of domains. Just as for neurotypical individuals participating in implicit learning studies, savants (particularly calendar calculators) cannot tell you how they know the right answer or they will give you false answers when queried. Furthermore, savants' engagement in high levels of training, practice and exposure to domain-specific information may lead to implicit learning of component properties. [Happé and Vital \(2009\)](#) suggest that reduced awareness of one's own mental states (part of a theory of mind deficit) may increase the likelihood of implicit learning, and reduce interfering attempts at explicit rule extraction, which are known to hamper performance on certain sorts of tasks (e.g. artificial grammars; [Reber 1993](#)). 'Systemizing', which includes implicit or explicit rule extraction as applied to predictable and lawful 'systems', is a purported strength in ASD and may be related to savant skill development (see [Baron-Cohen *et al.* 2009](#)). Thus far, the limited evidence suggests intact implicit learning among individuals with ASD ([Klinger *et al.* 2006](#); [Barnes *et al.* 2008](#)), although at least one study has found impaired implicit learning ([Mostofsky *et al.* 2000](#)).

Although researchers have suggested a role for implicit learning in savant skill development for some time ([Treffert 1989](#); [Hermelin 2001](#)), this possibility has not been assessed empirically using traditional tasks. In the most relevant study to date, a musical savant demonstrated outstanding incidental learning of digit-symbol pairs (with no instruction to remember these paired associations) from the coding subtest of the Wechsler Scales ([Lucci *et al.* 1988](#)). Even though there was limited opportunity to learn the associations (exposure time was only 90 s) and the savant performed poorly on the coding portion of the task (i.e. number correct), perfect recall of all nine paired associates was accomplished.

(c) *Information processing speed*

According to some theorists (e.g. [Anderson 2001](#)), information processing speed forms the basis of individual differences in IQ. Evidence is derived mostly from correlations (around $r = -0.50$;

[Grudnik & Kranzler 2001](#)) between measures of general intelligence and inspection time (IT), a method for assessing speed of information processing not reliant on motor speed. IT is measured by establishing the minimum stimulus exposure needed for an individual to accurately discriminate a simple stimulus feature. The IT task design avoids difficulties inherent to reaction time (RT) studies, such as motoric and 'thinking time' confounds especially relevant when an individual is unsure how to respond, possibly resulting in a 'speed/accuracy trade-off'.

IT among individuals with ASD has been reported to be (i) much better than expected, based upon measured IQ, (ii) equal to that of a typically developing group with mean IQ scores 25 points higher, (iii) significantly better than that of a non-ASD intellectually impaired group ([Scheuffgen *et al.* 2000](#)) and (iv) uniquely uncorrelated with IQ, unlike for controls ([Wallace *et al.* 2009](#)). [Scheuffgen *et al.*](#) argue that, if information processing speed is good among individuals with autism, some other aspect(s) of cognition are responsible for the low measured IQ frequently observed in autism—and suggest social insight and socially mediated learning to be responsible.

Rapid processing of stimuli would certainly be advantageous for mastering savant domains. [Anderson *et al.* \(1998\)](#) showed that the IT of a savant prime number calculator with autism was consistent with that of typical university undergraduates, but inconsistent with his own low measured IQ. Based on the findings from these studies, it may be that intact or superior processing speed is one factor contributing to the high rates of savant skills in ASD.

(d) *Neural correlates of calculation and artistic abilities*

A growing body of research has examined the neural correlates of calculation and to a lesser extent artistic abilities. Most functional neuroimaging studies (see [Dehaene *et al.* 2004](#) for review) indicate a role for the superior parietal lobe, particularly the intraparietal sulcus (IPS), in the processing of numbers (including [Cowan and Frith's](#) study of two calendar calculators, [Cowan & Frith \(2009\)](#)). The IPS also has been linked to calculation difficulties through structural neuroimaging studies. For example, dyscalculic adolescents with a history of very low birth weight and premature birth had grey matter reduction in the left parietal lobe (in the vicinity of the IPS) when compared with other adolescents with similar histories but no current presentation of mathematical difficulties ([Isaacs *et al.* 2001](#)).

