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Review

Veridical mapping in the development of exceptional autistic abilities

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ABSTRACT

Superior perception, peaks of ability, and savant skills are often observed in the autistic phenotype. The enhanced perceptual functioning model (Mottron et al., 2006a) emphasizes the increased role and autonomy of perceptual information processing in autistic cognition. Autistic abilities also involve enhanced pattern detection, which may develop through veridical mapping across isomorphic perceptual and non-perceptual structures (Mottron et al., 2009). In this paper, we elaborate veridical mapping as a specific mechanism which can explain the higher incidence of savant abilities, as well as other related phenomena, in autism. We contend that savant abilities such as hyperlexia, but also absolute pitch and synaesthesia, involve similar neurocognitive components, share the same structure and developmental course, and represent related ways by which the perceptual brain deals with objective structures under different conditions. Plausibly, these apparently different phenomena develop through a veridical mapping mechanism whereby perceptual information is coupled with homological data drawn from within or across isomorphic structures. The atypical neural connectivity characteristic of autism is consistent with a developmental predisposition to veridical mapping and the resulting high prevalence of savant abilities, absolute pitch, and synaesthesia in autism.

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1. Introduction: veridical mapping in autism and savant syndrome

The autism spectrum (AS) is characterized by variation across and within domains of functioning, as well as with regard to the specific combination, intensity, and number of traits manifested by diagnosed individuals. This heterogeneity was partly addressed in the DSM-IV and ICD-10 systems with subgrouping of persons across the autism spectrum according to polythetic diagnostic criteria. In the DSM-V, there is instead one categorical autism spectrum diagnosis, with clinical specifiers such as language, intelligence, and associated genetic syndromes (Szatmari, 2011). Although heterogeneity in autism is often considered symptomatic of an inability to delineate the essence of autism and the resultant use of excessively broad criteria or imprecise diagnostic methods, an alternative approach is to consider that heterogeneity might be important to our comprehension of autism. This suggestion is supported by the striking observation of within-subject heterogeneity in performance against a typical baseline, with peaks of ability in certain areas of functioning contrasting with deficits in other areas. Peaks, or exceptional abilities, are heterogeneous across autistics, as they encompass a wide range of superior perceptual abilities in auditory and visuo-spatial tasks, as well as specific focused or restricted interests (e.g., a specific period of history, a specific animal species), and specific savant abilities (e.g., calendar calculation, drawing) that are displayed by some, but not all, persons on the autism spectrum.

According to the enhanced perceptual functioning (EPF) model (Mottron and Burack, 2001; Mottron et al., 2006a), autistic perception involves enhanced low-level (e.g., discrimination) and mid-level (e.g., pattern detection) cognitive processing, and increased autonomy of perception with respect to top–down processes. The mechanism of veridical mapping (VM), an extension of EPF, has been proposed (Mottron et al., 2009) in an attempt to account for the role of perception in the high prevalence of savant syndrome in autism (Bennett and Heaton, 2012; Howlin et al., 2009; Rimland, 1978). Grounded in the enhancement of perception and pattern detection observed in autism, we propose that VM can account for enhanced memory for couplings between homologous parts of similar patterns both within and across perceptual modalities that underpin the genesis and development of savant abilities.

The aim of this paper is to further develop VM and to illustrate how it can account for savant syndrome in autism, but also for other phenomena often observed among persons on the autism spectrum and implicated in its apparent heterogeneity. In the first part of this paper, we argue that savant skills and peaks of ability in autism reflect the same heterogeneity and we review the evidence that they might rely on common cognitive, and possibly cortical, mechanisms. We then present seven components of VM based on observations from savant syndrome. In the second part of the paper, we describe how VM can account for structural commonalities among savant syndrome (using the example of hyperlexia, i.e., the precocious ability to read in advance of comprehension), absolute pitch (AP, i.e., the ability to name notes without reference to an external standard), and synaesthesia (i.e., the triggering of perception in one modality by perception in another modality), all of which are, or are likely, more prevalent in autism than in the typical population (Johnson et al., 2011; Rimland and Fein, 1988). Drawing on the literature about the neurological basis of hyperlexia, AP, and synaesthesia, we relate these phenomena to our understanding of the neurological foundations of these abilities in autistics. We then emphasize that the development of these three phenomena and their associated cognitive characteristics is due to common alterations of perceptual mechanisms. Finally, we conclude by applying our conceptualization of autistic domain-specific abilities to the understanding of the marked phenotypic heterogeneity in autism, particularly with regard to the presence or not of speech development delays and anomalies, and its relevance for the integration of autistics in a non-autistic world.

2. Domain-specific abilities in autism

2.1. Domain-general versus domain-specific abilities

Cognitive heterogeneity in the performance of AS persons has been characterized reductively as involving "splinter skills," a questionable term that may encompass both domain-specific, or savant, abilities (e.g., calendar calculation), and domain-general peaks of ability across an array of tasks (e.g., auditory and visuo-spatial). Most definitions of domain-specific abilities (Heaton and Wallace, 2004; Hill, 1978; Howlin et al., 2009; Miller, 1999; Nettelbeck and Young, 1999) involve a superior skill in relation to the individual's baseline cognitive performance and/or in comparison with the typical population. These skills are most commonly conceptualized within the context of a neurodevelopmental condition in which cognitive and adaptive functioning are atypical. Canonical examples of autistic savants include outstanding draftspersons and artists such as Stephen Wiltshire (http://www.stephenwiltshire.co.uk/), Nadia (Selfe, 2011), and E.C. (Mottron and Belleville, 1993, 1995), all of whom display exceptional skills in the manipulation of a specific material (three-dimensional graphic representations) in contrast with expectations associated with their developmental disabilities. Within this perspective, the conceptualization of savant abilities partly overlaps with that of domain-general cognitive peaks. One example of a peak of ability among autistics is their higher scores on the Wechsler block design (BD) task, which consists of reproducing a figure with bicolored cubes, relative to their scores on the other subtests of the Wechsler Intelligence Scales (Happé, 1994; Shah and Frith, 1993).

Domain-general and domain-specific skills differ both in terms of their prevalence among the population of autistics and the level of specificity of the material that is involved. Relative or absolute domain-general peaks of ability are common, even if they are not manifested by all autistic individuals. Although specific skills emerge in response to a specific task, the cognitive operations that gave rise to cognitive peaks may function similarly across a wide range of materials which share a specific dimension and can therefore be considered to be *dimension-specific* but *domain-general*. For example, the BD peak that is observed in approximately half of all autistic persons with speech delay (Caron et al., 2006) is representative of multiple visuo-spatial abilities, regardless of the material that is involved. In contrast, savant abilities, despite some similarities in the materials involved, are usually found in a unique subject in its specific form, as they are *domain-specific* and limited to a class of operations with a limited class of entities. These abilities are found only in small subgroups of autistics, even if one individual may present several domain-specific abilities. One such example is early hyperlexia *stricto sensu* for which a domain-specific ability, advanced decoding, is associated with autism and contrasts with apparent developmental level, or cognitive, communicative, and adaptive abilities (Grigorenko et al., 2003).

Contrasting domain-general and domain-specific skills is informative about the role of baseline intelligence in the definition and understanding of autistic peaks of ability. Both peaks of ability and savant syndrome can be understood in relation to baseline intelligence or level of adaptive functioning either within an individual's cognitive profile or across autistics. However, the more common domain-general peaks do not reflect enhanced performance relative to the average performance in the population of autistics, but rather among autistics as compared to typically developing (TD) persons with similar levels of intelligence. Accordingly, peaks of ability, such as the one observed on BD, are typically defined as performance significantly above average (here, 1.5 standard deviations above the mean of the other Wechsler subtests), under the assumption of a normal distribution of performance among both TD persons and autistics. However, the distribution of autistics' performance is skewed to the right, thus indicating a better performance.

We can hypothesize that an enhanced performance in domain-general peaks will not be observed if tasks are standardized on autistic performance. As a consequence, the extent of the size of any peak of ability is at least partly a function of the matching strategy used to compare the performance of autistics and that of non-autistics. If certain language-based instruments are used, autistics' intelligence risks being underestimated, thus their scores on areas of strength will be similar to those of TD persons with higher IQs on the same instrument. In contrast, the finding of superior performance of autistics may lose its statistical significance when tests which minimize mandatory language demands are used, as autistics will typically score higher and will, therefore, be matched to TD persons at a higher level (for a discussion of matching issues in the study of autistics, see Burack et al., 2004). Thus, some, but not all (e.g., pitch discrimination, Simard-Meilleur et al., 2012) domain-general peaks of ability may be favored or magnified by matching strategies. However, our focus in this paper is on the types of superior performance that are so robust that they transcend matching strategies, and on how these performances, in as much as they are found only among some autistics, contribute to within-group autistic heterogeneity.

2.2. Prevalence and specificity of domain-specific abilities in autism

Estimates of the prevalence of savant abilities among persons on the autism spectrum range from 1/200 (Hermelin, 2001) to 1/3 or even higher when not distinguished from peaks of ability (Bennett and Heaton, 2012; Howlin et al., 2009). A prevalence of 10% was classically reported by Rimland (1978) based on a postal survey of 5400 parents of autistic children that included questions about special abilities related to music, memory, numbers, and art. In a study with a large cohort of autistics, Howlin et al. (2009) found that 28.5% of the participants met criteria for a savant skill based on parental reports, and 17% met criteria for an exceptional skill within Wechsler intelligence scales. In a parental questionnaire screening, Bennett and Heaton (2012) found that 42% of a sample of 125 AS children and adolescents were reported by their caregivers to possess a skill that contrasted with their overall level of functioning. Among the AS persons in the database of the Specialized Clinic for Pervasive Developmental Disorders of Rivière-des-Prairies Hospital, savant abilities, as defined by the Autism Diagnostic Interview-Revised (ADI-R; Lord et al., 1994), were found in 45.3% (143/316) of AS individuals with speech onset delay or anomalies, and in 72.9% (97/133) of AS individuals without speech delay. In the same database, a BD peak was found in approximately half the AS population with speech delay or anomalies, and adding difficulty to the standard BD task raised the possibility of a BD peak in an even greater percentage (Caron et al., 2006). These numbers could be further increased as some kind of domain-specific superior ability is plausibly associated with expertise in any area of intense focused interest, and such interests are diagnostic of autism.

