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Neuropsychological Studies of Savant Skills: Can They Inform the Neuroscience of Giftedness?

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A selective review of past and present neuropsychological research on savant skills is highlighted, including both empirical findings and theoretical accounts. Results from this research are then compared to extant results within the giftedness literature. Three major conclusions are taken from this review of the research: (a) savant skills are inextricably linked to autism spectrum disorders; (b) neuropsychological models of autism spectrum disorders may help to explain the raised incidence of savant skills in this population and provide promising directions for future research; and (c) neuropsychological research into savant skills may have direct implications for better understanding the neuroscience of giftedness, particularly as it relates to domain-specific skills (e.g., mathematics), as opposed to general (i.e., high IQ) giftedness.

There are some interesting patterns of similarity in findings pertaining to various dimensions of human development and ability. Some of these patterns derive from research into the nature of autism, savant skills, and high intellectual functioning (see Table 1 for a listing and description of tasks commonly used in this research). This article explores some of these patterns and derives implications for the study of giftedness.

AUTISM AND SAVANT SKILLS

Autism Spectrum Disorders

Autism is a biologically based but behaviorally defined developmental disorder primarily affecting the areas of social interaction, communication, and flexibility of behavior. Current diagnostic conceptualization dictates that autism or autistic disorder (previously referred to as classical autism or infantile autism) is but one condition, which occurs along a spectrum of disorders (Gillberg, 1990; Wing & Gould, 1979), sometimes referred to as *autism spectrum disorders* (ASD) or *pervasive developmental disorders*. Autism is a lifelong disorder and may be diagnosed at any point during development, given that symptoms date from the first 3 years of life, although the majority of cases are diagnosed during the preschool and early childhood years. The commonly utilized diagnostic checklists are based on criteria for autism published in the DSM-IV (American Psychiatric Association [APA], 1994). The criteria are organized into three categories of symptoms, conceptually approximating Wing and Gould's (1979) *triad of impairment*: (a) impairment in social interactions, (b) impairment in communication, and (c) restricted, repetitive, and stereotyped patterns of behavior, interests, and activities.

One marked characteristic of ASD is the odd mixture of cognitive strengths and weaknesses. A particular individual may demonstrate limited ability to express or understand speech, while paradoxically demonstrating the ability to navigate fluently a driver's route without looking at a map. In even more extreme and rare cases, "islets of ability" known as savant skills are present. For example, Down (1887) described a patient with numerous cognitive difficulties who nevertheless memorized word for word all of Edward Gibbon's *The Decline and Fall of the Roman Empire*.

The Savant Syndrome: Features and Characteristics

The savant syndrome, despite its rarity, has been well documented in the medical and psychological research literatures for well over a century. Down's lecture to the Medical Society of London in 1887, in which he discussed a series of cases of individuals with disabilities who nevertheless displayed remarkable skills, began the still continuing inquiry into how and why savant skills emerge. This and other studies helped to establish the range of savant skills

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TABLE 1
Psychological Tests Used in Studies of Savant Skills and Their Functions

Test Name	*Domain Assessed*	*Layman's Description of Domains*
Wechsler Intelligence Scales for Children—Revised Wechsler Intelligence Scales for Children—III Wechsler Adult Intelligence Scales—Revised Wechsler Adult Intelligence Scales—III	Intelligence	Verbal and nonverbal intellectual functioning assessed through various age-appropriate tasks ranging from vocabulary knowledge to nonverbal problem solving (e.g., the Block Design subtest).
Inspection Time (IT)	Processing speed	How long you need a visual stimulus presented to make a consistently accurate "same-different" discrimination judgment?
Embedded Figures Test (EFT)	Cognitive style	Similar to "Where's Waldo?" A subject attempts to find as quickly as possible a hidden shape within a larger figure.
Hooper Visual Organization Test	Global processing	Given segments of a whole picture, can a subject piece them together?
Rey-Osterrieth Complex Figure	Visuospatial memory and organization	Given an abstract, novel line drawing can a subject accurately copy it and recall it from memory?
Wechsler Memory Scales—Revised	Short- and long-term memory	Verbal and nonverbal assessment of memory skills.
Wisconsin Card Sorting Test	Executive function, rule-learning, cognitive flexibility	Given a set of cards that can be matched on three dimensions (number, color, shape), subject is required to induce a rule and flexibly respond as the rule changes periodically.
Torrance Test of Creative Thinking	Flexible and creative thinking	Given cues or stems, a subject is asked to provide as many novel drawings/descriptions as possible under time constraints. This output is scored on fluency, flexibility, originality, and elaboration.
Autism Diagnostic Inventory	Autism symptoms; both current and historic	A standard parent interview used in the field to make a diagnosis on the autism spectrum based on both developmental history and current functioning.

and their exceptionality. For example, in his 1914 book, *Mental Deficiency*, Tredgold delineated the special aptitudes present in a group of 20 psychiatric patients. The list of skill areas resonates with those documented at present in the savant literature: calendar calculation (i.e., ability to name the day of the week on which a particular date [past, present, or future] has fallen or will fall), lightning mental calculation, musical abilities, mechanical skills, visual artistic abilities, and pseudo-verbal skills (e.g., hyperlexia or facility with foreign language acquisition). He also described such talents as remarkable in comparison to the population at large (not just compared to other patients), thus highlighting the salience and potential importance of such skill development.

Initially, individuals with intellectual impairments who nevertheless displayed strikingly exceptional skills were termed *idiot-savants*. Unlike current popular usage, *idiot* was previously a clinical term designating a category of mental retardation based on IQ level (i.e., IQ < 25), while savant, derived from the French verb *savoir*, "to know," means learned individual. Currently, *savant syndrome* (Treffert, 1989) has come into general usage. While the pejorative connotations of the idiot-savant label necessitated such a change, savant syndrome fails to convey the paradoxical nature of this intriguing condition.

Due to a lack of rigorous epidemiological investigations, the true prevalence of savant skills in ASD, in developmental disorders more broadly, and in typical development is unknown; however, several studies provide general indicators of the rarity of savant skills. Fifty-four savants were identified in 107 institutions for individuals with intellectual impairments, which resulted in an estimated savant skill prevalence rate of .06% among those with intellectual impairments (Hill, 1977). On the other hand, Saloviita, U. Ruusila, and L. Ruusila (2000) targeted all institutions in Finland currently serving individuals with developmental disabilities as well as subscribers to the two most widely circulated journals for the field of intellectual impairment, one of which catered to parents. In contrast to Hill's study, the savant skills survey revealed an incidence rate of 1.4 per 1000 (0.14%) individuals in the intellectually impaired population. Unfortunately, neither of these studies separated known (e.g., ASD) from unknown etiologies among the individuals with savant skills, so a significant number could have undiagnosed or unmentioned ASD. Based on parent reports, 531 out of 5400 children with autism (9.8%) were identified as having savant skills (Rimland, 1978). As a result, the discrepancy in findings, at least between the studies by Hill and Rimland, suggests that there is a significantly greater prevalence of savants in populations of individuals with autism as opposed to intellectually impaired individuals. Moreover, all of the potential savants studied by R. Young (1995) exhibited behavior associated with autism, regardless of their diagnosis. Case study descriptions of savants with complex patterns of disability (e.g., congenital blindness, intellectual impairment, and language disorder) also frequently make reference to behavioral features commonly associated with autism (e.g., musical savants; L. Miller, 1989).

Savant talent is occasionally seen in individuals with other developmental or neurological disorders, though they typically share key behavioral features with autism, such as obsessive, engrossing, and restricted interests (O'Connor & Hermelin, 1991). The diagnosis of autism requires evidence of repetitive behaviors and/or restricted interests that often interfere with daily functioning; however, they may also serve as motivators key to talent emergence (Simonton, 2001). O'Connor and Hermelin investigated restricted and repetitive behaviors in savants and found that regardless of diagnosis, savants demonstrated more of these behaviors than nonsavant controls matched for IQ and diagnosis. Moreover, although individuals with autism represent a relatively small proportion of the intellectually impaired population, the majority of talented, but intellectually impaired individuals have been diagnosed with autism. As alluded to earlier, in cases where savant talents were reported in individuals without autism, they frequently had developmental (e.g., Tourette's syndrome; Nelson & Pribor, 1993) or acquired disorders (e.g., frontotemporal dementia; B. L. Miller, Ponton, Benson, Cummings, & Mena, 1996; B. L. Miller et al., 1998) that include obsessive behaviors and/or restricted interests as clinical features. Therefore, converging evidence highlights the significance of obsessive and restricted interests in the development of savant talent, both in and out of the context of ASD, which may reflect practice effects and/or weak central coherence (WCC). Taken together this evidence strongly suggests that savant talent is most closely associated with ASD or at least ASD traits (Heaton & Wallace, 2004).