Although the neural correlates of artistic ability have not been examined thoroughly, at least one study has examined the neural correlates of drawing behaviour using functional neuroimaging. [Makuuchi *et al.* \(2003\)](#) consistently observed bilateral (particularly superior) parietal lobe activations across participants when they were asked to 'draw in the air' a contour of an object depicted on a screen. Furthermore, visual mental imagery, a skill potentially relevant to talent in the visual arts, is also associated with activation in the superior parietal lobe (e.g. [Guillot *et al.* in press](#)). Thus, based on the evidence collected so far, calculation and

artistic abilities share mediation within the (particularly superior) parietal lobes.

Savants, particularly those with autism, exhibit circumscribed interests, usually within their skill area (O'Connor & Hermelin 1991), which leads to considerable rehearsal, practice and training. There are several studies now showing measurable structural brain differences after individuals practise various tasks over shorter (e.g. juggling; Draganski *et al.* 2004) or longer (e.g. the 'Knowledge' learnt by London taxi drivers; Maguire *et al.* 2000) periods of training. Savants represent a clear case of expertise and over-learning within restricted domains. We therefore used structural neuroimaging to assess possible neural correlates of calculation and artistic expertise, with the prediction of changes in superior parietal regions implicated in both domains.

2. HYPOTHESES

(a) Neuropsychological study

In comparison with age- and IQ-matched neurotypical participants, GW is predicted to exhibit: (i) WCC, (ii) superior implicit learning, and (iii) superior IT. In comparison with the existing norms, it was predicted that GW would exhibit superior recognition memory, spatial reasoning abilities and mental calculation abilities. GW also is expected to demonstrate exceptional calendar calculation and a priming effect resulting in a relative RT gain when consecutive dates from the same calendar template are presented to him.

(b) Neuroimaging study

In comparison with age- and IQ-matched neurotypical controls, GW's cortex is predicted to be relatively thicker in superior parietal regions (areas implicated in both calculation and artistic abilities) but thinner in medial prefrontal and temporal areas (regions associated with social cognition, a domain of impairment in ASD; Frith & Frith 2006).

3. MATERIAL AND METHODS

(a) Participants

(i) Case GW

GW is a 42-year-old right-handed male diagnosed with Asperger's syndrome as an adult (and meeting screening criteria for an ASD according to the Social Communication Questionnaire), who demonstrates both superior calendar calculation skill and high-level artistic abilities. Atypically, GW reports he was not very interested in calendars as a child, but instead developed these abilities as an adult. However, GW reports that at age 5 or 6 years, he remembers seeing his grandmother's calendar and 'knowing' dates for 'only a couple of years'. Although he dabbled in young adulthood, GW did not begin calendar calculation over large ranges until he was 32 years old. Similar to other calendar calculators, he cannot tell you precisely how he does it, but he 'just knows' the answer and it usually 'feels right'.

GW reports that he has been drawing 'as long as he can remember' and has always excelled in this endeavour; he was usually considered the best drawer in his class throughout his school years. As a young child, his drawings were usually focused on a single object, but later his subject matter broadened in scope. GW's unique artistic style has changed over time, going from drawings of scenes and

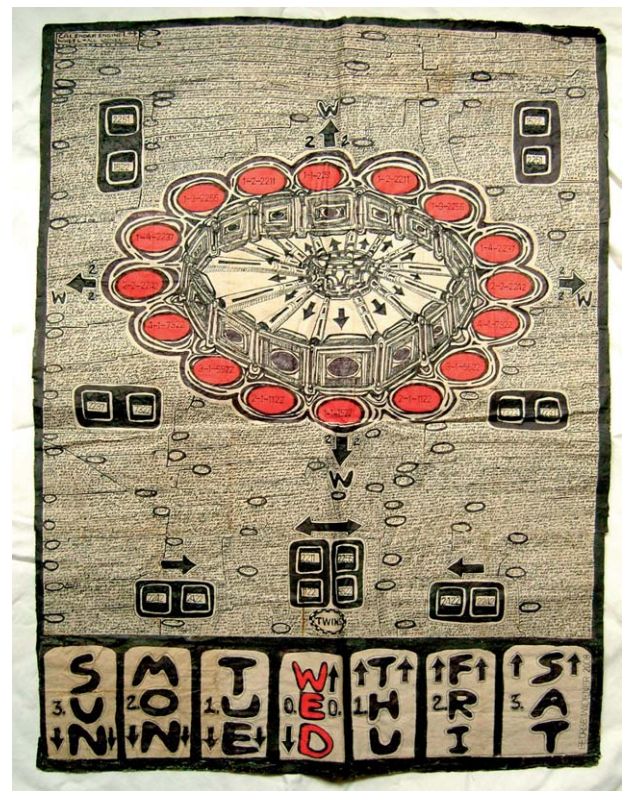


Figure 1. Example of GW's artwork.