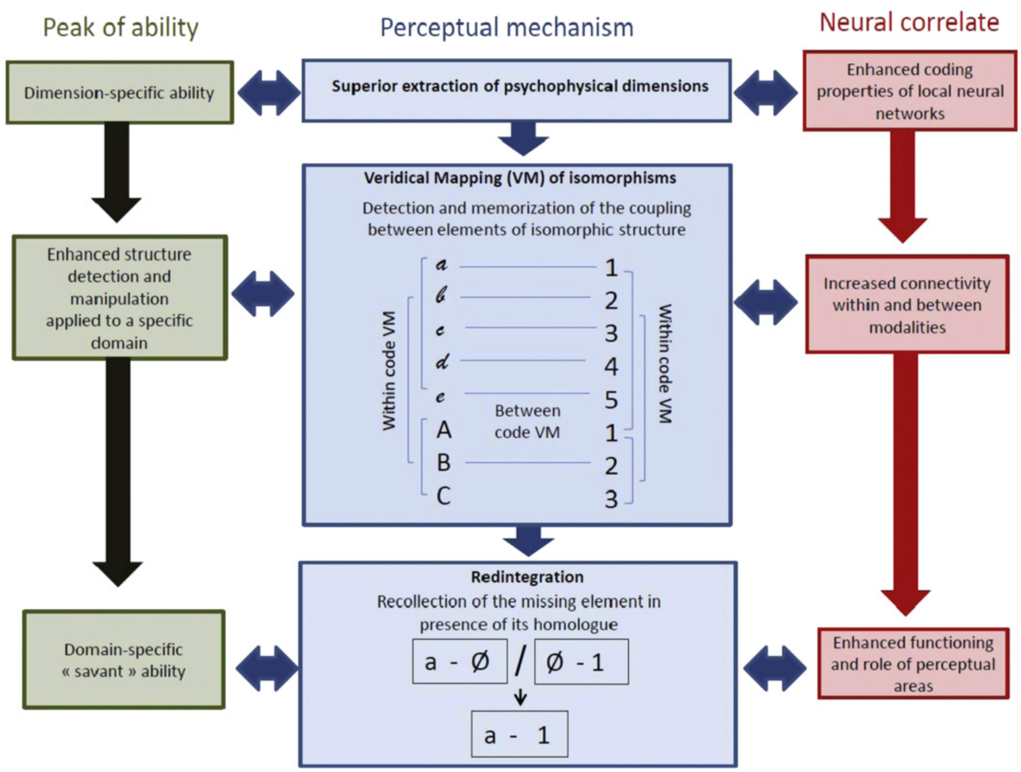

Fig. 1. Veridical mapping in autistic savant abilities. The arrows indicate plausible relations or implications.

With respect to specificity of savant skills to autism, most savants would receive a diagnosis of autism according to current diagnostic criteria (Heaton and Wallace, 2004). Thus, Heaton and Wallace conclude that "autism (or autistic traits) and savant skills are inextricably linked, and we should therefore look to autism in our quest to solve the puzzle of the savant syndrome" (p.889; see also Miller, 1989; Obler and Fein, 1988). This remains true even in cases of prodigious calculators with typical general intelligence (Fehr et al., 2010; Pesenti et al., 2001) for whom diminished sociability and intense focus on their specific interest suggest some relation to autism, despite the lack of a formal diagnosis.

2.3. Natural history and developmental considerations in savant syndrome

Savants are rarely able to describe the processes involved in skill acquisition and development as these abilities often emerge prior to the onset of communicative language and during the period of childhood amnesia, which is characterized by difficulties in recalling episodic memories. In a review of learning in autism, Dawson et al. (2008) concluded that savant abilities often appear precociously, feature the mastering of developmentally incongruous complex materials, and depend on implicit learning which eventually is integrated with explicit learning. This process does not involve the incremental trials-and-errors, developmental stages, and external rewards that characterize typical learning, and is instead associated with the highly focused all-absorbing interests characterizing autistics. The natural history and developmental trajectory of savant abilities will be presented in our section on hyperlexia, possibly the best-documented savant ability.

2.4. Relation between dimension-specific and domain-specific abilities

Domain-general and domain-specific abilities appear to be linked in some way. This is highlighted by Howlin et al.'s (2009) finding from a large-scale study that a significant percentage of autistics displayed both exceptional performance on one or more of the Wechsler subtests, and a savant ability. Whereas the direct link between dimension-specific and domain-specific abilities still needs to be clarified and computed for various types of perceptual abilities, their co-occurrence in autism at the group level indicates the possibility of a common mechanism or of a causal relation of between them (see Fig. 1). In this paper, we develop the hypothesis that savant abilities are domain-specific, i.e. they are constrained by the dimension-specific perceptual and structural properties of the domain of data involved in the exceptional ability. They would occur more frequently in autism because their development is facilitated by the strengths in dimension-specific perceptual abilities that are found among autistics.

2.5. Brain correlates of autism relevant for savant syndrome

Knowledge about the anatomical and functional brain characteristics observed in autism, and more specifically about their relation with perceptual strengths in autism, can enhance our understanding of savant syndrome. Four atypicalities of the autistic brain and their relation with VM and its perceptual basis in EPF, are outlined here, followed by a discussion of current knowledge on brain structure and functioning in savant syndrome.

2.5.1. Enhanced brain size and differences in cortical microstructure

Microstructural neuronal differences are observed between AS and TD persons and are relevant to our understanding of EPF in autism. Both a 60% increase in neurons in certain regions (Courchesne et al., 2011) and an overabundance of cortical minicolumns associated with increased brain weight and volume among autistics (Casanova and Trippe, 2009) have been reported. The accelerated brain growth during the first year of life among autistic children (see Courchesne, 2004, for a review) may contribute to enhanced brain size, which is either general (i.e., macrocephaly) or localized to specific cortical regions among autistic adults (Hyde et al., 2010). The latter finding suggests a potential structural basis for known functional differences (i.e., perceptual strengths). Enlarged regions appear to be scattered throughout the brain, but include primary and associative perceptual regions and may be correlated with some types of enhanced performance in autism, such as pitch processing (Foster et al., 2012). Moreover, in a preliminary study of the relationship between overall increase in brain volume and perceptual atypicalities, White et al. (2009) found a correlation between macrocephaly and an increased cost in switching from a local to a global dimension within hierarchical stimuli among AS persons. This is consistent with the EPF model's notion of a locally oriented default mode of information processing in this population (Wang et al., 2007).

2.5.2. Altered lateral inhibition

The correlation between enhanced auditory (pitch) and visual (spatial frequency and orientation of luminance-defined gratings) performance in low-level discrimination tasks, that appears to be unique to autistics (Simard-Meilleur et al., 2012), is evidence for common atypical early mechanisms that mediate low-level processes, such as temporal and spatial frequency processing. We suggest that the most plausible candidate for this type of common mechanism is an altered neuronal connectivity, specifically enhanced lateral inhibition (Plaisted, 2001). Consistent with this hypothesis, we found collinear facilitation, or increased sensitivity to visual targets, among autistics on a lateral masking paradigm for which target detection is measured as a function of target to flanker distance. Autistics also displayed enhanced sensitivity for orthogonally flanked targets with a larger range of contrast levels. These findings are indicative of an enhanced lateral inhibition within primary visual areas that alters perceptual feature extraction and increases figure-ground saliency by diminishing the detrimental effects of lateral spatial information (Kéïta et al., 2011; see also Vandenbroucke et al., 2008).

2.5.3. Superior activity in perceptual brain regions during pattern processing

Enhanced perceptual performance in autism is consistently reported for pattern processing tasks such as the Embedded Figure Test (EFT; Witkin et al., 1971). The EFT requires identification of a simple target embedded in a more complex background and is one of the best-documented examples of behavioral strengths among autistics (de Jonge et al., 2006; Edgin and Pennington, 2005; Jarrold et al., 2005; Jolliffe and Baron-Cohen, 1997; Morgan et al., 2003; Pellicano et al., 2005; Shah and Frith, 1983). In several fMRI studies of the neural underpinnings of this behavioral superiority, increased activity in cortical regions associated with visual processing was observed in autism, generally in association with reduced frontal cortex activity. For instance, in the first neuroimaging study of EFT performance in autism, Ring et al. (1999) reported enhanced ventral occipito-temporal activity in the autism sample, while greater prefrontal activation was observed in the TD group. Similarly, through a specific contrast isolating the local search components of the EFT, Manjaly et al. (2007) observed higher primary visual and extrastriate activity in autistic adolescents compared to superior parietal and premotor activity in TD participants. A consistent pattern of diminished activation in the left dorsolateral prefrontal and inferior parietal areas and enhanced activity in parietal and occipital areas associated with visuo-spatial processing was found among autistics as compared to typical individuals on the EFT (Damarla et al., 2010). A diminished left anterior frontal involvement in AS children compared to comparison participants, but without the superior occipito-temporal activity observed in other experiments, has also been observed (Lee et al., 2007). In all four studies, the AS and comparison groups displayed similar levels of performance on the EFT, suggesting a different, more perceptually based, strategy for pattern processing in autism.

The increased activity in cortical regions associated with visual processing reported in these studies is not limited to tasks centered on pattern detection, but can be observed in all tasks involving visual processing. Accordingly, in a quantitative meta-analysis of 26 neuroimaging studies with a total of 357 autistics and 370 non-autistics exposed to visual information across a wide range of cognitive tasks, we found that autistics consistently display increased activation of cortical areas associated with visual perception and expertise (e.g., fusiform gyrus) in comparison to non-autistic participants (Samson et al., 2011b). This underlines the robustness of an enhanced visual processing profile in autism.

2.5.4. Increased connectivity within perceptual areas and between perceptual and other brain regions

The finding of increased short-range connectivity, and in some cases of enhanced connectivity between perceptual regions and other parts of the brain, is particularly relevant for the understanding of enhanced pattern perception and the association among perceptual representations. According to the underconnectivity model (Just et al., 2004; see also Belmonte et al., 2004; Courchesne and Pierce, 2005), global underconnectivity and local overconnectivity are observed in autism. However, recent findings suggest that the autistic brain could be characterized by enhanced connectivity both locally (i.e., within perceptual regions) and globally (i.e., between perceptual and other brain regions). The availability of increased connectivity or synchrony might lead to, or result from, the development of highly specialized networks.

Increased connectivity within local networks has been found with different methods of brain imaging including functional MRI (Belmonte and Yurgelun-Todd, 2003; Monk et al., 2009) and EEG (Barttfeld et al., 2011; Murias et al., 2007), as well as in postmortem histological studies (Casanova et al., 2006; Hutsler and Zhang, 2010). For example, in fMRI studies, increased functional connectivity was found in pairs of areas within the medial temporal lobe among Asperger individuals (Welchew et al., 2005). Similarly, greater connectivity between the posterior cingulate cortex and medial temporal regions (Monk et al., 2009) and increased connectivity within the visual cortex (Turner et al., 2006) was observed in autistic participants compared to TD individuals.

Increased connectivity in AS individuals between perceptual and other brain regions has also been observed with different methodologies. In one example, enhanced functional connectivity in autism was reported between the thalamus, the perceptual gateway of the brain, and several areas throughout the cortex (Mizuno et al., 2006). Increased task-independent functional connectivity among autistics was also reported in frontal–frontal and occipital–occipital pairs of areas (Noonan et al., 2009), and superior EEG coherence between the visual cortex and other regions of the brain was observed in autism during REM sleep (Léveillé et al., 2010). It is therefore at least plausible that, far from an overall functional underconnectivity between sensory regions and other areas of the brain, perception in autism may be driving brain network activity under some physiological and experimental conditions.