Another potentially insightful approach to examining the mechanisms subserving savant skill expression is a closer investigation of the skill areas themselves. It is striking that savant skills exist within a limited and recurring group of domains. As previously noted, these include calendar calculation, music, art, mental calculation, and pseudo-verbal skills (including hyperlexia and facility with foreign-language acquisition). Therefore, it would be revealing to examine shared aspects of these domains. It may be apparent upon first glance that these domains are predominantly nonverbal and that even the pseudoverbal skills are generally free of higher level linguistic demands. Individuals with hyperlexia are by definition relatively deficient in their reading comprehension and even Christopher, the well-known savant who can easily grasp some aspects of a novel foreign language (O'Connor, Smith, Frith, & Tsimpli, 1994), displays verbal skills primarily in his facility with vocabulary and underlying grammar.

As aptly pointed out in previous research, a second commonality among these domains is their purported reliance upon right-hemisphere functioning (Rumsey, 1992; Treffert, 1989). This postulation is significant in supporting brain-based models (e.g., Treffert) that highlight the importance of right-hemisphere compensation (and subsequent hyperfunction?) due to left hemisphere damage/dysfunction. Although promising, this hypothesis is somewhat tempered by findings that aspects of musical cognition, for example, pitch and rhythm, are subserved primarily by the left hemisphere (Platel et al., 1997). But this idea may provide leads in elucidating brain-based mechanisms for savant skill presentation in both individuals with developmental disorders and those with acquired neurological damage.

Perhaps the most convincing finding is that all savant skill areas contain high internal structure (L. Miller, 1989). Indeed, previous research indicates that savant domains share reliance on rule-based knowledge (Heavey, Pring & Hermelin, 1999; L. Miller, 1989; Nettelbeck & Young, 1996; O'Connor & Hermelin, 1984, 1987a, 1987b, 1990; Sloboda, Hermelin, & O'Connor, 1985). Moreover, the underlying systems for each of the savant domains can be broken down into elemental components and reconstituted to form meaningful wholes. Evidence suggests that both disembedding and reformulation abilities are intact in autism. For example, savant artists apply a local processing strategy in picture production but are nevertheless able to produce output that is globally intact. Thus, while processing strategies are strongly featurally biased, this does not appear to convey a disadvantage within savant talent domains.

Savant skills were long thought to reflect exceptional (rote) memory by savants. While good memory is undoubtedly a piece of the puzzle to better understanding savant performance, the work of Hermelin and O'Connor, among many others, indicates that savant skills may reflect learned rules, not merely rote memory. For example, calendar savants have been shown to make systematic errors in their calendar calculation (Cowan, O'Connor, & Samella, 2003). Moreover, other work indicates that calendar savants have knowledge of calendar regularities, which are then used in completing calendar calculations (Cowan, O'Connor, & Samella, 2001; Cowan, Stainthorp, Kapnogianni, & Anastasiou, 2004; Hermelin & O'Connor, 1986; E. Ho, Tsang, & D. Ho, 1991; O'Connor & Hermelin, 1984). Performance by savant musicians has also provided evidence of skill acquisition and expression dependent on other, non-memory-related processes. Eight keyboardist musical savants and a comparison group of eight typical musicians were asked to replay four- and eight-chord sequences varying in structure (L. Miller, 1995). No differences emerged between groups so that as structure decreased so did the participants' abilities to replay the sequences. Moreover, this investigation found that when errors were made, savants were more likely than controls to impose structure in the reproduced segments. This implies that savants' performances are not based on simple encoding and retrieval; rather, output will remain faithful to structural rules of the system, even if an exact replica is not reproduced.

The Development of Savant Skills

Savant skills present a paradox to the notions of talent and disability; on one hand, they are reported to be *self-taught*, while on the other hand, they sometimes are dismissed as nothing more than the product of relentless practice and over-learning. Savant skills have garnered attention and amazement, not only because of the paradoxical presence of a well-developed skill in the context of disability but also because of the nature of the emergence of these skills. Some of the most well-known and puzzling cases of savant syndrome have presented spontaneously; that is, they emerged seemingly highly developed, with no hint to their previous existence. One of the most striking and famous examples of suddenly emerging exceptional artistic ability is Nadia, a young girl with autism who was studied extensively by Selfe (1978, 1995). By 3.5 years of age, Nadia was drawing remarkably life-like horses in perspective. Interestingly, her drawing did not follow a typical developmental progression; instead, it was well refined from the outset and did not change much over time. Her drawings recreating horses with such rich detail and accuracy in terms of proportion and perspective were often based on pictures she had seen only once, though the reproductions were not simple copies; rather, the output by Nadia showed her own "highly personalized style." This is but one famous anecdote; it is clear that not all savants reveal sudden onset of a well-advanced skill; however, the exceptional cases that do are important because they refute claims that savant skills are nothing more than well-rehearsed skills. Even though sudden skill emergence is likely rare, a commonly noted aspect of savant-skill development is the notion of their being naïvely learned or *self-taught* (i.e., not formally taught), standing in stark contrast to similar skills in otherwise typically developing (TD) talented individuals.

The role of practice in the development of expertise is a well-researched topic. Ericsson and Faivre (1988) provided startling examples of memory feats attained by TD individuals after extensive practice. For example, one individual, case SF, after 30 months of practicing about 1 hour a day, several days a week, gradually increased his digit span from 7 to over 80 digits. Analysis of strategies revealed that meaningful associations of learned material (digits, in this case) were needed to overcome short-term memory limitations. SF, a long-distance runner, could utilize his knowledge of running times for various types of distance races (e.g., marathon) to assist in encoding this digit information.

Interestingly, the researchers extended their argument and examples beyond memory alone to include skills such as absolute pitch (AP). For AP development, they argued that some instruction is required in order to pair a note name to a pitch. However, Heaton, Hermelin, and Pring (1998) addressed this particular issue in a musically naïve group of children with autism and in a matched control group of TD children. Using a paired learning design, in which a series of pitches each was paired with its own animal picture, after multiple learning trials the testing phase began. During testing, children heard a tone and were required to identify (through pointing to one picture among competing options) the animal that went with that pitch. Children with autism, despite having no previous note-naming abilities (and therefore no proclivity for practice), were superior to TD controls in identifying the corresponding pitch, suggesting that AP (or at least potential AP) may be a relatively common though hidden skill among individuals with autism. In the only documented case of a TD participant successfully trained to attain AP (Brady, 1970), the emphasis of training was identifying a single tone. Such a piecemeal approach fits nicely with research literature demonstrating a featurally biased cognitive style for people with autism (discussed more fully later) and also with the study by Heaton et al. (1998). Even more revealing for the issue at hand, the Heaton et al. study demonstrates a natural, unpracticed aptitude (criteria given by Ericsson and Faivre as necessary to show that performance was not acquired through practice) in autism for the development of AP.

The studies mentioned, and others (e.g., Chase & Ericsson, 1981) showing exceptional skill development after extensive practice, are indeed very striking, but whether these findings are directly applicable to savant-skill development remains an open question. Extrapolation of these studies' results to savant skills is not necessarily valid. One significant hurdle, yet to be crossed in practice-based studies, is the enrollment of participants with low IQ or other disabilities in order to equate context of skill acquisition. Just because a TD individual can obtain a specified level of expertise does not mean that a savant with a much lower IQ has reached this same end point via the same route. Furthermore, Hermelin (2001) aptly pointed out that practice by an adult over a limited period of time cannot adequately replicate savant skill development with (usually) childhood inception and therefore suffers from the same pitfalls as attempting to apply results of adult-based brain lesion studies to neurodevelopmental disorders.