buildings during adolescence, to more abstract impressionist style paintings as a young adult and then back again to technical-type drawings of real and/or imaginary machines, for example, although with more stylistic elements included (figure 1). GW's work has attracted interest from galleries across the USA and Europe resulting in numerous exhibitions and requests for commissioned artwork.

Two art judges (one has previously judged art competitions and the other has experience as a judge and also as a curator) were asked to evaluate GW's artwork. Both were highly laudatory of GW's work and style and, without hesitation, favourably compared GW's work with that of other contemporary artists who exhibit widely and sell very successfully.

(ii) Comparison groups

Seven neurotypical adult males of approximately the same age and IQ as GW (see table 1 for details) were recruited to serve as controls for the neuropsychological study. An additional group of 14 neurotypical adult males, group-matched to GW's age ($M=36.54 \pm 5.48$; $t=1.30$, $p=0.22$) and to his vocabulary score from the Wechsler Scale ($M=13.54 \pm 1.90$; $t=0.78$, $p=0.45$) in 13 out of the 14 (one missing), acted as controls for the neuroimaging study.

Informed consent was obtained from all participants.

(b) Measures

(i) Standardized neuropsychological tasks

Wechsler Adult Intelligence Scale-3rd Edition (WAIS-III) is a widely used assessment of intelligence with excellent psychometric properties. Case GW was tested on 11 subtests from the WAIS-III. The vocabulary and block design short form of the WAIS-III was administered to estimate full-scale IQ in the control group.

Picture recognition is a subtest from the Woodcock-Johnson-Revised (WJ-R) Cognitive Battery testing visuospatial recognition. The participant views briefly a number of

Table 1. GW's scores from clinical neuropsychological measures. (Note: WAIS-III subtest and GDA scores are presented in scaled score format ($M=10\pm 3$) while WAIS-III index and IQ scores as well as WJ-R and WRAT-3 scores are presented in standard score format ($M=100\pm 15$.)

measure	GW's score
Wechsler Adult Intelligence Scale-III (WAIS-III)	
vocabulary	12
similarities	4
information	14
<i>verbal comprehension index: (vocabulary + similarities + information)</i>	100
arithmetic	11
digit span	9
comprehension	9
<i>verbal IQ</i>	98
picture completion	14
block design	11
matrix reasoning	13
<i>perceptual organization index: (picture completion + block design + matrix reasoning)</i>	116
digit symbol	7
picture arrangement	8
<i>performance/non-verbal IQ</i>	104
<i>full-scale IQ</i>	100
Woodcock-Johnson Revised (WJ-R)	
picture recognition	111
spatial relations	113
Wide Range Achievement Test-3 (WRAT-3)	
arithmetic	110
Graded Difficulty Arithmetic Test (GDA)	
	16

line drawings of everyday objects, and must then choose those previously seen from an array of familiar and distracter images.

Spatial Relations is a subtest of the WJ-R in which participants must select which parts from an array would be needed to form a target whole or complete shape.

Wide Range Achievement Test-3 (WRAT-3) Arithmetic Subtest measures basic mathematical skills, requiring solution (using paper and pencil) of simple to complex mathematical problems ranging from basic mechanics to algebraic equations.

Graded Difficulty Arithmetic Test (GDA; Jackson & Warrington 1986) requires participants to answer rapidly (within 10 s) 12 addition and 12 subtraction problems varying from two digit \pm one digit numbers to three digit \pm three digit numbers, without the use of paper and pencil.

Previously administered to GW, and reported here as relevant, were: the *Wisconsin Card Sorting Test (WCST)* assessing cognitive flexibility; copying and drawing *Rey-Osterrieth Complex Figure* from memory after a 30 min interval; and the *Hooper Visual Organization Test* assessing the ability to identify a whole object from its cut up and rearranged parts.