2.5.5. Structure and function of the savant brain

Existing knowledge on functional and structural characteristics of the autistic brain has unfortunately not yet been translated into a clear understanding of the neurological correlates of savant syndrome. In the rare cases of brain imaging studies of savants that report atypical brain structure and/or function, the relative contributions of autism and of expertise are not disentangled from that of savant abilities as such, which are related to autistic expertise.

Neuroimaging case studies of savant syndrome provide evidence of neurological atypicalities. These include greater activation of the fronto-temporal network involved in a memory retrieval task in an autistic calendar calculator during a calendar task (Boddaert et al., 2005), and enhanced brain volume in the left hemisphere as well as increased cortical thickness in supplementary motor cortex and in the fusiform gyrus in an autistic savant with outstanding visuo-spatial abilities (Cooperrider et al., 2011). Using a letter recognition task for isolated versus embedded letters, Neumann et al. (2011) found maximal electromagnetic brain activity in the right primary visual cortex on both conditions among a group of adult autistic savants with outstanding memory or calculating abilities, whereas IQ- and age-matched TD individuals showed maximal activity in right frontal regions in the embedded condition and in the right precuneus in the isolated condition. This was interpreted as an indication that the disembodying process of embedded stimuli that was necessary for TD participants was not required for effective processing by autistic participants, since they completed the embedded task using perceptual processes associated with the isolated condition among the TD participants.

In other studies, differences were found in the savant brain when compared to groups of participants who are neither savants nor autistics, indicating that these findings remain unspecific. For example, G.W., an adult calendar calculator and draftsman, presented a bilaterally thicker cortex in the parietal lobes, within the regions typically involved in calculation and visuo-spatial abilities (Brodmann Area 7), in comparison to 14 non-autistic participants (Wallace et al., 2009). Similarly, larger right hemisphere structures and larger white matter volumes in the right amygdala, hippocampus, frontal lobe, and occipital lobe were observed in a 63-year-old autistic savant artist compared to a group of seven TD artists (Corrigan et al., 2011). In addition, Cowan and Frith's (2009) finding of activity in regions typically involved in computational tasks among two calendar calculators is not easily interpretable without a comparison group of non-savant autistics.

In sum, the lack of non-savant autistics or non-autistic experts comparison groups diminishes the interpretability as well as the significance of the findings. Thus, existing brain imaging research on savant autistic abilities does not enable us to distinguish task-related atypicalities in brain activity in savant syndrome as opposed to autism; nor does it inform us about the role of expertise in savant performance and mechanisms.

3. Veridical mapping in domain-specific autistic abilities

After our review of the EPF associated cognitive and brain correlates which are relevant to VM and might underlie savant abilities in autism, we now turn to a discussion of how the mechanism of VM, which is based on enhanced pattern detection between isomorphic perceptual and non-perceptual structures (see Fig. 1 for a summarized schema), might account for the higher incidence of savant abilities among autistics. Through observations drawn from savant syndrome, we present the seven components of VM and evidence for this specific mechanism.

3.1. Savant abilities involve materials with a high density of isomorphisms

The materials involved in domain-specific savant abilities often involve human codes such as arithmetical structures, written codes, calendars, music scales, 3-D regularities, and natural taxonomies that all feature structural redundancy (Mottron et al., 2009). Accordingly, savant domains are characterized by multi-level isomorphic relations. An isomorphism is a reciprocal relation among either concrete or abstract materials which preserves their structure, despite structure-irrelevant differences. Materials involved in most savant abilities are isomorphic in the sense that the same or similar elements or patterns are represented in the materials that are involved, and multi-level in the sense that structures are hierarchically organized in embedding and embedded patterns within the domain. For example, in arithmetic, it is the recurrence of numbers organized with a decimal base, which organizes the relevant syntax. In music, it is the recurrence of the 7- or 12-note pattern along the harmonic scale, but also the harmonic rules for a given style, such as baroque or jazz music. In written material, it is the recurrence of letters, texts, and syntactic rules. In addition to these large-scale isomorphisms (e.g., syntax), these materials also share the property of being comprised of a constellation of basic, fixed elements, such as letters, numbers, notes, and units of 3-D construction, such that all these structures can emerge through the perceptual laws of grouping. Accordingly, these materials can be ideally processed by a cognitive architecture with enhanced pattern processing abilities.

3.2. Savant abilities are based on the early implicit within- and between-code mapping among large isomorphic structures

Mottron et al. (2009) proposed that the mechanisms involved in savant abilities initially entail VM between perceptually presented isomorphic patterns. It is *veridical* in the sense that the mapping emerges when there is a sufficient level of similarity between at least two structures. The *mapping* involves the coupling of homologue elements of recurrent isomorphic patterns, as in grapheme-phoneme correspondence, and is the basic mechanism for structure detection. This relation can involve considerable resemblance despite a certain level of distortion or noise. For example, two occurrences of the same printed letter in different fonts can still be categorized as perceptually isomorphic. Alternatively, the same mechanism can be used to equate a structural similarity, as in the correspondence between two homologous series of numbers, such as between integer numbers and their expression in factors. Examples of this VM mechanism can be seen in hyperlexia, which entails the production of a phonemic representation of a written word with the mapping of graphic and oral codes; in calendar calculation, which involves responding to direct questions such as "what day of the week was the (year–month–day number)" based on the mapping between calendar structures at multiple levels (week, month, years, leap years, centuries); in AP, which involves providing pitch labels or locations in the presence of pitches and is based on the isomorphism between tone scales and the ordered structure of pitch labels or locations; and in prime number detection, which entails the mapping of series of integer numbers with their factor composition. By establishing a correspondence between two perceptually presented structures based on an isomorphic relation, VM allows access to non-verbal abstract relations, and therefore represents an alternative to the typical access to abstraction through language.

The involvement of VM in savant abilities is supported by the few self-reports of savants who were able to describe the mechanism of their ability after it developed. One such informant, G.T., a 9-year-old savant, was able to provide extremely accurate and rapid estimates of time, distance, and weight. For example, his estimation of the elapsed time between 15 and 95 s displayed a deviation rate between 1.1% and 3.3%, around one-tenth the deviation rate of IQ-matched TD children. His parents reported that he spent hours estimating the surfaces of rectangles and circles, and determining time in relation to the size of projected shadows (Soulières et al., 2010). When questioned about the mechanisms he used to perform these calculations, G.T. described how he determined the length of a bicycle ride by iteratively adding the number of pedal revolutions needed to complete it, and estimated weights under 10 kg by summing a gold standard of 35 g, the weight of a cereal bar. The latter explanation was validated by a deviation from accurate weight that increased dramatically (from 15% to 140%)

for estimations smaller than 35 g. Thus, G.T.'s superior estimation abilities appeared to result from his ability to map a code (e.g., measurement units such as grams or centimeters) to the absolute values of a continuous dimension of a physical aspect of the world (e.g., weight, length, pitch). G.T.'s insights support the notion that this mapping between isomorphisms appears idiosyncratic to the individual (Bogyo and Ellis, 1988), with the result of apparently arbitrary limitations in their domain of application (e.g. computation within calendars, but not in arithmetic).

Although some savants, such as G.T., are able to provide conscious accounts of their abilities later in life (Bouvet et al., 2012), most are not able to verbalize their mapping strategies, both because their abilities generally emerge early in life when verbal skills are minimal and because some savants, including those whose savant ability involves verbal or numerical material (Horwitz et al., 1965), never develop speech. Thus, savants do not seem to use typical learning processes through explicit language-based strategies for their skills. Rather, their skill acquisition appears to be characterized by a learning process which is driven by enhanced perception and perceptual expertise that is relatively autonomous from higher-order processes.

3.3. Material and operations involved in a domain-specific ability depend on episodic exposure to this material

Whereas a savant ability may (Mottron et al., 1996) or may not (Pring and Hermelin, 2002) be manifested as an overt "special interest" for the material, the period of life during which a savant encounters the relevant material can usually be identified. We have documented how early encounters leave traces in the savant capacity, as in the examples of an exposure to boilers in E.C.'s capacity of drawing 3-D pipes, then mechanical objects (Mottron and Belleville, 1993); an encounter with a calendar in D.B.C.'s subsequent superior calendar performance (Mottron et al., 2006b); an encounter with obituaries in the specificity of N.M.'s performance for proper names, but not common names (Mottron et al., 1996); and the presence of a keyboard at home for savant musicians (Miller, 1989). As a consequence, the domains of ability are both dependent on external parameters, such as exposure to domain-specific material, and on the personal motivation of the child who, in response to this material and independently of academic and parental training, develops expertise. This suggests that savant abilities and their associated autistic interests may not necessarily be that "restricted" under favorable circumstances, as suggested by numerous reports of creativity (e.g., Pring et al., 2012), rapid incorporation of new techniques (e.g., Pring et al., 1997), and abilities which flourish via the provision of opportunities (e.g., Hermelin et al., 1989; Miller, 1989).

3.4. Superior performance of savants on domain-relevant tasks results from a combination of enhanced perception and expertise

Superior performance of savants in comparison to non-savant experts is related to the combination of three factors. One, the perceptual and implicit processes that are essential to some savant abilities are faster than the verbally mediated and explicit operations that characterize typical performance. Two, low- and mid-level perceptual operations are enhanced in autism and therefore provide superior cognitive architecture with more fine-grained information. Three, savants are also experts, over-exposed to specific materials and over-trained on specific operations.

In our description of how EPF among autistics may lead to the development of savant abilities, Mottron et al. (2009) proposed that the enhanced detection, retention, and manipulation of patterns plays an essential role. In the visual modality, enhanced pattern coupling is evident in both visual search and embedded figures tasks. Both tasks involve the mapping of a probe to targets presented in a noisy environment. The relevant low-level visuo-perceptual foundations for enhanced pattern detection are manifested in superior autistic detection of symmetry in noise (Perreault et al., 2011). This is associated with an enhanced role of perception in high-level operations, as displayed by non-savant autistics who typically combine faster problem solving with greater activity in visual expertise cortical regions. However, savant expertise only emerges when enhanced perceptual mechanisms are combined with other factors. For example, over-exposure to the material involved in the savant ability results from the amount of time invested in focused interests. An example of how autistic interests are consistently associated with savant ability is provided by the case of N.M., who spent a lot of time copying lists of names prior to the emergence of his savant ability to remember proper names. However, the cognitive mechanisms used by savants cannot be explained by training only. Comparisons of the modus operandi of savants and typical persons with seemingly matched skills, such as between a savant who can remember proper names and a directory assistant in Canada's telephone company, or between autistic draftspersons and typical architects, reveal considerable differences between autistic and non-autistic experts, including reduced interference and top–down effects in autism (Mottron et al., 1996).