In summary, although practice may play an important role in talent development (savant or nonsavant) it is insufficient to account for most, if not all cases of prodigious skill, especially the rare cases when skills suddenly emerge with no previous hint of their existence. Moreover, as discussed later, the untaught, sudden emergence of skills argues for strong consideration of implicit learning mechanisms leading to early development of savant skills.

Savant Skills and Intelligence

Because of the striking combination of ability and disability, intelligence theorists have attempted to account, to at least some extent, for the savant syndrome. Exhibiting a single or sometimes multiple high-level skills in the context of low IQ presents a paradox. Some investigators have chosen to consider such skills as *unintelligent* by claiming that savant skills are overlearned and/or acquired through rote memory, and thus superfluous to the concept of intelligence (e.g., Howe, 1989). Other investigators (e.g., Hermelin & O'Connor, 1990) contended that these skills are the product of rule-based (implicit) learning in savant domains, based on findings of high IQ TD individuals failing to master skills displayed by savants.

Although very few intelligence theories account for savant skills in their formulations, there are a few notable exceptions. Outstanding among these is Anderson's theory of the minimal cognitive architecture at the heart of intelligence and cognitive development (Anderson, 2001). Briefly, this theory posits that knowledge, as assessed by traditional IQ measures, is acquired via two main routes, thinking and dedicated processing systems known as *modules*. One significant constraint on thought is the speed of a basic processing mechanism, which in turn determines individual differences in general intelligence. Moreover, speed of processing constitutes the unchanging, innate basis of these individual differences. The idea that a basic speed of processing mechanism contributes to or underlies aspects of intellectual functioning is not new and is in fact a major component of a number of theorists' views of general intelligence (e.g., Eysenck, 1988; Jensen, 1982; Nettelbeck, 1987). Evidence to support the relationship between a basic processing mechanism and intellectual functioning exists mainly in the form of correlations between measures of general intelligence and inspection time (IT), now the predominant way to assess speed of information processing. As defined by Anderson and Miller (1998), IT is "the stimulus exposure duration required by a subject to make a simple perceptual judgment, for example, the relative length of two lines" (p. 239). So, IT describes the minimum stimulus exposure at which a person consistently and accurately discriminates a stimulus feature. Exposure time of the stimulus is therefore varied in order to determine optimal performance. In this way, IT avoids difficulties inherent to RT studies, such as motoric and thinking time confounds when responding. These are especially apparent when the participant is unsure how to respond, which may result in a speed/accuracy trade-off. Indeed, IT may inherently tap neural processing speed, possibly one of the biological underpinnings of intelligence. Based on meta-analytic studies of TD adults and children, the correlation between IT and intelligence seems to hover around −.50 (Grudnik & Kranzler, 2001; Kranzler & Jensen, 1989; Nettelbeck).

In Anderson's model, the second significant method of knowledge acquisition occurs via modular processing. In theory, these dedicated processing mechanisms provide complex representations of the world that cannot be provided by the more general, central processes of thought and are hence independent of them. In practice, this then implies that modular processing should not be related to IT, the underlying mechanism of general intelligence. Both notions of processing speed and modular processing have particular relevance to understanding savant skills, considering how commonly descriptions include ease and speed with which tasks are completed by savants and the domain specificity of their skill (i.e., independence of the skill from intellectual functioning or skills in other domains). When testing calendar calculating savants, Hermelin and O'Connor (1983) found that their RT on most tasks was commensurate with their relatively low IQ, but when asked calendar questions, their RT was far better than predicted by their IQ.

IT among individuals with autism (Scheuffgen, Happé, Anderson, & Frith, 2000) has been compared to that obtained in a group of IQ-matched controls and in relation to expectations based on their own IQ scores. Interestingly, IT in autism was much better than expected, based upon the group's measured IQ; IT in the autism group was equal to that in a TD group with IQ scores 20 points higher on average and significantly better than that of an IQ-matched, intellectually impaired group. Therefore, this possible underpinning of intelligence was intact (or better) among individuals with autism, indicating that some other aspect(s) of cognition contributing to IQ is responsible for the depressed aspects of the IQ profile frequently observed in autism. Furthermore, 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 IQ. Anderson and colleagues' study is consistent with findings from the aforementioned study (Scheuffgen et al., 2000) in that people with autism demonstrate an IT commensurate with or superior to their own IQ. Therefore, it may be that superior processing speed is necessary for the development of some savant skills.

Several cognitive theories unrelated to intelligence theories also have attempted to explain the presence and ontogeny of savant skills, particularly in the presence of ASD.

NEUROPSYCHOLOGICAL THEORIES OF SAVANT SKILL DEVELOPMENT

Weak Central Coherence

In her seminal discussion of the characteristic cognitive features of autism, Uta Frith (1989) described the tendency of individuals with autism to favor local over global processing (a reverse of the typical trend) as a weak drive for central coherence (WCC). Frith conceptualized central coherence in typical development as a driving force to bring together vast amounts of information, implying cognitive efficiency reliant on the use of context and meaning to aid information processing. In essence, strong central coherence is not seeing the trees for the forest.

A characteristically spiky profile of intelligence subtest scores is well documented in the ASD literature, typically with elevated performance on Block Design in the Wechsler Scales (Happé, 1994; Lincoln, Allen, & Kilman, 1995; Rumsey, 1992). This visuospatial task represents a prototypical measure of central coherence; approaching the block design task at a detailed level (constituent parts instead of the gestalt or big picture) may result in superior performance. Indeed, given the affinity for approaching the task at a detailed level, individuals with ASD avoid the difficulty that unimpaired persons experience when completing this type of task, that is, trouble with inhibiting the perception of the gestalt so that the percept can be broken down into its constituent parts. As a result, they are little aided by presegmentation of the designs to be copied, unlike comparison groups matched for age or ability (Shah & Frith, 1993).

Similarly, when given the Embedded Figures Test (EFT; Witkin, Oltman, Raskin, & Karp, 1971), individuals with ASD perform comparably or superior to matched controls (Shah & Frith, 1983). The EFT requires one to find as quickly as possible a simple object or figure (e.g., a triangle), which is hidden within a picture of a larger, more complex object (e.g., a crane). Scoring is based on number correct and time needed to locate the hidden figure. Shah and Frith (1983) interpreted their findings in the following way: for TD individuals, the larger, more complex figure was more compelling and thus more difficult to inhibit in order to find the embedded shape. In individuals with ASD, the part is salient and there is little distraction from the gestalt.

Studies exploring coherence issues in ASD have not been limited to the visuospatial domain; processing of meaning in verbal material also has been investigated. Results from these studies suggest that meaning is extracted in ASD at the level of single words but is not automatically constructed when stringing together words; that is, for word lists in which all or subsets of these words are semantically related or at the level of sentences and narratives (e.g., Frith & Snowling, 1983; Kenworthy et al., 2005). For example, the meaning of a sentence determines the pronunciation of an ambiguous word in the Homograph Test (Happé, 1997; Snowling & Frith, 1986). This is demonstrated using *tear* in the following sentence: "In her eye, there was a big tear" versus "In her dress, there was a big tear." Children with autism often fail to utilize preceding sentence context for determining pronunciation (Happé, 1997; Lopez & Leekam, 2003; Snowling & Frith, 1986).

WCC goes some way toward explaining "islets of ability" in ASD, such as the ability to notice subtle changes in the environment or facility with jigsaws. However, how does this theory address the extreme form of cognitive strengths in autism, so-called savant skills? A small group of studies has directly or indirectly addressed this question. In an elegant series of studies, Heaton (2003) characterized the processing of musical information in autism as qualitatively different from that found in typical development. Superior ability to associate a pitch with a picture for later recall was noted in the autism group, but chord disembedding performance by children with autism was better in one condition and equivalent in another to that observed in the matched control group, depending upon the experimental paradigm utilized. These findings dovetail with those from other groups. When comparing performance between a group of high-functioning individuals with autism and a matched control group in their ability to make same-different judgments of pairs of melodies, Mottron, Peretz, and Ménard (2000) found similar results to Heaton, suggesting intact global musical processing. However, individuals with autism were better than controls at detecting changes in contour-preserved but featurally modified melodies, suggesting a featural bias in the domain of music. A later study by Bonnel and colleagues (2003) showed enhanced pitch discrimination abilities in autism, indicating good feature level processing in music. In perhaps the most significant study for better understanding musical savant skills in ASD, Heaton et al. (1998) demonstrated stable and superior memory for exact pitches in ASD. In the experimental task, participants were asked to pair a picture with a tone in an associative learning paradigm. Heaton and colleagues indicated that an information-processing bias favoring pitch over melodic information may predispose individuals with ASD to acquire AP much more commonly than is normally the case.