(ii) *Experimental tasks*

EFT (Witkin et al. 1971) requires participants to find as quickly as possible a simple shape (e.g. a triangle) hidden within a larger, more complex figure. A combination of seven items from the children's and eight items from the standard (adult's) EFT were administered. Scoring is based on per cent correct and time (limit of 60 s per item) needed to locate each embedded figure.

Implicit learning was assessed using a new pattern sequence task combining serial RT/statistical learning methods (Kirkham *et al.* 2002). Participants pressed the green mouse button when they saw a green shape and the yellow mouse button when they saw a yellow shape appear in the centre of the computer display; no button press to be made to any other coloured shape (i.e. blue triangle or pink square). Within the structured condition, the appearance of the pink square predicted perfectly the appearance next of the green circle, while the contingency for all non-predictable shape co-occurrences was equated at 33 per cent. The chance of any of the four possible shapes appearing was equated (i.e. 25% each) across the entire task. In order to document implicit learning, an RT difference score was calculated by subtracting the RT to the green, predictable shape from the RT to the yellow, non-predictable shape with the resulting quotient divided by the participant's RT to the yellow shape, to account for differences in baseline visuo-motor speed. The gain in proportional RT between the first and second halves of the task was used to indicate a 'learning effect'.

IT was measured using a computerized task (Anderson *et al.* 1998), with four blocks of 25 stimulus presentations of a 'space invader' figure with two antennae of either the same or different lengths. The participant was asked to indicate whether the lengths of the antennae were the same or different by pressing one of two buttons. Stimulus duration (followed by a mask) was systematically varied to establish a 70 per cent accuracy level, using a parameter estimation by sequential testing (PEST) procedure (see Scheuffgen *et al.* (2000) for further details).

(iii) *Questionnaires*

GW and the matched controls were asked to complete the *Folk Physics Test (Baron-Cohen et al. 2001)* which is composed of 20 multiple-choice questions designed to assess an individual's understanding of the workings of macro- (e.g. gravity) and micro-level physical systems based on everyday experience with the physical world. The *Systemizing Quotient (SQ; Baron-Cohen et al. 2003)*, a self-rating scale, was used to assess a participant's tendency to 'systemize' in everyday contexts.

(iv) *Savant domain assessment*

Calendar Performance Tests (Cowan et al. 2003) were given to assess the knowledge of day-date correspondence (accuracy and RT) over a large span of years in the Gregorian calendar (90 items), and later years from the Julian calendar (25 items). Calendar knowledge was also assessed by having GW calculate the day on which two identical dates from different years fell (18 pairs); the dates shared the same calendar template (e.g. 5 April 2005 and 5 April 1994), which should result in faster RT on the second date if (implicit or explicit) knowledge of this template was used as a strategy (Hermelin & O'Connor 1986). Priming was therefore assessed and operationalized through the calculation of a percentage savings score.

(v) *Cortical thickness quantification from structural neuroimaging*

One hundred and twenty four contiguous 1.5 mm axial slices from T1-weighted magnetic resonance images were obtained with a three-dimensional spoiled gradient recalled echo in the steady state on a 1.5 T General Electric Signa scanner (Milwaukee, WI, USA). Grey and white matter surfaces with over 80 000 polygons, each fitted and nonlinearly aligned, were derived (Robbins *et al.* 2004).

Table 2. Performance on experimental tasks administered to GW and the comparison group, and matching variables: mean \pm s.d.

	GW	control group ($n=7$)	t	p -value	Cohen's d
age	42	40.68 \pm 7.45	0.17	0.87	0.17
full-scale IQ	100 ^a	111.57 \pm 11.80	0.92	0.39	0.98
vocabulary	12	12.29 \pm 3.40	0.08	0.94	0.09
block design	11	11.71 \pm 1.60	0.42	0.69	0.44
EFT					
percentage correct	93	86 \pm 10	0.65	0.54	0.70
mean time	9.07	19.59 \pm 7.40	1.33	0.23	1.42
implicit learning					
proportional RT gain: first versus second half	0.10	0.06 \pm 0.18	0.20	0.85	0.22
IT (ms)	39	33.43 \pm 8.54	0.61	0.56	0.65

^aBased on all subtests from the WAIS-III, not the two subtest short form (vocabulary and block design) as used for the control group.