In sum, the unique combination of factors that are specific to autism and those that are shared by non-autistic persons might explain the considerably superior performance of autistic savants compared to non-autistic persons, regardless of their level of training (Dubischar-Krivec et al., 2009; Heaton et al., 2008a; Mottron and Belleville, 1995; Ockelford et al., 2006; Thioux et al., 2006). While over-exposure and overtraining may be implicated in all expert performance, the unique perceptual and cognitive characteristics that are outlined in our model account for qualitative differences and enhanced performance by autistics in specific domains.

3.5. Savant performance involves non-strategic recall or redintegration

VM is a mechanism of structure detection; redintegration is a mechanism of structure recall in the presence of its components or of isomorphic structures. The elementary operations that characterize savant ability all involve a strong memory component (Heaton and Wallace, 2004; Miller, 1999). Savant performances share some aspects with cued recall in the sense that savant activity is frequently evident in question–response tasks (e.g., what day of the week was the 10th of December, 1976?), in spontaneous activities in which a part of a remembered pattern (speech code) is produced in presence of a cue (written code), and in retrieving stored visual or verbal information (savant drawing). However, cued recall may be atypical in that recall and production are neither directional, as in the case in which only a specific cue can trigger the recall, nor strategic, as in voluntary, conscious memory search. Therefore we contend that the production of savant ability requires the production of a pattern in the presence of a degraded part of this pattern, a form of redintegration (Schweickert, 1993), in addition to other more typical memory and verbally mediated processes such as conscious memory search. In particular, parallel access to perceptual information would explain multidirectional access to information, as the cueing value of the pattern segments is distributed randomly and equivalently across components, allowing for multidirectional recall. This is in contrast to directional cued recall, with strategic, verbally mediated memory search, or with any top–down relation with material that is perceived or remembered.

We tested this hypothesis of non-strategic recall in two savants with different abilities. One, E.C., an exceptional savant draftsman, was asked several times to copy and recall the same drawing.

Whereas typical experts and non-expert comparison participants consistently display hierarchical recall with an average of 90% of fixed transitions between drawing parts, E.C. displayed only around 20% of fixed transitions across the two conditions. This echoed the observation that E.C. produced a perfectly proportioned drawing despite a spontaneous and random order of construction that began with the drawing of any part of the object and then skipping to another part, and then to another until the drawing was finally completed. A video analysis of his drawing sequence showed that he mostly used a proximity rule, with each feature being followed by a contiguous one, but he could begin with any part of the reproduced pattern. This random order of construction, despite the conservation of proportion, has been found in several savant artists (e.g., Selfe, 1983). While this was first interpreted as evidence of a predominance of local processes in graphic construction, we now underline that the entire pattern influences the recall of each of its elements, as indicated by the perfect conservation of the proportion. This provides a striking contrast with the disorganized drawing of patients with aperceptive agnosia, or right hemisphere injury, which are actually "local," and in which global structure is disorganized. Yet, the notion that autistic draftspersons, such as E.C., rely on top–down organization to construct their drawings with proper perspective was not supported, as E.C. produced apparently perfect linear perspective without using perspective vanishing points, suggesting that he did not rely on conscious construction informed by linear perspective algorithms.

The lack of a fixed transition in the graphic recall of E.C. has a striking correspondence with the bidirectional access to calendar information evident in calendar calculators. For example, D.B.C., an autistic calendar calculator, was able to respond to reverse questions (e.g., what month of the year 1952 began with a Friday?) with the same speed and accuracy as direct questions (e.g., what day of the week was the 13th of June 1952?) (Mottron et al., 2006b). This suggests that the cueing value of both questions is similar, thereby excluding an algorithmic approach according to which responses to questions that are more similar to the logic of the algorithm would be faster. In order to further discount the role of hierarchical recall, we questioned D.B.C. about an entire year of calendar calculation across multiple testing sessions and found that his error pattern did not differ across calendar categories and was unstable across sessions, thereby suggesting a stochastic degradation that did not reflect the plausible influence of a computation algorithm on an error pattern.

3.6. Understanding of linguistic codes is achieved in perceptual, non-linguistic ways

In addition to the case of hyperlexia, in which decoding skills are initially ahead of receptive skills, letters and numbers are involved in many savant abilities. Based on a study of 96 AS children and adolescents, Klin et al. (2007) concluded that restricted interests predominantly for printed language are characteristic of both savants and of autistics per se. Typically, these interests are initiated at a period of development during which speech is not yet mastered and involve specific arrangements of printed material (e.g., lists, columns, letter/digit matrices as in calendars). Restricted interests and superior processing for visual patterns that are structured by phenomenal rather than semantic commonalities indicate an entry point into the developmental attainment of linguistic representations. The example of hyperlexia, for which a perceptual strategy leads to a meaningful use of language, is especially informative in this regard. This "non-linguistic" access to language is unique to autism, and underlines the enhanced role of perception in higher-order abilities and intelligence in this group (Koshino et al., 2005; Soulières et al., 2009). For these reasons, encounters with printed material represent an opportunity for non-speaking autistics to interact with society, a task that typically requires considerable language and language-related skills.

3.7. During development, savant abilities become gradually more explicit, and merge with typical reasoning/algorithmic processes, resulting in a unique combination of perceptual and abstract structure

As the VM mechanism is based on mapping between isomorphisms, savant syndrome represents a unique pathway to arrive at abstraction via perception. The historical focus on contrasting concepts, such as rules versus regularities (Hermelin and O'Connor, 1986), top–down versus eidetic memory (Treffert, 2006), explicit versus implicit (O'Connor, 1989) and typical versus exceptional learning (Ericsson and Faivre, 1988), led to the underestimation of the complexity of the relations among the lower- and higher-order processes that are involved in savant ability. A gradient links the most atypical and possibly the most implicit and perception-based mechanisms, which are evident in the early stages of skill acquisition, to their combination with more typical, explicit and higher-level operations at later developmental stages. In some cases, such as prime number detection, these later stages include the use of plausibly non-perceptual mappings (e.g., factorization). This gradient parallels the finding that savants most often acquire communicative use of language after the onset of their savant abilities, allowing them to merge their atypical perceptual savant grounding with more typical strategies and levels of competence. Early reports (Selfe, 1983) of cases in which speech onset was followed by the spontaneous extinction of savant abilities have been cited as evidence of the incompatibility between savant and verbal abilities. However, multiple reports of verbal savants, the fact that some explicit arithmetic rules are involved in calendrical and arithmetical calculation (Hermelin and O'Connor, 1986), the sensitivity of calendrical performance to some structural constraints of the material involved (e.g., distance effect for future dates in calendar calculation, Thioux et al., 2006), and brain activity in regions involved in typical computation (Cowan and Frith, 2009), do not support this position. Concordantly, a creative use of structures, reflecting a higher-order manipulation and combination of auditory or visual patterns, is evident in 3-D drawing and musical improvisation (Pring et al., 2012), and plausibly in any savant ability.

4. Related models

The mechanism of VM is related, to different degrees, to several models of autism. In a later section on AP, we will discuss the weak central coherence model. Here we briefly summarize how VM relates to the EPF model, from which it arises, as well as to models involving reduced generalization and hyper-systemizing in autism.

4.1. Enhanced perceptual functioning

The EPF model (Mottron and Burack, 2001; Mottron et al., 2006a, 2013a) encompasses the enhanced performance, role in cognition, and autonomy of a non-systematized series of perceptual functions. Based on the example of superior pitch and luminance discrimination, we emphasized the role of enhanced feed forward low-level perception in the entire autistic cognitive architecture. One EPF principle (Mottron et al., 2006a, p. 35), "perceptual expertise underlies savant syndrome," is a foundation for the current paper. Subsequent findings of superior symmetry perception (Perreault et al., 2011), superior mental rotation (Falter et al., 2008; Soulières et al., 2011a), and a superior role of perception in intelligence (Soulières et al., 2009) furthered the EPF premise that perception in autistic individuals is capable of sophisticated operations. In the same direction, an *associative*, rather than a *primary*, perceptual region displays enhanced fMRI activity at the group level in autism (Samson et al., 2011b). Thus, VM includes the role of enhanced *mid-level* perception in non-strategic, bottom–up or parallel structure detection, and its role in the development of domain-specific abilities. More specifically, VM is concentrated on the role of autistic perception in mastering abstract language and mathematical structures.

4.2. Reduced generalization

Grounding access to abstract structures on the detection of isomorphic relations may appear at odds with Plaisted's reduced generalization theory (RGT), which entails the "reduced processing of the similarities that hold between stimuli and between situations" (Plaisted, 2001, p. 159) among autistic people. This model is inspired by apparent difficulties with generalization in typical learning, enhanced detection of minor changes, and empirical evidence of enhanced discrimination of very similar stimuli (Plaisted et al., 1998) but comparatively inferior use of grouping by similarity versus grouping by proximity (Falter et al., 2010).

EPF and RGT share an emphasis on low-level perceptual hyper-discrimination, and its consequences on similarity detection. The local bias that is observed in autistic people (Mottron et al., 2013c; Wang et al., 2007) results in increased salience for difference over similarity, specifically for objects that are similar globally but different locally. However, this is limited to perception and evidence showing unimpaired grouping in autism (Falter et al., 2010) shows that the local bias does not straightforwardly result in impaired perception of similarity relations. This is evident in the findings that ERP indices of grouping on the Kanizsa triangle or Mooney face tasks (Brown et al., 2005; Stroganova et al., 2012; Sun et al., 2012) are consistent with an enhanced participation of low-level processes in autism despite typical or quasi-typical behavioral performance. Moreover, in Falter et al.'s (2010) study of grouping by similarity versus grouping by proximity, some incidental issues concerning the extraction of low-level physical dimensions (here, color analysis) may be responsible for the diminished performance on similarity grouping. Accordingly, aspects of the perception of colors, which are involved in the detection of similarity, may be impaired among autistic people (Franklin et al., 2008, 2010).

In assessing the extent to which the RGT correctly accounts for some evidence of reduced gestalt grouping by similarity among autistic people (Bolte et al., 2007; Falter et al., 2010), difficulties in accounting for a quasi-typical categorization performance (Molesworth et al., 2005; Soulières et al., 2011b) and the often replicated enhanced performance on pattern matching tasks (for a review, see Mottron et al., 2013a) must be considered. Accordingly, embedded figures, visual search, mental rotation, and block design tasks all imply detection of a similarity between a probe and a target. The autistic perceptual system is therefore more flexible than would be suspected, in the sense that it can detect subtle differences (local bias, superior discrimination) when necessary, but is even faster when the task necessitates detecting a similarity. Thus we suggest that the core notion of RGT of "reduced processing of features held in common between stimuli" suffers from imprecision about the level at which a "feature" is understood, and is not supported by either the evidence of superior performance on pattern matching or the spontaneous orientation toward isomorphic material among autistic people.

Further, the level at which VM operates is that of grouping. Two structures can be veridically mapped together because their elements are: (a) similar; (b) moving in the same direction; (c) in the same spatial relation with another object; (d) collinear; (e) close; or (f) in an identical relational position with another object. This leads to an indefinite number of possible isomorphisms between two structures. Therefore, while the similarity principle in autism may be weaker or relatively less prevalent in ecological situations than grouping ability, VM between groupings is still a directing principle of autistic cognition.