Heaton et al.'s (1998) findings fit well with the broader AP literature in which featural processing was linked to AP in the early years (Takeuchi & Hulse, 1993). A powerful argument was then put forward connecting these data to the development of savant musical skills in individuals with ASD. It may be that AP then serves as a necessary (but alone insufficient; Heaton, Pring, & Hermelin, 1999) precursor for the development of savant musical skills; every musical savant so far identified has possessed AP (L. Miller, 1989).

In art skills, detail focus may be important as well. For example, Mottron and Belleville (1993) studied a savant artist who utilized a relatively piecemeal approach to his drawings, especially when contrasted with the approach of a control subject, a professional draughtsman, who began his drawings with outlines before progressing to details or featural elements. Pring et al. (1995) found superior block design performance among savant artists with autism. Documenting this segmentational style of processing in both artistically gifted groups implies that the detail-focused cognitive bias present in ASD also may be responsible for the overrepresentation of savant skills. Finally, Cox and Eames (1999) studied two savant artists with strikingly dissimilar drawing styles but found that performance on the EFT was elevated in both cases, demonstrating a common ability to focus on local elements.

A compelling argument has also been put forward to delineate the relationship between a detail-focused processing style and savant skills in calendar calculation (Heavey et al., 1999) and in mental arithmetic (Heavey, 2003). Heavey and colleagues explained that dates can be viewed as fragments of the calendar, which may hold particular fascination for certain individuals, especially those with autism (e.g., consider the frequently mentioned early interest in birthdays as reported by parents). Given the evidence above for segmentational facility in individuals with ASD, combined with the idiosyncratic interest in calendar information, the stage is set for the possible development of calendar calculation skill.

Happé and Frith (2006) also pointed out that task success could be achieved by local instead of global or truly "configural" coherence. Indeed, these authors provided the example of stringing together calendar facts for calendar calculation as an index of local coherence (somewhat akin to grammatical processing in language), something savants with autism are good at doing. In terms of arithmetic ability, Heavey (2003) noted that a cognitive style characterized by field-independent processing is a known correlate of mathematical ability (Benbow, 1988). The tendency toward segmentation is prevalent among mathematical savants; many tend to proceed by breaking down operands into their respective factors or into smaller integers. Indeed, I have noted that an arithmetical savant with whom I worked displayed a propensity for segmentation of larger numbers into smaller, but equivalent, chunks to facilitate calculation. Moreover, this proposition also fits with evidence from prime number calculating savants. Anderson et al. (1998) noted that one savant had discovered the Eratosthenes method in which arriving at a decision as to whether a particularly large number is prime can be deduced by breaking down the number into all constituent prime numbers up to the square root of the number and testing for a remainder.

A number of case studies of savants, though not explicitly making the connection, contain evidence of WCC. For example, Stevens and Moffitt (1988) found that an individual with exceptional mental calculation abilities displayed borderline impairment in his ability to integrate visual information holistically, as required by the Hooper Visual Organization Test. Lucci, Fein, Holevas, and Kaplan (1988) also demonstrated many characteristics of WCC in their case study of Paul, a musically gifted boy with autism. He excelled on block construction, puzzle assembly, and paired associate learning tasks, while his approach to copying/drawing the Rey-Osterrieth Complex Figure was very disorganized, with a piecemeal approach. Moreover, his memory for short narratives was poor, standing in stark contrast to his excellent rote memory for discrete pieces of information.

Although these findings across studies and savant domains indicate a strong link between WCC and savant skills, it should be noted that many of these same findings also have been used to support the Enhanced Perceptual Functioning (Mottron, Dawson, Soulieres, Hubert, & Burack, 2006) alternative account.

Enhanced Perceptual Functioning

In the latest theoretical account of savant skill development, originally delineated in 2001 (Mottron & Burack), but recently updated (Mottron et al., 2006), Mottron and colleagues outlined a model proposing enhanced perceptual functioning (EPF) in autism. In the EPF a dichotomy is delineated between domain specific, neurally-specified, low-level cognitive mechanisms and domain general, distributed, high-level cognitive mechanisms. Within this framework, Mottron et al. have hypothesized that individuals with autism demonstrate highly developed low-level perceptual skills, likely due to hyperfunctioning of brain regions typically involved in primary perceptual functions or due to reduced functioning of high-level mechanisms. Savant skills are therefore predicted to be largely perceptually based within various modalities. From this model, an early emerging cognitive deficit leads to compensatory cognitive strengths that are practiced and over-learned to the point of becoming one or more restricted interests. This developmental approach to savant skill emergence is a significant strength. However, this model predicts only one area of talent per savant, which runs counter to findings in the literature and assumes that all savant skills are reliant on good low-level perceptual functioning, which may be difficult to explain in some instances (e.g., number and calculation skills).

Furthermore, despite its obvious strengths, Mottron and Burack's (2001) proposal that savant abilities never include aspects of relative weakness among persons with autism fails to account for several individuals described in the savant literature. For example, Smith and Tsimpli (1995) described a savant who shows outstanding foreign language acquisition abilities, while Dowker, Hermelin, and Pring (1996) described a savant poet. There also are examples of savants with autism who are very sensitive to the affective dimensions within their talent domain. For example, Richard Wawro, the savant artist described by Hermelin, Pring, Buhler, Wolff, and Heaton (1999), is very sensitive to color, and in his compositions he changes and intensifies colors in order to manipulate overall mood.

Extreme Male Brain Theory

Building on the early writings of Hans Asperger (Frith, 1991/1944), Baron-Cohen (2002) developed the extreme male brain theory of autism. This model defines the "male brain" and "female brain" psychometrically; that is, based on the extensive research findings regarding gender differences in cognition. As a group, women outperform men on measures of empathy, social judgment, ideational fluency, verbal fluency, fine motor coordination, and so on, while men exhibit superior performance on tasks measuring mathematical reasoning, finding a part within a whole, mental rotation, some spatial skills, and so forth. Male-brain types are considered to be more developed in terms of folk physics or systemizing but less developed in terms of folk psychology or empathizing and vice versa for the female-brain type. Broadly speaking, systemizing is understanding closed systems and their logic, including mechanical, constructional, mathematical, and spatial skills, while empathizing encompasses emotional processing and mind reading; that is, the ability to attribute mental states to oneself and others allowing one to make sense of and predict others' behavior. An individual may have neither a male nor a female brain type (i.e., fall between the two extremes) and designation of this type is not dependent on one's chromosomal gender.

Findings from a series of studies by Baron-Cohen and collaborators (e.g., Baron-Cohen & Hammer, 1997; Baron-Cohen, Wheelwright, Spong, Scahill, & Lawson, 2001; Lawson, Baron-Cohen, & Wheelwright, 2004) and others (e.g., Binnie & Williams, 2003) have demonstrated that indeed individuals with autism and Asperger's syndrome demonstrate an extreme form of the psychometrically defined male brain in that they perform well on tasks of folk physics and poorly on tasks of folk psychology. Most of the systemizing research has relied on questionnaires to assess interests and behaviors thought to reflect a bias toward and/or facility with systemizing. However, Baron-Cohen et al. (2001) devised a task to assess intuitive or folk physics (one's understanding of the physical causal world), with only real-world experience to guide these deductions. In other words, this task is appropriate for those who have no knowledge of physics per se. Baron-Cohen and colleagues administered this task to a group of individuals with ASD and to controls and, as predicted, individuals with ASD outperformed the control participants.