Each vertex of the white matter surface corresponds to a grey matter surface counterpart, thereby creating linked polygons on the grey and white matter surfaces. The distance between corresponding vertices of the grey and white matter boundaries is then used to define cortical thickness. A 30 mm surface-based blurring kernel that maximizes statistical power and minimizes false positives (Lerch & Evans 2005) was used. Cortical thickness (CT) was calculated in native space at 40 962 cortical points in each hemisphere for a total of 81 924 cortical points across the entire cortex. Using z -scores ((control group CT mean – GW's CT)/control group CT standard deviation), maps were created in which GW's cortex was at least: one standard deviation thinner than the mean of the control group (figure 2a) or one standard deviation thicker than the mean of the control group (figure 2b) for each of the 81 924 vertices.

4. RESULTS

(a) Neuropsychological tasks and questionnaires

Table 1 shows GW's scores on the standardized neuropsychological assessments. Note that GW's IQ was in the average range, and neither digit span nor arithmetic was outstanding within the Wechsler Scales, although the GDA did show extremely good skills of mental addition and subtraction.

Table 2 shows GW's performance, and that of the comparison group, on the experimental tasks, as well as the short-form IQ subtests used for approximate matching. GW showed fast and accurate EFT performance, and IT performance as good as that of the controls, who had slightly higher measured IQ. Group differences (using a modified t -test; Crawford & Howell 1998) did not reach significance; however, a large effect size (Cohen's $d > 0.80$) was noted for EFT speed.

The positive proportional RT scores for both GW and controls indicate that an RT benefit was derived from the predictable sequence of shapes, even after accounting for baseline differences in RT. In other words, implicit learning of shape co-occurrences was demonstrated for case GW and for the group of controls as a whole.

In previous testing (3 years earlier), GW exhibited some difficulty in completing the WCST. He was able to use feedback to shift problem-solving sets, but he sometimes 'lost set' and then became fixated on

matching sets by colour. GW adequately copied the Rey–Osterrieth Complex Figure, but when asked to recall the figure approximately 30 min later, his strategy was fragmented leading to a disorganized figure. His performance at recall fell in the bottom 10 per cent of performance on this task for comparably aged neurotypical adults. On the Hooper Visual Organization Test, GW excelled at identifying objects based on line drawings of their parts, correctly identifying all 30 items.

On the questionnaire measures, GW's self-rating for systemizing (33) was not significantly higher than the mean for the comparison group (24.9 \pm 9.9; $t = 0.76$, $p = 0.47$), but the effect size was large (Cohen's $d = 0.82$). His Folk Physics performance (55%) was below that of the comparison group ($M = 63.57 \pm 18.19$), again with no significant difference ($t = 0.44$, $p = 0.67$; Cohen's $d = 0.47$).

(b) Savant domain assessment

Overall calendar performance was excellent, with 92 per cent correct for dates 1828–1836 and 2017–2024, 85 per cent for years 1772–1777 and 2072–2165, and 96 per cent for 2363–8378 in the Gregorian calendar. For dates from the Julian calendar (1591–1751), GW obtained 84 per cent correct.

The priming study showed that GW saved just less than 1 (0.83) second per pair (15 s across 18 pairs). Although this is a small amount, the baseline RTs were very fast: a total of 48 s on initial items and 33 s on the second items in pairs, amounting to a savings of 15/48 = 0.3125 or 31.25 per cent savings, which is a relatively large savings score and evidence of 'priming' based on knowledge of calendar regularities.

(c) Cortical thickness quantification

For GW relative to controls ($z > 1$), thinner cortex was found in bilateral superior frontal gyrus, medial prefrontal cortex (Brodmann area 8), left primary motor/precentral gyrus (Brodmann area 4) and left middle temporal gyrus (Brodmann area 39) among others (figure 2a), while thicker cortex was limited to bilateral portions of the superior parietal region (Brodmann area 7; figure 2b).