4.3. Hyper-systemizing

According to Baron-Cohen (Baron-Cohen, 2006, 2008; Baron-Cohen et al., 2009), autistics, and to a lesser extent Asperger individuals, are characterized by hyper-systemizing. Systemizing is defined as the drive to construct or analyze systems, i.e., sets of rigid "if p, then q" rules which are able to predict changes in the lawful nonsocial ("non-agentive") world. The canonical examples of Baron-Cohen's systems are the strict implications found in input–output relationships, as in the laws of physics, in biological taxonomies, and even in the memorized representation of a predictable event. Baron-Cohen assigns AS individuals to several fixed "systemizing mechanism" levels on the premise that the highest level of systemizing is associated with the most limited abilities, including low IQ and inability to learn language (Baron-Cohen, 2006). VM superficially resembles hyper-systemizing in the importance of details and regularities, and in the incorporation of "if p, then q" rules when they are useful. However, VM involves non-strategic integration of information within and across multiple scales. Rules, not limited to cause and effect, are detected and used, but autistics are not chained to them; nor does VM result in autistics being inherently unable to cope with systems that are less than lawful. For example, VM allows Paul, a 4-year-old autistic child with very low measured intelligence (Atkin and Lorch, 2006), to nevertheless spontaneously master the notorious complexities and irregularities of English orthography (see, e.g., Seymour et al., 2003) at a level more than twice his chronological age.

5. Veridical mapping in savant abilities, absolute pitch and synaesthesia

Having presented the nature and components of VM, we now explore the heuristic value of this mechanism in explaining savant abilities (with the example of hyperlexia) and two other related phenomena (AP and synaesthesia) that are also more common among autistics than in the general population.

5.1. Veridical mapping in savant abilities: the example of hyperlexia

5.1.1. Definition and heterogeneity

The term hyperlexia was coined by Silberberg and Silberberg (1967) to refer to "extraordinary reading skills despite serious linguistic, cognitive, and behavioral disorders" (Aram and Healy, 1988, p. 70). However, descriptions date back to 1930 or earlier, when Phillips (1930) provided the first description of hyperlexia in a report of three unambiguously autistic children, who displayed cognitive disability as well as other savant abilities (respectively computation, mechanics, memory for music). The definition of hyperlexia usually includes: (1) reading skills that are markedly superior to comprehension skills; (2) co-occurrence with a neurodevelopmental condition that involves a delay in several areas other than reading; (3) restricted and repetitive interest in printed material; and (4) an early and untaught onset of the ability. Like definitions of savant syndrome, absolute (compared to typical age-matched peers) and relative (compared to other competences) assessments of superior performance are part of the definitions of hyperlexia. However, hyperlexia is one of the savant abilities for which an absolute strength, evidenced by reading levels that exceed chronological age-appropriate norms, is necessary for diagnosis:

hyperlexic autistic children begin reading at least 1 year before precocious typical children (Niensted, 1968).

5.1.2. Prevalence in autism

Classical hyperlexia is found in an estimated 5–10% of autistic children (Burd and Kerbeshian, 1985). However, when less stringent criteria for hyperlexia are adopted (reading/IQ differences superior to 10% of the population) (Jones et al., 2009b), the prevalence rate rises to 14%. When a less stringent criterion of discrepancy is used (Grigorenko et al., 2002), the prevalence rate is as high as 20%. Autism is the neurodevelopmental condition most commonly associated with hyperlexia, and even in cases where there is no clear diagnosis, the behavioral characteristics and cognitive profile (e.g. peaks in BD performance and deficits in comprehension) are clearly autistic-like (Aram and Healy, 1988).

Among all the savant abilities, hyperlexia is the most continuous between autistic savants and non-savants, as the latter group displays a less extreme variant of the reading profile associated with hyperlexia. For example, one-third of a group of 48 autistics (mean age 10 years) displayed severe reading comprehension impairments in comparison to their decoding abilities, and one-tenth showed a discrepancy of more than two SD. Only one person in this group displayed better comprehension than reading abilities, whereas this profile was found in one-third of a group of typically developing children (Nation et al., 2006). Thus, hyperlexia represents an extreme version of the cognitive profile that is observed among a large percentage of autistics, and which allows autistic children and adults with limited or no speech to master literacy either by typing on computer keyboards that produce script or voice or by using various instruments of augmentative communication. These individuals are usually considered to be of typical intelligence, although their adaptation difficulties and the quality of their typed or electronically spoken material mean that they meet criteria for hyperlexia.

5.1.3. Natural history and development of hyperlexia

Hyperlexia, which is most frequently documented at the period of life when it begins, is the only savant ability about which we are able to learn from the description *in statu nascendi*. The systematic review of tens of cases by Aram and Healy (1988) and subsequently updated reviews (Grigorenko et al., 2003; Nation, 1999; Newman et al., 2007) offer a detailed picture of its early onset. Hyperlexia is always self-taught and even frequently discouraged by caregivers. First word reading is observed between 2½ and 3½ years with "striking uniformity" (Aram and Healy, 1988, p. 89), although some reports mention even earlier onset. For example, hyperlexia has been reported in children aged 1 year (Goodman, 1972), 15 months (Elliott and Needleman, 1976), and 18 months (Silberberg and Silberberg, 1968). Early reading occurs consistently before speech (Aram et al., 1984) or in association with speech delay or atypicality. Transient or permanent echolalia is a quasi-constant associate (Aram and Healy, 1988). Non-reading speech production of units larger than one word does not occur before 3 years in hyperlexics and usually around 4–5 years. Apparent intellectual disability (although most instruments devised to measure intellectual performance are poorly able to detect normal intelligence in autism before 5 years of age), and a delay in achieving developmental milestones despite typical IQ, are the rule in published cases. A co-occurrence of hyperlexia and other savant abilities for structured material (music and numbers) is frequently reported. Most descriptions emphasize that outstanding performance in decoding skills is accompanied by an "obsessive" search for and restricted interest in printed materials (Goodman, 1972).

While hyperlexia was initially considered a cognitive dead-end, there are indications that it is followed by a typical understanding of the written material, and eventually by more oral language. Aram and Healy (1988) suggested the notion of "filling the gap" between meaningless reading and understanding, but the evidence appears to be limited to a few cases (e.g., Elliott and Needleman, 1976). While hyperlexic children display a deficit in comprehension relative to full scale IQ (FSIQ) (Newman et al., 2007), their understanding of what they have read is consistent with their verbal IQ level, which evolves positively as the child develops (Jones et al., 2009b; Nation, 1999). Hyperlexic children also display superior vocabulary when compared with age-matched, non-hyperlexic children, and present an overall profile of performance in reading that resembles that of reading-matched, non-autistic peers (Newman et al., 2007). Reports of autistic adults who read meaningfully despite the lack of speech, and our own observations through retrospective interrogations of early hyperlexic periods of verbal autistics, suggest that this favorable outcome for hyperlexia may be quite usual.

5.1.4. Low-level foundations of hyperlexia

As is the case with other savant abilities in autism, hyperlexia is associated with dimension-specific abilities (visual pattern perception) in areas that are plausibly related to the domain-specific ability (hyperlexic reading). Children with hyperlexia, and with co-occuring specific language impairment (SLI), outperform non-hyperlexic children with SLI in visuo-spatial and visual memory tests, pointing to the involvement of dimension-specific skills in domain-specific abilities (Cohen et al., 1997). This is not a surprise, as letters and words are visuo-spatial patterns, and enhanced pattern detection has been demonstrated in autistics without reported savant talents. Indeed, pattern matching, construction, and rotation of visuo-spatial information appear to be consistently superior among autistics as compared to FSIQ-matched TD persons (e.g., Caron et al., 2006). What is true of patterns in general is also true for letters: the superiority of autistics, even without acknowledged hyperlexic abilities, to map letters in different orientations has also been demonstrated and is evident among those with a BD peak (Soulières et al., 2011a). In turn, configural similarity between a probe and a target is the basis of visual search and hidden figures tasks, the areas of greatest strength in visual perception among autistics (Mottron et al., 2006a). This ability, which is perceptual in nature (Joseph et al., 2009; Remington et al., 2009, 2012), emerges early in development among autistic children (Kaldy et al., 2011), coinciding with the age at which hyperlexia is identified.

5.1.5. Brain correlates of hyperlexia

The only information on brain correlates in hyperlexia is from the study of Ethan, a 9-year-old hyperlexic boy who had limited speech, clear autistic features, and reading abilities that were 6 years higher than would be expected based on his chronological age (Turkeltaub et al., 2004). Neuroimaging results showed marked differences between Ethan and a group of reading age-matched TD children, as Ethan showed superior activation in the right posterior inferior temporal sulcus, a region involved in visual form recognition, in addition to typical left hemisphere phonological decoding systems. These visual perception areas are typically activated during early reading acquisition but not when reading is mastered (Turkeltaub et al., 2004). This finding demonstrates the superior role of perception in autistic hyperlexia, and is consistent with evidence suggesting increased activation in regions associated with visual perception among autistics during the completion of intelligence tests (Soulières et al., 2009) and working memory tasks involving letters (Koshino et al., 2005).

As hyperlexia is assumed to be highly prevalent in autism (Grigorenko et al., 2003), the overall brain correlates of the two phenomena might be expected to be similar in terms of local and general cortical activity. In our quantitative meta-analysis (Samson et al., 2011b) in which we grouped brain activation patterns of 98 autistic and 105 TD participants during written word processing, we observed significant differences with increased extrastriate, fusiform gyrus, and medial parietal activity, and diminished activity in the middle posterior temporal gyrus, left inferior frontal gyrus, and bilateral lateral prefrontal cortex in the autistic group. Although word processing elicited activity in brain areas that belong to the typical reading network, their activity was not as left-lateralized as it was in TD individuals. Higher activity in response to words in the extrastriate cortex, the fusiform gyrus, and the medial parietal cortex indicates a stronger use of perceptual expertise in the processing of written sentences and words in autism that could possibly also underlie hyperlexic abilities in this population.