According to Baron-Cohen's (2006) systemizing theory of ASD, people with ASD are keyed into closed systems with minimal variance, such as the fairly lawful nature of savant domains, and are unable to process and are distressed by open systems with maximal variance, such as social behavior. This perspective may be complementary to the WCC account in that good local coherence as predicted by WCC may allow for the methodical approach to building up to and better understanding systems that are reminiscent of savant domains. However, systemizing theory, unlike WCC, offers a perspective on why individuals with ASD possess a drive to master systems, such as taxonomic categories or savant domains like music and numbers. Nevertheless, the relationship between measures (e.g., self-report) of systemizing and savant skills has yet to be examined.

OTHER COGNITIVE FINDINGS RELATED TO SAVANT SKILLS

Memory

Several famous savants who draw/paint from memory alone (e.g., Hermelin et al., 1999) resulting in almost perfect, photographic reproductions have led to speculations regarding the role of memory in savant skill expression. Nevertheless, savants rarely exhibit superior performance on standardized tests of memory (Howe, 1989), presumably because of extraneous demands. Empirical demonstration of outstanding savant memory can be elusive; therefore, it may be that methodological limitations, such as reliance on standardized tests, rather than truly unexceptional memory that accounts for the lack of experimental validation.

Indeed, it has been suggested frequently that savants show exceptional rote memory (Hill, 1978) partly because rote memory is thought to be unusually intact in autism (Happé & Frith, 1996; Rumsey, 1992). However, rote memory alone clearly does not explain savant talents within the classical domains of music, art, and calendar calculation, where greater flexibility in the manipulation of domain-specific information is essential and indeed evident in savants. To this end, Hermelin and O'Connor (1986) documented the use of two Gregorian calendar rules in a group of eight savants, the corresponding months rule and the 28-year rule. Moreover, investigations into the musical memory of savants (Sloboda et al., 1985; R. Young & Nettelbeck, 1995) show that although long-term memory is good, or indeed exceptional, reproduction of heard material is not verbatim, and reproduction errors preserve the important structural characteristics of the compositions. These studies remain important in demonstrating that savant skills cannot be explained away as merely feats of memory. Converging evidence therefore suggests that memory is an important cognitive component of savant skill but does not account fully for these skills.

Implicit Learning

Implicit memory and learning have traditionally been conceptualized as the effect of past experiences upon current performance, when one is not intentionally trying to recall the past experience. Definitions may differ in their particulars, but the majority involve the theme of an implicit knowledge base developed through nonconscious learning. It is unclear exactly how implicit learning plays a role in savant-skill development (Kalbfleisch, 2004). Given that implicit learning, in theory, is dissociable from explicit learning processes (e.g., Rugg et al., 1998), a generally or relatively heightened implicit learning capacity in savants could, in itself, underlie their attraction to and facility with materials in a specific set of domains. Therefore, it could be that an inherent preoccupation with structure and predictability, as would be the case for most, if not all, individuals with ASD, plays a prominent role in skill expression, or it could be due to overexposure to the material in question, which leads to the emergence of awareness and knowledge of its elemental properties. Perhaps even more likely, it could be a combination of these factors operating to various degrees depending on the individual in question but placing parameters on skill development. To this end, Spitz (1995) has proposed that overlearning, at least in the case of calendar calculation, may result in implicit learning of calendar structure, facilitating the development of such skill.

Implicit learning per se has not been well addressed within the ASD literature. However, the limited research thus far suggests intact implicit memory in individuals with ASD of average range IQ.

Bowler, Matthews, and Gardiner (1997) used a word stem repetition-priming task in testing a group of adults with Asperger's syndrome. Results confirmed comparable priming effects between a group of individuals with Asperger's syndrome and a control group matched on IQ and age. Similarly, Renner, L. G. Klinger, and M. R. Klinger (2000) documented intact implicit memory in a group of high-functioning children with autism through the use of a visual-perceptual repetition-priming task involving the very brief presentation of pictures.

Two unpublished studies by Wallace (2006) and L. G. Klinger, Lee, Bush, M. R. Klinger, and Crump (2001) documented intact implicit learning in groups of children with high-functioning ASD. However, there has been one exception to findings of intact implicit learning in autism. Mostofsky, Goldberg, Landa, and Denckla (2000), using a serial reaction time task, found a deficit in implicit learning for children with autism as compared to matched controls. Individuals with autism were not only slower in general on the task, but they did not show the characteristic decline in reaction time associated with learning. However, the version of the serial reaction time task used in this study raises the possibility that the predictable sequence came to explicit awareness for some if not all of the TD individuals (Willingham, Salidis, & Gabrieli, 2002) raising questions as to whether the task assessed "implicit" learning.

Going with the trend in findings, what is the implication of intact (and perhaps surprisingly good, given developmental level) implicit cognition in ASD, as documented in these studies? Speculatively, these skills may be tied to the purported ease with which savants naturally learn within their interest area. Interestingly, Lucci and colleagues (1988) noted that Paul, a musical savant, demonstrated excellent incidental learning of digit-symbol pairs (where there was no explicit instruction to retain this pair-wise information for later recall) from the Coding subtest of the Wechsler Intelligence Scales for Children—Revised Edition. He recalled perfectly all nine pairs and, remarkably, this occurred despite his poor performance on the task itself (as measured by number completed) and his limited exposure (90 seconds) to the information. Similarly, although not investigating implicit learning per se, Pring and Hermelin (2002) devised an intriguing experiment in which a calendar savant and two control subjects (including a mathematics professor) were asked to complete an associative learning task whereby they learned novel digit-symbol pairs. The savant, unlike the control participants, was able to quickly and efficiently learn the new associations (even after the associations/rules were altered) without any errors on first testing of rule learning. These are not the first allusions to the potential importance of implicit learning to savant skill development (e.g., Hermelin, 2001; Spitz, 1995; Treffert, 1989); however, these are some of the only data providing (indirect) support for a hypothesized superiority.

Domain Specificity of Savant Skills

Studies of TD chess experts reveal much better (and superior to controls) chess-related memory than general memory (Green & Gilhooly, 1992). Similarly, there are indications that certain cognitive processes, while impaired (e.g., cognitive flexibility) or average (e.g., memory) on standardized neuropsychological assessment of savants, may in fact be better when assessed within the savant domain. For example, previous results indicate that many savants with ASD are perseverative on tasks like the Wisconsin Card Sorting Test (e.g., Steel, Gorman, & Flexman, 1984), yet they show good flexible knowledge of the calendar when asked questions from different angles (Cowan et al., 2003; Wallace, 2006). For example, correct answers have been obtained when asking questions using not only the standard format such as "What day of the week was September 30th, 1980?" but also different formats, such as "In what years does January 15th fall on a Monday?"

This juxtaposition of good flexibility in one domain and poor flexibility in another seemingly parallels Heavey et al.'s (1999) demonstration of unexceptional scores on conventional memory tests by calendar savants, yet when these savants were presented with a list of "items" in a format roughly akin to a date from a calendar, they outperformed controls. Providing another example, one savant's memory for musical pieces was outstanding, compared not only to his overall cognitive functioning but also to that of a TD pianist (Sloboda et al., 1985). Also, among individuals with ASD who memorize bus schedules, O'Connor and Hermelin (1989) found enhanced domain-specific memory for numbers recognizable as "home" or familiar routes versus memory performance in line with their IQ for those numbers that were not familiar.

Since executive functions (including cognitive flexibility and fluency) and memory are conceptualized as central, domain-general cognitive functions, savants provide evidence for interesting dissociations based on the domain in which these functions are exercised. Studies by Ryder, Pring, and Hermelin (2002) comparing savant artists with autism to control groups of TD art students, nonsavant individuals with autism, and individuals with intellectual impairment demonstrate that on tasks of design fluency and visual synthesis, savants with autism showed a fluency deficit as severe as that found in the nonsavant controls with autism. However, on the Torrance Test of Creative Thinking, the drawing output of the savants with autism was more elaborate than that of the two IQ-matched control groups (individuals with autism and with intellectual impairment); thus, while these savants showed a pervasive fluency deficit characteristic of autism, they were nevertheless able to produce highly elaborated and original responses within their talent domain. These domain-specific findings are striking and could reflect modular knowledge practice/expertise effects or most likely the dynamic experience-dependent plasticity that operates on savant-skill development.