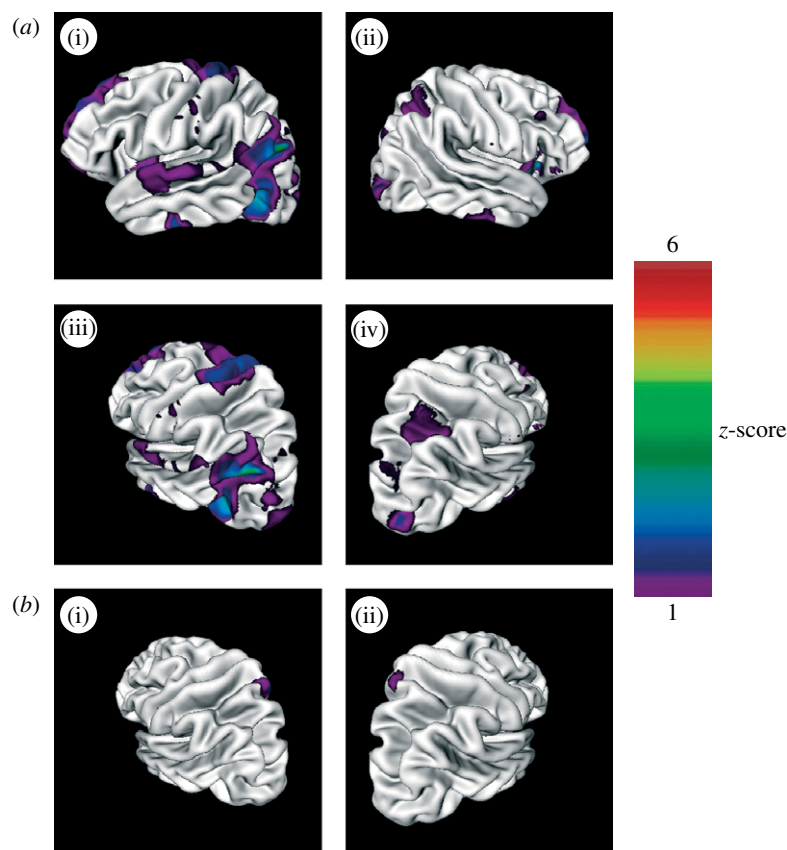


Figure 2. Cortical regions (ai-iv) thinner and (bi,ii) thicker for GW than for controls.

5. DISCUSSION

(a) *Neuropsychological study*

GW's easily quantifiable skill, calendar calculation, was 'prodigious' (Treffert 1989), even by calendar savant standards. Although GW is not flawless in his calendar calculations, his excellent performance in terms of accuracy and RT did not vary considerably based on temporal distance from the present and his calendar range is practically endless (years tested here ranged from 1591 to 8378). Similarly, the two art judges enthusiastically endorsed GW's artistic abilities as comparable with those of professional artists who regularly exhibit in the community.

Overall GW's general, verbal and non-verbal IQs fell in the average range, but with considerable scatter across the subtests. GW's perceptual organization index was one standard deviation above his verbal comprehension index, but was not exceptional. This relative visuospatial strength was corroborated on the Hooper test and WJ-R visuospatial tasks.

GW scored in the average to above average range on a measure of written arithmetic. However, GW's GDA (mental calculation) total score (correctly answering 21 out of 24 items, each within 10 s) placed him in the 99th centile (Jackson & Warrington 1986). Therefore, it is likely that a significant component to GW's superior calendar calculating ability, especially his extraordinary range, is good, rapid mental calculation ability. Indeed, Cowan *et al.* (2003), also using the GDA, found that 4 out of 10 calendar savants performed at superior levels when compared with the same standardization sample.

Memory has been implicated in calendar calculation and other savant skills although rarely do savants score highly on standardized tasks. GW performed above average on a visuospatial recognition task, roughly commensurate with his overall IQ (as was his digit span). However, there is evidence that GW's memory, especially for numerical information, is excellent, similar to previous reports of superior memory within a savant's area of talent (O'Connor & Hermelin 1989). He recently memorized the exact populations for hundreds, if not thousands, of cities in the USA, based on the latest census data. When informally questioned on approximately 50 randomly chosen cities (population above 30 000), GW incorrectly recalled only a single digit among these population values. Moreover, when asked again eight months later the populations associated with 10 out of these 50 cities, he made no errors.