5.1.6. Hyperlexia and the seven components of veridical mapping

(a) Language is a domain that is rich in isomorphisms, which coincide with the recurrence of its units and its syntactic constraints.
(b) The structure of hyperlexia is, by nature, a grapheme-phoneme mapping with a relatively high level of veridicality. The findings that many hyperlexic children are able to read distorted words or pseudowords (Atkin and Lorch, 2006; Goldberg and Rothermel, 1984) are understandable as irregular spelling does not alter the stability of the pronunciation of a specific, irregular word.
(c) The 'exposure' component of hyperlexia is demonstrated by its association with restricted interest in letters, which results in an over-exposure to this material.
(d) The 'expertise' component results from the over-exposure, which in itself is a product of the repetitive interest and repetitive search for printed material.
(e) The act of reading consists of providing a verbal code in the presence of an isomorphic code using concurrent, multi-level correspondences. The use of redintegration processes in hyperlexia is supported by evidence that hyperlexic individuals are faster and more accurate in redintegrating degraded words, a finding previously interpreted as reflecting superior pattern detection and recognition (Cobrinik, 1982). This pattern detection is resistant to noise. Goldberg and Rothermel (1984) demonstrated that altering the case, orientation, linearity, spacing, or even adding plus signs between the letters of words had minimal or no effect on reading efficiency in hyperlexic children. This was interpreted as the demonstration of an abstract knowledge of orthographic code. However, this and consistent evidence of reverse reading among hyperlexic individuals may also be interpreted as evidence of an enhanced parallel pattern recognition system, in which each part of the pattern pertaining to one code is mapped with its homologue in another code. The notion of parallel mapping between graphic and phonemic codes is further supported by evidence that scrambled word order in a text results in larger decrements in reading speed for typical as compared to hyperlexic readers (O'Connor and Hermelin, 1994).
(f) Hyperlexia, with its characteristic decoding advantages on reading, represents the canonical example of a perceptual use of linguistic units.
(g) Hyperlexia is a route for later access to meaning, which is consistent with the general developmental trend of merging perceptual abilities into higher-order processes.

5.2. Veridical mapping in absolute pitch

5.2.1. Definition

Receptive AP, the most frequent form of AP ability, is an involuntary evocation of a pitch label when exposed to a musical tone. Therefore, it is the reverse of the prototypical manifestation of synaesthesia, which involves the experiencing of a sensory stimulation (e.g., a color) when exposed to a perceptual, most frequently a verbal, inducer (e.g., a letter). However, both abilities require early, involuntary, and stable mappings between perceptual and verbal representations.

5.2.2. Prevalence in autism

Based on early and/or non-epidemiological evidence, AP has an estimated prevalence of 5% (Rimland and Fein, 1988) to 11% (DePape et al., 2012) in autism as compared to 1 in 10,000 in typical populations (Takeuchi and Hulse, 1993). AP is consistently observed among savant autistic musicians (e.g. Miller, 1999; Sloboda et al., 1985; Young and Nettelbeck, 1995) and frequently co-occurs with other types of savant abilities such as 3-D drawing, mental computation, and superior estimation abilities (Bor et al., 2007; Heaton et al., 2008b; Mottron et al., 1999; Soulières et al., 2010). Conversely, autistic features are also observed in AP possessors, indicating a non-random link between the two conditions. In a comparative study of 33 classical musicians without and 13 with AP, Brown et al. (2003) identified group differences on a range of experiential, personality, and cognitive factors. The musicians with AP were considered socially eccentric and scored in the range of individuals with a broad autism phenotype on language and personality variables. They also showed the relative BD peak characteristic of autistic people with delayed speech onset. Consistent with these observations, recent findings suggest that musicians with AP possess more autistic-like traits than non-AP musicians (Dohn et al., 2012).

5.2.3. Development of autistic absolute pitch

According to some authors, anyone can develop AP if trained to make associations between musical tones and their corresponding verbal labels before the age of 5 years (Miyazaki, 1988; Takeuchi and Hulse, 1993). This evidence is reinforced by the developmental shift from AP to relative pitch (RP; i.e., the ability to identify notes relative to one another) during development (Saffran and Griepentrog, 2001; Saffran and Thiessen, 2003; Stalinski and Schellenberg, 2010). Although typical AP usually emerges following a certain level of musical training, among autistics it normally precedes the development of musical skills. For example, Young and Nettelbeck (1995) noted that perfect pitch displayed by T.R., a young autistic musical savant with AP, provided an important basis for the development of his musical skills. Similarly, Brenton et al. (2008) described a 4-year-old autistic boy who demonstrated AP and was even able to identify the tone of a fan buzzing in the key of F, although he had not received any formal music training and did not demonstrate savant skills for music. A.C., an autistic artist, was able to remember the pitch of certain environmental sounds at a very early stage of development, and subsequently acquired the ability to map tones and their corresponding labels without formal training (Heaton et al., 2008a). These cases suggest that AP emerges prior to, and in some cases independently of, musical training among autistics. This pattern stands in contrast to the strong association between early musical training and AP documented among typically developing AP possessors (Baharloo et al., 1998; Chin, 2003; Gregersen et al., 1999).

5.2.4. Low-level foundations of absolute pitch in autism

The superior occurrence of AP in autism has been linked to overall perceptual atypicalities observed in the framework of both the EPF and weak central coherence (WCC) models of autism. Both encompass the enhanced detail or local processing abilities that are evident in autism, but differ with regard to their origins. For WCC, this bias toward local processing originates from an impaired ability to process elements together, whereas EPF postulates that this bias is one among the multiple correlates of altered autistic perception. In music, pitch processing requires a detail-oriented, local level of processing (Peretz, 1990). Enhanced pitch discrimination and memory is one of the most documented strengths among autistics (Bonnel et al., 2010, 2003; Haesen et al., 2011; Heaton, 2003; Heaton et al., 1998; Jones et al., 2009a; Mottron et al., 2000), and might indicate that AP is related to enhanced low-level processing of perceptual material in this group although not among typical AP possessors (Bachem, 1955; Miyazaki and Rakowski, 2002; Vangenot, 2000). For example, Heaton et al. (1999) described a musically untrained autistic adolescent with AP who attained ceiling scores on tests of pitch interval discrimination as well as on tests of pitch labeling and memory.

Similarly, AP is characterized by an unusually high degree of naming accuracy among autistics who possess note names. As compared to typically developing participants with AP and very high levels of musical training, Heaton et al. (2008a) found that A.C., an autistic individual with multiple savant skills, scored higher on pitch naming for sine and complex tones and attained 100% accuracy scores across all trials. When he was asked to name fundamental frequencies in French and English words, his correct discrimination scores exceeded those of the AP possessor comparison participants by six standard deviations. Similarly, Young and Nettelbeck (1995; see also Pring, 2008) found that another savant, T.R., was able to identify the individual component notes in highly complex chords (i.e., chord disembedding) and his scores on tonal memory tasks were near ceiling. He was also able to reproduce by ear the first six–seven bars of tonal and atonal melodies after only one hearing on the piano.

In addition to superior pitch discrimination, autistics who are neither savants nor AP possessors demonstrate a superior capacity to map pitches with percepts belonging to other modalities. This was highlighted in a two part-study by Heaton (2003) who trained IQ and age-matched groups of musically naïve autistic and TD children to associate animal pictures with musical tones. The participants were then presented with the learned tones in random sequence and asked to point to the animal picture that had previously been presented with each of the tones. In a second experiment, three of the animal tones were presented together and the participants were asked to point to the animal picture whose note was missing. The autistic participants outperformed their TD counterparts in both experiments.

Empirical findings of intact processing of the global aspect of hierarchical musical stimuli among musically naïve non-savant autistics were cited in contradiction to the WCC model (Foxton et al., 2003; Heaton, 2005; Heaton et al., 2007; Mottron et al., 1999, 2000). No impairments of global musical processing have been found in the few cases in which global musical processing was specifically examined in musical savants. Consistent with this evidence, Mottron et al. (1999) found that a savant autistic, Q.C., was able to recognize melodies in transposition (in which the absolute pitch values of individual tones are modified while pitch intervals are kept unchanged) as identical to target melodies, indicating that her AP abilities did not interfere with her RP abilities. If the findings point to a superior autistic analytical way to process musical information, the failure to find any indications of deficit in the processing of higher-order musical information is evidence against the notion of a global processing deficit as an explanatory mechanism for enhanced pitch processing in autism.

5.2.5. Brain correlates of absolute pitch in autism

A pitch-evoked response within the lateral portion of Heschl's gyrus has consistently been reported among TD adults. Indeed, neurons in this region respond both to the low-level acoustical features of sounds (e.g., intensity) and to the pitch percept (the individual note) (Griffiths, 2003; Griffiths et al., 2010; Humphries et al., 2010; Patterson et al., 2002; Woods et al., 2010). The processing of pitch intervals also involves non-primary and associative auditory regions, mainly in the anterior and posterior superior temporal gyri (Tramo et al., 2002; Warren and Griffiths, 2003; Zatorre et al., 2002). AP possessors, in comparison to non-AP possessors, display stronger activity in response to pitch information in the superotemporal regions associated with auditory expertise (Belin et al., 2004; Leech et al., 2009) and categorization (Liebenthal et al., 2010). For instance, Schulze et al. (2009) observed an increased superior temporal sulcus activity in response to tests of pitch memory among individuals with AP. Higher levels of superotemporal activity, which is correlated with pitch naming accuracy, has also been observed among AP possessors as compared to both RP musicians and non-musicians during speech processing (Oechslin et al., 2010). Moreover, AP musicians show activity in the dorsolateral prefrontal cortex during a single note naming task whereas non-AP musicians show activity in this region only when naming musical intervals (Zatorre et al., 1998). These frontal regions are associated with object labeling and conditional learning (Petrides, 1985, 1990) and conditional associations between pitch and label (Bermudez and Zattore, 2005). The AP possessors also display atypical superior temporal gyrus asymmetry, specifically within the auditory associative regions known as the planum temporale, a part of the superior temporal gyrus containing the auditory association cortex. Among musicians with AP, the leftward planum temporale asymmetry is higher than among musicians without AP (Hirata et al., 1999; Schlaug, 2001; Schlaug et al., 1995; Wilson et al., 2009; Zatorre et al., 1998; but see Keenan et al., 2001).

In terms of connectivity among auditory regions, Loui et al. (2010) observed an increased volume of fibers in the superior temporal lobe among AP possessors, suggesting that the ability to link a label and a pitch is associated with increased white matter connectivity within the auditory sensory and association cortices. Accordingly, the accuracy of pitch identification was correlated with volume of tracts connecting superior temporal regions. A recent study demonstrated increased functional connectivity, in the superior temporal regions involved in auditory perception, in individuals with AP compared to non-AP individuals on a non-AP related task (i.e., arousal rating of musical stimuli) (Loui et al., 2012). Individuals with AP showed enhanced connection strength between functional regions (or nodes), greater connectivity between neighboring nodes, and stronger local information processing efficiency compared to non-AP individuals. This was observed both for the music listening task and the resting silence periods, suggesting that increased functional connectivity might be an intrinsic property of the AP brain that translates into better pitch processing abilities. The functional connectivity measures were correlated with performance on a pitch labeling test conducted outside the MRI scanner in AP and non-AP individuals. Structural hyper-connectivity was also observed in the peri-sylvian regions in AP possessors (Jäncke et al., 2012). This hyper-connectivity might reflect a higher neuronal density in the white matter tracts that contain mainly short-range connections (Herbert et al., 2004; Shih et al., 2011). These findings lead to the hypothesis that overall increased local connectivity found in autism facilitates the development of AP.