Based on findings from these studies of cognition, a model could be proposed in which WCC is a required building block for savant-skill development and in which other key cognitive functions (e.g., implicit learning) need to be intact (at least) in order for one to exhibit talented or prodigious savant-skill levels. One could conceptualize an additive and/or interactive model for these core cognitive domains. Though implicit learning performance has not been shown definitively to be superior for individuals with ASD, featural processing has been shown consistently to be favored by individuals with ASD. To this end, enhanced low-level discrimination and featural processing may lead to the development of a differently organized implicit cognitive system than would otherwise be the case. For individuals with ASD this system may be especially sensitive to domains containing high internal structure, such as music and calendars, and a prevalence of simple (usually perceptual rather than conceptual) information. This provides one speculative way that these cognitive mechanisms may not only act to enable an individual with ASD to develop savant-like skill but also interact with one another to this end. See Table 2 for a listing and description of published savant case studies, mostly asserting neuropsychological functioning.

BRAIN-BASED AND GENETIC ASSOCIATIONS WITH SAVANT SKILLS

Brain-Based Findings

Though the vast majority of savant skills occur in the context of ASD, there also are reports of savant-type skills within non-ASD populations. Miller and colleagues (B. L. Miller et al., 1996) described five previously nondisabled patients with frontotemporal dementia (FTD) who acquired new artistic skills with the onset of FTD. Several of these individuals had no previous history of particular artistic abilities, yet prodigious art skills emerged as the dementia progressed. Consistent with characteristics and traits of many savants, the modality of skill expression in these five older adults was visual, not verbal; the images were meticulous copies that lacked abstract or symbolic qualities; episodic memory was preserved but semantic memory was devastated; and there was intense, obsessive preoccupation with the artwork. The authors hypothesized that selective degeneration of the anterior temporal and orbitofrontal cortices decreased inhibition of visual systems involved with perception, thereby enhancing artistic interest and abilities. Kapur (1996) refered to such processes as *paradoxical functional facilitation* and speculated that this process accounts for unexpected behavioral improvement in discrete domains following brain injury.

Snyder and Mitchell (1999) argued that savant brain processes occur in each of us but are overwhelmed by more sophisticated conceptual cognition, which also is reminiscent of the seminal description of WCC by Frith (1989), indicating that individuals with autism focus on the trees rather than the forest. Snyder and Mitchell concluded that savants with autism have “privileged access to lower levels of raw information” not usually available (p. 591). Snyder and colleagues (2003) tested this hypothesis in 11 male volunteers using transcranial magnetic stimulation (TMS), a noninvasive technique involving excitation of neurons using a weak electrical current. They applied TMS to the left frontotemporal cortex while the participants carried out two drawing tests. TMS did not lead to any systematic improvement in naturalistic drawing ability, but it did lead to stylistic change in the drawings of 4 of the 11 participants. In a similar study using TMS to attempt to induce savant-level skills in 17 TD volunteers, Morrell, Young, and Ridding (2000), using a wide variety of tasks designed specifically to test savant abilities, failed to find skill enhancement. They concluded that the potential for savant skills may be limited to a small proportion of TD people just as they appear to be in people with developmental disabilities. These TMS studies therefore highlight the specialized nature of cognitive processes underlying savant performance in a select subset of individuals despite claims that these skills lie dormant in us all. Moreover, TMS is a powerful technique for localizing potentially important neuroanatomical regions but suffers equally from a one-point-in-time perspective. In other words, utilizing TMS to interfere with a potentially important brain region (e.g., frontotemporal cortex) in adults ignores important developmental aspects of skill development; interfering with this region is not the same as growing up with this skill.

Taking a different approach, at least one recent case study (Boddaert et al., 2005) reported functional brain activity (using positron emission tomography [PET]) associated with calendar calculation. During calendar calculation (as compared to rest), an adult with autism activated brain regions previously associated with memory, including the left hippocampus, left frontal cortex, and left middle temporal lobe. These findings reiterate the importance of memory processing for savant performance.

Good (particularly mental) arithmetic skills, though not required for calendar calculation, have been shown to influence calendar range (Cowan et al., 2003; Rumsey et al., 1992). Given that arithmetic skills may be related to calendar calculation ability, consideration should be given to studies examining cases of good mental calculation.

Investigators have begun to examine the brain basis of these mental calculating skills. Utilizing PET, Pesenti and colleagues (2001) compared brain activation patterns between TD controls and an arithmetic prodigy (RG) as they performed mental calculations. When completing simple calculations, both the expert and nonexperts showed activation in the brain bilaterally. However, when RG accurately and quickly completed more complex calculations, in

TABLE 2
Summary of Previous Case Studies of Savants, Organized by Domain of Talent

Participant(s)	*Skill(s)*	*IQ*	*Controls*	*Main Findings*	*Authors*
Calculation and Number Skills					
24-year-old male twins with II	Calendar calc	FSIQ = 60–70	None	In addition to calendar calculation, the twins can accurately answer if it was sunny, cloudy, or rainy, when given a date; George's calendar range is at least 6000 years; both twins could also answer accurately questions such as "In what years does 21 April fall on a Sunday?" or "What date is the 3rd Monday in April 1936?"—in contrast, neither twin can add, subtract, multiply, or divide simple, single-digit numbers.	Horwitz et al., 1965
16-year-old female with visual impairment and II	Calendar calc	WISC VIQ = 51	5 same-age girls with II and normal vision, 5 same-age TD girls with normal vision	Strong interest in calendars; calendar calculation accuracy far above that in the two control groups; ability to remember dates by association with particular incidents.	Rubin & Monaghan, 1965
13-year-old male with II and epilepsy	Calendar calc	FSIQ = 61	None	Difficulty with leap years limiting his range; based on report and deduction, he seems to have memorized a series of base dates from which he counts forward or backward to derive an answer.	Hoffman, 1971
53-year-old male with II/ encephalitis	Calendar calc and music	Stanford-Binet at age 6 years FSIQ = 54	None	Did not demonstrate exceptional short-term memory (though digit span was higher than overall IQ), mental calculation, or eidetic memory; testing calendar performance did not reveal much in the way of systematic error or response patterns; he could mentally add single-digit numbers, though he used his fingers for sums greater than 10.	Hill, 1975
24-year-old male with II	Calendar calc	WAIS FSIQ = 53 VIQ = 51 PIQ = 60	None	Strong left hemisphere specialization (as indicated by eye movements in response to questions presented bilaterally) for calendar questions while moderate for math questions; no specialization for music or spatial questions.	Burling et al., 1983
14-year-old male with autism	Calendar calc	WISC FSIQ = 54	None	Calendar range of 1900–2060; interested in birthdays, memorizing those of the staff members and other pupils; liked drawing calendars for particular months—on those drawings, some months were accompanied by what turned out to be (discovered through questioning) a representation of the moon; able to accurately answer questions such as "In what years will 9 October be on a Wednesday?"	Howe & Smith, 1988
38-year-old male with autism	Calendar calc	WAIS FSIQ = 71 VIQ = 68 PIQ = 78	None	Calendar range of 1899–2011; difficulty with simple division; as an adolescent he would repeatedly read and memorize hospital telephone numbers from phone books.	Hurst & Mulhall, 1988
18-year-old male with excised left hemisphere at 8 years	Calendar calc	WAIS-R FSIQ = 84 VIQ = 81 PIQ = 81	None	Reported visualizing the current year's calendar before beginning serial calculations; better than chance though not exceptional by calendar savant standards; RT and accuracy were positively correlated with distance from the current year; concurrent verbal and visual working memory tasks did not significantly interfere with calendar performance.	Dorman, 1991
19-year-old male with II	Calendar calc	WISC FSIQ = 75 VIQ = 66 PIQ = 91	None	Only began calendar calculation 3 years prior to the study, but he had an unusual prior interest in reading and keeping calendars; no errors in 20th and 21st centuries; systematic errors were obtained for testing of dates before or after these centuries indicating consistent methodology; seemed to use the 28-year rule based on his occasional writings on paper during solution of problems; when given impossible dates, he gave answers at random and did not protest; for a 10-year span was able to convert, without errors, the Gregorian calendar to the Chinese calendar; able to answer questions of the variety "What year is it when 15 March falls on a Friday?"; good visual digit span of 12 vs. auditory digit span of 7.	E. Ho, Tsang, & D. Ho, 1991
17-year-old male with Tourette's syndrome	Calendar calc	WAIS-R VIQ = 74 PIQ = 64	None	Unable to provide answers to calendar questions preceding his birth; could provide the day and date for past events he experienced; he could not explain how he answered these questions, but denied "remembering" them.	Moriarty et al., 1993