A difference in speed of calendar calculation, expressed as a savings score, was demonstrated between those (pairing of) items where the same calendar template could be used and those where it could not. This finding not only corroborates indirect documentation of rule use by calendar savants (Hermelin & O'Connor 1986), but also provides evidence of calendar structure knowledge by GW, ruling out the explanation that his calendar skills are nothing more than memory feats. Indeed, taken together with GW's good mental calculation abilities, it is clear that GW, similar to other calendar savants, may rely on both memory and rule use in his calendar calculation, with good calculation abilities serving to extend his calendar range well into the future.

In contrast to GW's flexible approach to art (given the various styles and techniques he has used, unlike many other savant artists), he demonstrated perseveration and an occasional inability to maintain a problem-solving set on the WCST. Also surprising was GW's poor incidental memory for the Rey figure. His reproduction from memory was characterized by a fragmented approach, similar to the graphic savant described by Mottron & Belleville (1993). This might be taken as a sign of detail focus or weak coherence. Also suggestive of this cognitive style is GW's accurate and fast EFT performance, which compared with that of control participants was not significantly different, but was associated with a large effect size.

GW demonstrated intact implicit learning and IT that was comparable with that of the control group. At least one previously studied savant has shown surprisingly good IT, although he also had intellectual impairments, unlike case GW (Anderson et al. 1998). In accordance with the trend in findings among those with ASD, GW not only demonstrated implicit learning but his performance was comparable with that of controls. Therefore, it may be that intact, rather than enhanced information processing speed and implicit learning predict assets in ASD.

GW's grasp of intuitive physics did not exceed those of matched neurotypical controls, although his self-rated systemizing tendencies were (non-significantly, but with large effect size) higher and comparable with those of other adults with ASD (Baron-Cohen et al. 2003). In summary, findings from studying GW's calendar calculation implicate good memory, superior mental calculation and knowledge of calendar templates as underlying elements for his talent. More generally, GW's neuropsychological profile is consistent with a detail-focused cognitive style, as well as intact implicit learning and IT, all of which may be related to his multiple savant skills.

(b) Neuroimaging study

Consistent with predictions, relative to the mean cortical thickness of the control group, GW's cortex was: (i) thinner in regions associated with social cognition and other domains impaired in ASD (Frith & Frith 2006), but (ii) thicker in a bilateral segment of the superior parietal lobe, which has been connected with drawing and other visuospatial functions (Makuuchi et al. 2003; Simon et al. 2004) as well as calculation abilities (Dehaene et al. 2004). Without longitudinal imaging we cannot establish whether these anatomical differences played a part in the initial selection of GW's talent domains, or are the result of talent development and practice. However, the growing literature on brain changes with expertise development (e.g. Maguire et al. 2000; Draganski et al. 2004) suggests, perhaps, that GW's increased superior parietal thickness may have been acquired through practice of calendar and drawing skills. Increased cortical thickness in this region does not appear to be part of ASD *per se*: Hadjikhani et al. (2006) documented cortical thinning in areas associated with social cognition, similar to those shown here, in a group of adults with ASD (of a similar age to GW) relative to controls. However, these investigators did not identify

any regions of cortex that were thicker among adults with ASD relative to controls. Although the cortical thickness findings supported *a priori* predictions, they (particularly thicker superior parietal cortex for the savant) should be considered preliminary (requiring replication) because more conservative criteria, addressing the potential issue of multiple comparisons, might provide different results.

6. CONCLUSIONS

Consistent with recently delineated models of savant skills (e.g. Heaton & Wallace 2004), good memory, mental calculation, visuospatial processing as well as (implicit) knowledge of calendar structure and WCC characterized the cognitive profile of case GW. Possibly reflecting these assets in visuospatial processing and calculation, the superior parietal region of GW's cortex was the only area thicker than that of the neurotypical control group. By contrast, cortical thinning for GW as compared with neurotypical controls was noted in several regions associated with social cognition (e.g. superior and medial prefrontal cortices). These findings may be best viewed from a learning/practice-based model, in which domains (e.g. calendars, art, music) tapping into existing ASD-related strengths, such as detail-focused processing, are further enhanced through over-learning and reflected in cognitive profiles and brain structure.

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