According to the EPF model, an enhanced role of pitch processing, independent of AP, would be expected within more complex auditory processing. This was supported by Samson et al.'s (2011a) fMRI study of simple, spectrally complex, and temporally complex sound processing. In this study, autistics, when compared to TD persons, displayed greater primary activity (i.e., Heschl's gyrus) and reduced activity of non-primary structures (i.e., superior temporal gyrus) in response to increasing temporal complexity. These data reveal an enhanced role of lower-level perceptual processes in auditory processing in autism and are consistent with the EPF model in this modality.

5.2.6. Absolute pitch and the seven components of veridical mapping

(a) The multi-level recurrence of within-code isomorphisms is particularly characteristic of music. Music includes simple forms and pitches that share a phenomenal resemblance, are presented in homogeneous series (octaves), and are associated through non-arbitrary harmonic rules (Jackendoff, 1987). The recurrence of octave structure along pitch scales is isomorphic to that of pitch labels.
(b) Tones, scales, and pitch labels are mapped without explicit learning.
(c) Although anterior to musical training, AP in autism requires exposure to musical material and structure.
(d) Autistic AP, in the framework of the EPF model, is associated with superior pitch processing and enhanced pattern detection.
(e) The production of a missing element (pitch labels or keyboard locations) when exposed to a pitch can be assimilated into the redintegration of a larger structure in the presence of a partial cue. Any corresponding element of a pitch scale can be produced in the presence of its corresponding element of an isomorphic pitch scale.
(f) Verbal codes for pitches in pitch-verbal mappings do not involve meaning, but rather the integration of domain-specific auditory and verbal (or visual for keyboards) elements in a common multimodal patterns. Pitch labels are structured by the physical differences and regularities among pitches, and have a perceptual-like characteristic. Persons with AP "hear" the name of notes during a melody.
(g) AP merges with higher-level processing of musical information along development. When present, it is merged with musical expertise, with adaptive benefits. The detrimental effects of AP that are found among TD persons, such as the inability to hear music without activating pitch names or resistance in transposition, have not been reported in savants.

5.3. Veridical mapping in synaesthesia

5.3.1. Definition and heterogeneity

Synaesthesia involves structural similarities with both AP and savant abilities. It is also a relatively rare domain-specific ability that involves mapping among series of percepts and, frequently, linguistic units. It is characterized by fixed, paired, typically cross-modal associations that result in highly specific sensory stimulation (a "concurrent," e.g., a color or taste) when exposed to an inducer (e.g., a letter or pitch) (Bargary and Mitchell, 2008; Cytowic, 2002; Hochel and Milán, 2008; Mattingley et al., 2001). For example, for form-color synaesthetes, the perception of a number may induce the perception of a color, like the number "5" in blue, and this association will remain stable over time. The heterogeneity of synaesthesia is intrinsic to its definition and coincides with its domain-specific nature. There are around 50 types of synaesthesia (for a review see Simner, 2010), which differ from each other with regard to the modality and types of percepts involved, but share the same structure of a fixed pairing among series of patterns. Included among the most common forms of synaesthesia are colored-graphemes, in which letters and digits induce color perceptions (Rich and Mattingley, 2002), and time–space, in which weekdays, months, or numbers are spatially ordered in a consistent way (Smilek et al., 2007). As in autism and AP, genetic factors play a significant role in the etiology of synaesthesia, with concordance rates in first degree relatives above 40% (Barnett et al., 2008a).

5.3.2. Prevalence in autism and association with savant abilities

Early reports of very low synaesthesia prevalence in the general population (e.g., 1/2000 or .05%; Baron-Cohen et al., 1996) have been superseded by consistently higher rates (e.g., 4.4%; Simner et al., 2006). However, there is preliminary evidence that an even higher prevalence can be found among autistic people and particularly among savants. For example, Johnson et al. (2011) reported that the prevalence of synaesthesia was 12% among 142 verbal autistic and Asperger individuals but only 4% among 49 TD persons, thereby suggesting a link between synaesthesia and autism. Preliminary work also points to an overrepresentation of grapheme–color synaesthesia in Asperger syndrome (Neufeld et al., 2012).

A link between savant syndrome and synaesthesia is not a new idea (Azoulai et al., 2005; Baron-Cohen et al., 2007; Bor et al., 2007; Murray, 2010; Simner et al., 2009b). Bor et al. (2007) proposed that whenever autism and synaesthesia co-occur, as in the case that they report, the likelihood of savant syndrome is increased; however, they did not explain why. Simner et al. (2009b) contend that time–space synaesthesia, at least for representations related to the inducer (e.g., a date) or the concurrent stimulation (e.g., its localization on a visualized timeline), is associated among non-autistic persons with a memory benefit that shares some similarities with savantism. They also demonstrated that persons with time–space synaesthesia possess above average skills on 3-D spatial mapping tasks, such as mental rotation, which are also observed among autistics (Falter et al., 2008; Soulières et al., 2011a). A link between autism and synaesthesia was also highlighted in a whole-genome scan study of 43 families with auditory–visual synaesthesia (Asher et al., 2009), in which the marker with the highest LOD score, which indicates the degree of genetic linkage, was also found to be linked to autism (IMGSAC, 2001).

The co-occurrence of AP and synaesthesia has been described in case studies of typical persons, including professional musicians such as Messiaen (Bernard, 1986), Sarajev, Vanechkina (2001), and Scriabin (Mulvenna, 2007), as well as non-musicians (Carroll and Greenberg, 1961; Haack and Radocy, 1981; Hänggi et al., 2008). Synaesthesia has also been described in a person diagnosed with Asperger syndrome (Bor et al., 2007), in a person whose description is consistent with Asperger syndrome (Parker et al., 2006), and in the self-reports of autistic individuals (Cesaroni and Garber, 1991; O'Neill and Jones, 1997). Besides the sporadic co-occurrence of AP and synaesthesia, AP possessors who do not self-report as synaesthetes have more stable color–tone associations than non-AP possessors (i.e., AP possessors associate the same color to the same tone more often than non-AP possessors) (Block, 1983), thereby suggesting the possibility of mechanisms that are common in these two abilities.

5.3.3. Natural history and development of synaesthesia

Autobiographical self-reports of synaesthetes confirm that this ability is precocious (Tammet, 2006). A systematic documentation and empirical study of groups of child synaesthetes is currently being carried out but the youngest participants were only 7 years old, at last report (Green and Goswami, 2008). Synaesthesia seems to be an active developmental process that continues up until late childhood. For example, Simner et al. (2009a) found that synaesthetes acquire an average of 6.4 new grapheme–color associations during a 1 year period at around 6 years. As is the case for savants within their domain of interest, the synaesthetes' inducers are idiosyncratic to the individual and are constant throughout life.

5.3.4. Low-level foundations of synaesthesia

Synaesthesia is associated with modality-specific enhanced low-level perception. Due to the fact that synaesthesia is intrinsically material-specific, perceptual abilities within this group have been studied within the relevant specific modality. Enhanced color perception has been observed in color synaesthetes with grating discrimination tests, and enhanced touch perception has been observed in touch synaesthetes compared to non-synaesthetes (Banissy et al., 2009). A difference at early perceptual levels of processing has been shown to distinguish synaesthetes from non-synaesthetes (Goller et al., 2009). For example, Barnett et al. (2008b) found that linguistic-color synaesthetes showed an enhanced cortical response (C1) which appeared between 65 and 85 ms in visually evoked potentials for high spatial frequency Gabor patches, which are preferentially processed in the parvocellular pathway. This difference in evoked responses is observed for stimuli which do not trigger synaesthesia, suggesting that it may be associated with generally enhanced perceptual processing for low-level stimuli. Enhanced cross-modal interaction between auditory and visual modalities in grapheme–color synaesthetes was observed by Brang et al. (2012), who suggested that overall enhanced cross-modal processing in modalities unrelated to the synaesthetic experience is characteristic in synaesthesia.

5.3.5. Brain correlates of synaesthesia

The subjective experience of synaesthesia is supported by PET (Paulesu et al., 1995) and fMRI (Hubbard and Ramachandran, 2005; Nunn et al., 2002; Rouw and Scholte, 2007) findings. Nunn et al. (2002) found that synaesthetic colors triggered by spoken words activated the posterior fusiform gyrus, an area involved in color perception (left V4), in synaesthetes but not typical persons. Grapheme–color synaesthesia is associated with increased white matter density in the retrosplenial cortex (Hupé et al., 2011), an area known to be involved in memory function (Vann et al., 2009). Similarly, increased structural connectivity (Hänggi et al., 2011; Rouw and Scholte, 2007), increased grey matter volume, and increased cortical thickness are observed in grapheme–color synaesthesia (Jäncke et al., 2009) as well as in multi-synaesthesia (Hänggi et al., 2008). Along the same lines, Banissy et al. (2012) reported grey matter volume differences within the visual system in synaesthesia involving color, in the form of increased volume in the left posterior fusiform gyrus, a region involved in color processing, and decreased volume in the left anterior fusiform and the visual area V5/MT, implicated in motion processing, supporting the idea of a specific role of perception in synaesthesia.

The multiple observations of structural hyper-connectivity in synaesthesia are consistent with the observations of structural hyper-connectivity for AP possessors (Jäncke et al., 2012; Loui et al., 2010) supporting our conceptual grouping of AP and synaesthesia. Evidence of functional and anatomical validation of atypical neural architecture in synaesthesia has led to hypotheses about its genesis and correlates. On the one hand, typical pruning of connections with contiguous perceptual regions fails to occur, resulting in automatic cross-activation (e.g., Maurer, 1997; Ramachandran and Hubbard, 2001) or, on the other, there is horizontal connectivity but diminished descending influences (Grossenbacher and Lovelace, 2001). Whatever the mechanisms involved, the notion of enhanced anatomical connectivity between neighboring regions is consistent with the immutability of synaesthesia in the individual's life.