(*Continued*)

TABLE 2
(*Continued*)

Participant(s)	*Skill(s)*	*IQ*	*Controls*	*Main Findings*	*Authors*
44-year-old male with autism and Tourette's syndrome	Calendar calc	VIQ < 40 PIQ = 66	None	Could open a box of matches, quickly close it and accurately estimate the number enclosed; yet he had impaired verbal and nonverbal memory at immediate and delayed recall.	Nelson & Pribor, 1993
46-year-old male with autism	Calendar calc	PPVT = 78 Ravens = 108	One TD adult, one mathematics prof	Fast, spontaneous ability to recognize new simple rules and relationships; the savant's associative learning (of various letter-number combinations) was significantly better than that of the TD adult and comparable to that of the math professor.	Pring & Hermelin, 2002
22-year-old male with autism	Calendar calc	WAIS FSIQ = 66 VIQ = 83 PIQ = 45	None	Using PET, calendar calculation was associated with a brain network (i.e., left hippocampus, left middle temporal gyrus, and left inferior frontal gyrus) previously implicated in studies of memory.	Boddaert et al., 2005
29-year-old male with autism	Math	WAIS FSIQ = 91 VIQ = 94 PIQ = 89	None	Excellent auditory rote memory (two tests of digit span) in contrast to poor executive functioning (Wisconsin Card Sorting Test, the Trail Making Test) and memory for complex visual (ROCF) and verbal (orally presented stories) material; scored 140 (at the 99th percentile) on a math achievement test.	Steel et al., 1984
34-year-old male with Asperger's syndrome	Mental calc	WAIS-R FSIQ = 99 VIQ = 114 PIQ = 82	None	Ceiling performance on the Digit Span subtest of the WAIS-R reflecting excellent auditory rote memory (particularly for numbers), above average score on the arithmetic subtest of the WAIS-R; knew simple rules (e.g., all squares end in the digits 0, 1, 4, 5, 6, 9) that aided his calculations.	Stevens & Moffitt, 1988
36-year-old male with autism	Mental calc	PPVT = 52 Ravens ≥ 90th percentile	5 high-IQ TD adults	Faster and more accurate than controls in mentally solving multi-digit multiplication problems; with assistance, able to learn a novel algorithm based on converting Celsius to Fahrenheit, but practice brought only limited improvement.	Kelly et al., 1997
21-year-old male with autism	Prime number calc	PPVT = unscorable Ravens = 140	Expt 1: 1 adult male in his late 30s with a degree in math and electronics; Expt 2: 7 second-year undergrad males ages 19 to 20 majoring in math	He was more accurate and quicker than the control in prime number identification; his IT was commensurate with an average to above average IQ, which contrasted with his verbal IQ; he utilizes an established rule to calculate prime numbers.	Anderson et al., 1998
16-year-old male with II	Mental calc	WISC-R FSIQ = 51 VIQ = 47 PIQ = 65	None	Impaired concept formation and color-word interference effects; a structural brain scan (MRI) revealed increased volume in the right temporal region (reversed from normal); using SPECT during mental calc versus baseline, marked generalized increased perfusion, particularly over the right parietal region.	González-Garrido et al., 2002
Artistic Abilities					
34- to 36-year-old male with autism	Drawing	WAIS FSIQ = 88	Control draughtsman	Unlike the control, he exhibited anomalous hierarchical organization of local elements and global configuration of visual stimuli (Navon-type task, im/possible figure drawing, order of graphic recall).	Mottron & Belleville, 1993
46-year-old male with autism and visual impairment	Painting	PPVT = 47 Ravens = 55	None	Comparing photographs of models and resulting paintings demonstrates alterations due to his individual style and visual impairment as well as subtle memory transformations.	Hermelin et al., 1999
9-year-old male with autism	Drawing	Scores not provided, but PIQ subtest performance in the average to below average range	None	Exceptional visual memory; SPECT shows bilaterally increased frontal perfusion and bilateral anterior temporal lobe hypoperfusion, which was more pronounced on the left than the right side; these findings parallel those of individuals with frontotemporal dementia who have developed art and other skills (or had the preexisting skill altered) after onset of the dementia.	Hou et al., 2000

Musical Ability					
35-year-old male with II	Music and memory	WAIS FSIQ = 73 VIQ = 52 PIQ = 92	None	Musical ability judged to be “outstanding”; after viewing a novel 2.5-page printed passage once or twice, he can reproduce verbatim its contents; he also displays an excellent memory for personal and historical events; scored at a superior level in recalling digits in a reversed order and in his memory for sentences.	Anastasi & Levee, 1960
34-year-old male with II and cerebral palsy	Music	FSIQ = 40	26-year-old male professional musician	In response to different styles of music for improvisation, he produced more music than the control; the improvisation of the control more closely reflected the melodic line, tonality, and texture of the piece while his improvisation included more cadenzas, transitions, and elaborations.	Hermelin et al., 1989
12-year-old male with autism	Music	WISC-R FSIQ = 105 VIQ = 100 PIQ = 111	For IT: the savant’s 15-year-old younger brother and his 11-year-old younger brother as well as the mean IT from a sample of 87 adults	His IT was commensurate with his older brother’s but better than his younger brother’s and those of adults on whom this IT task has been used; scored 140 on quantitative reasoning index of the Stanford-Binet; AP confirmed via two tests; he could accurately repeat, after hearing it only once, seven bars of a novel (to him) piece with only one (harmonic) note error; on the WISC, he obtained ceiling performance on the Block Design, Digit Span, and Coding/Digit Symbol subtests.	Young & Nettelbeck, 1995
17-year-old female with autism	Music	WAIS-R FSIQ = 71 VIQ = 73 PIQ = 70	CA and MA matched controls of various sample sizes (range = 3–16) for neuropsych tasks as well as a sample of musicians (*n* = 3) for musical tasks	Confirmed AP ability and exceptional long-term memory for musical pieces when played on a piano; intact hierarchical local-global processing; cognitively inflexible (WCST, Trails B, Alternate Uses Test).	Mottron et al., 1999
Other Skills					
Adult male with a gunshot wound to the head, entering through the left temple at 9 years	Mechanical	None	None	Mechanical ability emerged after brain injury, in contrast to struggles in relearning language, reading, writing, and arithmetic.	Brink, 1980
31-year-old male with autism	Foreign languages	WAIS VIQ = 98 PIQ = 52	None	Good conceptual and functional lexical knowledge but limited syntax (based on native English) prevents native speaker-like fluency.	O’Connor et al., 1994
45-year-old female with Asperger’s syndrome	Poetry	Inconclusive—because of non cooperation and poor understanding of the requirements	Semi-professional female poet in her early 30s with physical and sensory disabilities including moderate hearing loss	Unlike the control, she shows poor formal language as opposed to good use of poetic devices (e.g., rhyme, alliteration, and metaphors), in-depth self-analysis, and detailed description of interpersonal relationships and of nature and landscapes.	Dowker et al., 1996
36-year-old male with autism	Memory	WAIS-R estimated VIQ = 65	8 IQ matched adults, 9 normal IQ adults, one overtrained adult	Recall of proper names (not common names or neologisms) superior to that for IQ matched controls and commensurate with that for individuals of higher IQ; he showed similar frequency effects (better recall for more frequently occurring proper names) to controls; face recognition superior to IQ matched controls and commensurate with that of higher IQ controls; when asked to match proper names and professions with novel and famous faces, his performance was equivalent to that of matched controls.	Mottron et al., 1996

Note. II = intellectual impairment, FSIQ = Full Scale (Total) IQ, VIQ = Verbal IQ, PIQ = Performance (Nonverbal) IQ, WISC = Wechsler Intelligence Scales for Children, WAIS = Wechsler Adult Intelligence Scales, PPVT=Peabody Picture Vocabulary Test, IT = Inspection Time, WCST = Wisconsin Card Sorting Test, MRI = Magnetic Resonance Imaging, SPECT = Single Photon Emission Computed Tomography.

contrast to controls, he recruited a system of brain areas implicated in episodic memory, including right medial frontal and parahippocampal regions. This finding corresponded to a previous behavioral case study involving RG (Pesenti, Seron, Samson, & Duroux, 1999), which showed that RG not only had a greater short-term memory store for numerical information than did controls but that he also had a great deal of arithmetic data readily and quickly available via long-term memory. In this way, he exploited the unlimited storage capacity of long-term memory to maintain the sequence of steps and intermediate results needed for the more complex calculations. In contrast, the nonexpert group relied on more typical and limited span short-term working memory. Pesenti et al.'s study (2001) stands out not only because it designates unique brain mechanisms in the expert when he performs his special skill but also suggests that the prodigy is relying on some special memory recruitment when performing his skill, as may be the case for certain savants.