5.3.6. Synaesthesia and the seven components of veridical mapping

(a) The majority of synaesthetic inducers involve linguistic units (letters, digits, calendar structures, musical notes), while the majority of synaesthetic concurrents involve pitches, colors, and time measurements. All comprise series of homogeneous elements ordered in a meaningful and consistent way.
(b) According to Riggs and Karwoski (1934), "every case of synaesthesia, whether simple or complex, whether emotional or ideational, consists essentially of a parallel arrangement of two gradient series." They also quote Myers (1911) who noted that the development of synaesthesia requires "a tendency to form associations between corresponding members of two homologous series," and Lemaitre (1901) who proposed a "law of parallelism" in this regard. The finding that both the inducer and concurrent belong to large isomorphic series has subsequently been neglected or at best marginally considered as "a cross-modal magnitude code" which "may facilitate the learning of cross-modal correspondences that are present in the environment" (Spector and Maurer, 2009, p. 182).
(c) Despite evidence that cross-modal associations occur soon after birth (e.g., Wagner and Dobkins, 2011; Walker et al., 2010), the fixed and stable mappings that characterize synaesthesia do not emerge until mid to late childhood with the child's exposure to the inducers, such as letters and digits (Simner et al., 2009a).
(d) Synaesthesia is associated with the enhanced processing of material even when performing unrelated operations. For example, grapheme–color synaesthetes present with superior color processing (Yaro and Ward, 2007) and digit memory (Smilek et al., 2002).
(e) Although elements (e.g., digits or dates and spatially extended lines of time) belong to large, parallel isomorphic structures, a synaesthetic experience occurs only for elements of these structures, regardless of their order of appearance. Therefore, these large structures are recalled randomly and partially. However, despite some exceptions (time–space synaesthesia), synaesthesia is most frequently unidirectional. For example, while music can induce color, the reverse is not common.
(f) As with hyperlexia, synaesthesia represents a canonical example of a perceptual, non-linguistic use of verbal codes which can even be inconsistent with their typical semantic and referential use (Green and Goswami, 2008).
(g) Synaesthesia associates two isomorphic structures, one of which is intrinsically perceptual (a color) and one of which is frequently a perceptual representation of a linguistic unit (the pattern of a letter). Thus, this represents a bridge between perception and abstraction, and enables the heuristic use of perception within abstract reasoning. It represents a positive addition to typical creativity processes, particularly in the arts (Mulvenna, 2007). The autobiographical writings of synaesthetic artists, the most famous of whom are Olivier Messiaen and Alexander Scriabin, describe how their perceptual experiences enhance their creativity, indicating that they are positively integrated into higher-level, conscious, and purposeful realizations. In this regard, synaesthesia, like autism, involves an enhanced role of perception in creativity. However, questions about the negative consequences of synaesthesia in learning or in skewing rational thinking have also been raised (Hochel and Milán, 2008).

6. Causal relations among savant abilities, absolute pitch, and synaesthesia

We have presented evidence of complex and rich relations among savant syndrome (illustrated by the example of hyperlexia), AP, and synaesthesia, and propose that a conservative position in which these can be considered random occurrences and independent mechanisms is hardly tenable. One possible source of relation among the three phenomena, when observed in autism, would be that they all reflect the action of the same neurocognitive VM mechanism that is applied to different domains, with only minor differences among subtypes (e.g. directionality, idiosyncratic mapping versus mapping shared by a community). On this basis, we propose that AP in autism should be defined as a specific, musical form of synaesthesia that, along with other savant abilities, should be grouped into the broader category of domain-specific abilities. This is consistent with the plausible suggestion that AP and synaesthesia frequently co-occur among non-autistic persons and even more so among autistic people, even if AP appears to be associated with unique characteristics when manifested in autism. The automatic generation of a pitch label in response to a heard pitch, the automatic production of a phoneme in the presence of a grapheme in hyperlexia, the generation of a day of the week in response to a date in calendar calculation, and the neurophysiological cross-activation of a concurrent percept by an inducer percept in synaesthesia may all, with minor domain-driven variations, reflect earlier veridical mapping and further redintegration. In all these cases, a percept activates its homologue in an isomorphic perceptual structure because the template of this percept (e.g., a pitch in pitch scales) is connected to its isomorphic pattern (e.g., a pitch label within a verbal scale of pitch labels) even if they are not in the same modality.

We propose that essential aspects of the EPF model—enhanced low-level perceptual performance, enhanced role of perception in higher cognitive processes, and enhanced pattern perception—play an important role in these domain-specific abilities through the veridical mapping of isomorphic perceptual patterns. This ability would generate the detection and redintegration of very large isomorphic structures, either within or across modalities, among autistic savants. The true rate at which these three phenomena (savant abilities, AP, and synaesthesia) co-occur remains unknown, but one or more may be of a "first takes all" type or require environmental contributions during a certain developmental period. This could explain why they may not routinely co-occur even in autism, despite being accounted for by the same type of neural mechanisms, as could the partial independence of their genetic bases.

Recent findings show a relation between brain connectivity and perceptual abilities, such that greater auditory brain activity, enhanced local functional brain connectivity, and superior pitch labeling performance are associated in AP. In other words, more connected local brain networks support superior pitch processing ability in the AP population (Loui et al., 2012). This may similarly be the case for other conditions with perceptual strengths, such as synesthesia and savant abilities. Accordingly, atypical functional connectivity, mainly in the form of enhanced local connections, could be a precursor to the development of such specific perceptual abilities. In autism, with increased availability of local brain connectivity, this mechanism might be more extreme, pervasive, and versatile, leading to the development of more frequent and general perceptual strengths. It is possible that the relation between the emergence of superior perceptual abilities and atypical cortical connectivity is continuous and depend on how, when and to what extent the connections of local neural networks are modified.

The genetic alteration responsible for reduced pruning in specific regions (Baron-Cohen et al., 1996; Spector and Maurer, 2009) that is suspected in synaesthesia may have an effect on learning which is partially similar to the effect of the genetic modification that results in the enhanced perception-related connectivity that is hypothesised for autism. Increased local connectivity involving perceptual cortical regions and enhanced perceptual processing and memory are shared by savant autistics in their domain of ability, and by synaesthetes in their induced modality. In all cases, enhanced low-level perceptual processing would feed forward to the level of pattern processing and, as a result, specific perceptual expertise would lead to—or benefit from—enhanced local connectivity within and between perceptual areas. This relation would be particularly relevant for autism, in which the availability of enhanced functional connectivity could enable a perceptually driven, autism-specific, mechanism for learning. Further, the immutability of an ability along the lifespan, its rapidity, its automaticity, and its developmental course may result from increased structural connectivity between and among perceptual regions. Importantly, the fact that the mechanism of VM retains low-level perceptual properties of the material involved may contribute to the domain-specific nature of autistic abilities.

7. Veridical mapping and autism spectrum heterogeneity

Within the autism spectrum, heterogeneity of speech abilities encompasses precocity, largely typical structure, expertise, and high vocabulary among Asperger persons; but delayed onset and/or marked atypicalities among autistic people *stricto sensu*, in whom speech may also be extremely sparse or absent. Primary issues regarding this heterogeneity involve how and when language is mastered. A large majority of autistic people present either a significant speech delay or a loss of spoken words that is associated with a phase of echolalia and/or stereotyped language, and pronoun reversal in the development of speech. Among those autistics who present speech atypicalities such as echolalia, a minority do not present a speech delay, although they have the same visuo-spatial strengths as those with speech delay (Nader et al., 2012). Therefore, several domain-general perceptual peaks are largely associated with AS people with delayed and/or altered speech development (Barbeau et al., 2012; Bonnel et al., 2010; Heaton et al., 2008b; Jones et al., 2009a). Similarly, some domain-specific savant abilities like hyperlexia are intrinsically associated with speech delays in their canonical forms. Delayed speech onset appears to be associated with a "perceptual learning" of language through VM, which favors written over oral material, and echolalia in speech acquisition.

The VM mechanism leads to a second level of heterogeneity among autistic people with speech delay or atypicalities, domain-specific heterogeneity, in the sense that a domain-specific mapping is engraved for each individual, and constrained by anecdotal perceptual properties. In addition to the sources of variability shared by all human beings and to those specifically associated with autism, variability would further be increased by the extent to which structures of the environment would be perceived as similar and extended to isomorphic structures. As a result, autistic heterogeneity would be related to the random encounter of a specific material, as well as to the effect of a common mechanism by which these mappings are endorsed by physical connectivity.

In Asperger individuals, language is learned in a quasi-typical way as speech is mastered on time, and the unique early differences with typical development in this regard are early speech milestones and the use of more precise and sophisticated vocabulary and syntax. Asperger people share with autistics an orientation toward printed language and numerical materials, which are involved in a large majority of their restricted interests (Klin et al., 2007). However, in contrast to autism, VM does not primarily act on perceptual aspects of language and other structures in Asperger individuals. Instead, mappings occur between verbally expressed structures, with a predominance of systematized content and taxonomies (Mottron et al., 2013b). This is consistent with the concept of systemizing (Baron-Cohen et al., 2009).

In contrast with autistics, for whom domain-specificity is associated to low-level perceptual properties of the domain of interest, domain-specificity is manifested in Asperger individuals by preference for elements semantically close to their domain of interest. Thus, Asperger individuals benefit from their precocious mastering of oral language even in relation to TD children, whereas autistic children need longer to develop language perceptually. However, both subgroups demonstrate the same type of strengths in the manipulation of some perceptually presented structures (Soulières et al., 2011c), and AP and synaesthesia are reported in AS people with and without speech delay. We do not know why language appears to be learned more conventionally in one AS subgroup, but suspect that the combination of domain-general and domain-specific abilities is deeply involved in this distinction. While enhanced pitch processing and domain-general visuo-spatial strengths are strongly aggregated with subgroups defined by speech delays and anomalies, we are still uninformed about the direction of causality between these two phenomena.

8. Is veridical mapping adaptive?

Could savantism pave the way to domain-general knowledge for each autistic person, and therefore represent an autistic access to culture? The autistic developing brain deals with available structures or isomorphisms by identifying their perceptual similarity, mapping them with linguistic representations, and stabilizing the connections between the homologous parts of these isomorphisms. The VM mechanism enables the ordered memory of these structures, thereby facilitating further manipulation at an older age and in multiple contexts. For autistic people, VM enables the representation of structures via an alternative to the typical language-based learning strategies adopted by TD individuals and probably, with some alterations, by Asperger people. The example of hyperlexia suggests that an in-depth focus on a domain via a reliance on isomorphisms may lead to, or be consistent with, more abstract ulterior mappings. VM may represent a way for autistics to "crack the codes" used by TD individuals and is therefore adaptive, in the sense that VM can increase access to culture and essentially, to language. For Asperger individuals, traces of this principle can be found in the common structure of their intensely focused interests, which represent a heuristic mechanism in their access to knowledge.

In this extension of the EPF framework, enhanced music or drawing skills are domain-specific, but result from a common mechanism. This suggests that the same brain has the potential to specialize across multiple contrasted domains, and is consistent with the notion that savants with multiple abilities are the rule rather than the exception. The "restriction" of interest and of idiosyncratic domain-specific abilities may represent a partial consequence of limited access to structured material rather than a necessary component of savantism. Accordingly, we no longer support the notion of a stopping rule (Mottron et al., 1999) according to which later savant abilities cannot develop after one has emerged and absorbs an individual's entire resources.

Any domain that elicits particular interest and is rich in multilevel isomorphisms could be learned and could lead to knowledge and ability. The condition for the extension of a domain-specific ability to another domain-specific ability may be constrained by the prerequisite of some low-level perceptual commonalities and a high level of isomorphism between the old and the new domain, while still being possible. While clearly different from language-based categorical generalization, this mechanism may represent a potential route by which the autistic person can gain access to culture. This pathway may be optimally open only during certain developmental periods, as discussed with regard to the emergence of AP and synaesthesia, and savant abilities are often first manifested around the same age regardless of the different skill domains. However, little is known about developmental windows in autism, and the example of individuals who acquire language late in development suggests that learning may be particularly prolonged over the lifespan in autism (Dawson et al., 2008). The availability of learning opportunities and access to materials is therefore paramount. This proposition should be considered with future research in which domain-specific interests and abilities are considered as channels to access culture rather than as sporadic rewards.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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