Genetic Findings

Other biological mechanisms also may play a prominent role in savant-skill development. Indeed, there is some evidence that savant skills have genetic relevance. One linkage study (Nurmi et al., 2003) has associated regions of chromosome 15 with savant-related items from the Autism Diagnostic Inventory, a gold-standard measure of autism symptoms for diagnosis, though an attempted replication of these findings failed (Ma et al., 2005). Genetically informative populations, such as Prader-Willi syndrome (disorder of chromosome 15) and Williams syndrome (deletion of a portion of chromosome 7), also may elucidate this relationship. For example, surprisingly good performance on jigsaw puzzles has been noted among individuals with Prader-Willi syndrome (Dykens, 2002) and strong interest and ability in music has been described among individuals with Williams syndrome (Levitin, 2005).

As discussed later, it seems that individuals with similar skills to savants (e.g., musicians with AP and artists) also display some of the unique cognitive characteristics of these individuals, such as good segementation abilities (Brown et al., 2003; Pring et al., 1995). To date, inheritance patterns of savant skills per se have not been assessed fully via family studies, although there is a limited literature on the heritability of savant-related skills. For example, family studies (Baharloo, Service, Risch, Gitschier, & Freimer, 2000) and twin studies (Drayna, Manichaikul, de Lange, Snieder, & Spector, 2001) suggest that AP, a skill overrepresented among individuals with ASD and seemingly universal among savant musicians (L. Miller, 1989), is highly familial and heritable. Moreover, preliminary work from R. Young (1995) indicates that relatives of savants may be more likely to exhibit savant-like skills than do relatives of nonsavant individuals.

Of course, environmental factors (e.g., socioeconomic factors and exposure to material within savant domains via education and training) need to be accounted for and may also prove informative, as they have in models of gene-environment interplay in the expression of skills such as AP (Zatorre, 2003). Taking it a step further, it may be that relatives of individuals with ASD (with or without savant skills) exhibit more skills within savant domains partly because of their propensity to demonstrate subclinical ASD traits (e.g., good segmentation abilities/WCC; de Jonge, Kemner, & van Engeland, 2006; Happé, Briskman, & Frith, 2001) that are associated with savant domain skills among non-ASD gifted individuals (e.g., Brown et al., 2003; Pring et al., 1995).

Savant skills provide a testable model for assessing knowledge organization within the brain and savant-like skills increase linkage to key genetic regions (Nurmi et al., 2003) and have demonstrated high heritability (Baharloo et al., 2000; Drayna et al., 2001). Nevertheless, the biological mechanisms underlying savant skill expression, particularly in ASD, remain largely unknown and open for future inquiry.

Findings from Research Comparing Savant Skills and Giftedness

Findings from investigations comparing savants and similarly talented TD individuals (across domains) often implicate similar mechanisms underpinning skill in both groups. For example, in a previously mentioned study involving a prime number calculator with autism, Anderson et al. (1998) found that both this individual and a trained mathematician used an algorithm described by Eratosthenes in the third century B.C. (for another perspective, see Yamaguchi, 2005). Similarly, Kelly, Macaruso, and Sokol (1997) found that a calculating savant used similar computational strategies to those of normal expert calculators. One study indicated that, compared to a control group matched for nonverbal IQ and diagnosis, savant artists with autism have superior perceptual-motor skills; they were less likely to commit errors in mirror drawings and on tests of fine motor skill and they were both quicker and more accurate in completing jigsaw puzzles (Hermelin, Pring, & Heavey, 1994). In another series of experiments, Hermelin and O'Connor (1990; O'Connor & Hermelin, 1987a, 1987b, 1990) showed that savant artists' visuospatial recall and recognition were commensurate with their IQ, but their picture matching and graphic copying skills were commensurate with those of TD talented controls. Finally, Ryder and colleagues (2002), using a test of visual synthesis, found that originality scores for savant artists equaled those of gifted art students.

WCC is well documented in individuals with ASD, including those with savant skills. Pring and colleagues (1995) showed that preference for detail-focused information processing may be a shared skill between savant artists with autism and artists without a developmental disability. In other words, the ability to see the gestalt or whole in terms of its constituent parts may facilitate the emergence of artistic talents in all individuals, not simply those with ASD. Corroborating this notion is the anecdotal evidence that classes for teaching drawing skills to children and adults often ask students to copy upside-down pictures. Presumably, part of the reason for this approach is to have people adopt a more part-oriented style, disrupting their usual configural bias. Similarly, gifted individuals are more likely to exhibit a field-independent learning style (a component of which includes breaking down a whole picture into its component parts) than are other TD individuals (Witkin & Goodenough, 1977; Young & Fouts, 1993), again reminiscent of WCC. Finally, social eccentricity and high scores on the Block Design task, both of which characterize ASD, have been reported among people who possess AP, even when compared to non-AP musicians (Brown et al., 2003). These findings point to a shared ability by talented individuals (whether ASD or TD) to focus on details and this detail focus may contribute to talent development in both groups.

The importance and role of motivation, although difficult to quantify, cannot be overstated in the expression of savant-like skills, whether in the context of ASD and other neurodevelopmental disorders or among TD individuals. For ASD, the lines between what is termed *motivation* and what is called a *restricted interest* are often blurred. Nevertheless, this strong drive to pursue one's interest(s) only serves to maintain and possibly expand skill development. Indeed, motivation, in the form of intense practice, has been implicated in skill development in a variety of talent domains for savants, prodigies, and other talented individuals. Ericsson and Charness (1994) as well as Howe, Davidson, and Sloboda (1998) have taken this view to its most extreme by accounting for prodigal and savant performance purely through these individuals' strong interests and intense practice. However, the notion that exceptional performance in most domains can be replicated through extensive practice has been met with much resistance. Indeed, the demonstration of rule use, top-down influences, and sudden skill emergence (precluding the influence of practice) all serve to refute this contention.

Discrepancies in paths to skill development (in TD versus ASD) attributable to atypical development (beyond low IQ) also may prove revealing. For example, cultural and societal factors may help to explain why calendar calculation skills are unique to individuals with ASD versus TD individuals. Although individuals with calendar skills may be encouraged and reinforced for their success in calendar calculation (compared to their other daily living and academic endeavors in which they may struggle), an argument could be made that individuals with ASD, because of difficulties in theory of mind and social understanding, are not as susceptible to conform to the broader culture's norms. Hence, a seemingly idiosyncratic skill like calendar calculation can develop and thrive in this context, while it would face more obstacles in the context of typical development. Though there are key distinctions between savants and TD gifted individuals, similar mechanisms may operate on domain-specific skill.

SUMMARY AND CONCLUSIONS

Savant skills often are presented as amazing and exceptional, almost to sensational levels. Hence, they often have been described in a way that has seemingly little scientific relevance. In contrast, what is becoming clear from the burgeoning literature is the potential relevance of savant skills not only to better understanding talent and skill development in general but also to elucidating models of intelligence, learning, and memory, and etiological mechanisms operating on various levels (i.e., gene, brain, and behavior) in ASD. Additionally, savant skills provide an unobstructed window through which to observe and study domain-specific skill. Given demonstrated mechanistic commonalities that may underlie savant skills and certain forms of giftedness (i.e., domain specific, not global, high IQ forms), the study of savant skills indeed may inform the neuroscience of giftedness.

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