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Advances in autism genetics: on the threshold of a new neurobiology

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Abstract

Autism is a heterogeneous syndrome defined by impairments in three core domains: social interaction, language and range of interests. Recent work has led to the identification of several autism susceptibility genes and an increased appreciation of the contribution of *de novo* and inherited copy number variation. Promising strategies are also being applied to identify common genetic risk variants. Systems biology approaches, including array-based expression profiling, are poised to provide additional insights into this group of disorders, in which heterogeneity, both genetic and phenotypic, is emerging as a dominant theme.

Autistic disorder is the most severe end of a group of neurodevelopmental disorders referred to as autism spectrum disorders (ASDs), which share the common feature of dysfunctional reciprocal social interaction. A meta-analysis of ASD prevalence rates suggests that approximately 37 in 10,000 individuals are affected¹. ASDs encompass several clinically defined conditions (see BOX 1 and the Diagnostic and Statistical Manual of Mental Disorders), pervasive developmental disorder - not otherwise specified and autistic disorder are the most common, whereas Asperger syndrome appears less frequently. Boys are at increased risk for the ASDs, an effect that becomes even more pronounced in so-called high-functioning cases.

A chronological overview of research in the ASDs underscores the short history of genetic work in this area as well as the diversity of the methods used. Before the 1970s, autism was not widely appreciated to have a strong biological basis. Instead, various psychodynamic interpretations, including the role of a cold or aloof style of mothering, were invoked as potential causes. The importance of genetic contributions became clear in the 1980s, when the

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DATABASES

Entrez Gene: <http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?db=gene> [CADPS2](#) | [CNTNAP2](#) | [GABRB3](#) | [NLGN3](#) | [NLGN4X](#) | [NRXN1](#) | [SHANK3](#) | [UBE3A](#)

OMIM: <http://www.ncbi.nlm.nih.gov/entrez/query.fcgi?db=OMIM> [Angelman syndrome](#) | [autistic disorder](#) | [cortical dysplasia-focal epilepsy syndrome](#) | [fragile X syndrome](#) | [Joubert syndrome](#) | [Rett syndrome](#) | [Timothy syndrome](#) | [tuberous sclerosis](#)

FURTHER INFORMATION

Geschwind laboratory homepage: <http://geschwindlab.neurology.ucla.edu>

Autism chromosome rearrangement database: <http://projects.tcag.ca/autism>

Autism Genetic Resource Exchange (AGRE): <http://www.agre.org>

Autism tissue program: <http://www.brainbank.org>

Database of Genomic Variants: <http://projects.tcag.ca/variation>

Diagnostic and Statistical Manual of Mental Disorders: <http://allpsych.com/disorders/dsm.html>

SUPPLEMENTARY INFORMATION

See online article: [S1](#) (table)

co-occurrence of chromosomal disorders and rare syndromes with the ASDs were noted². Subsequent twin and family studies provided additional support for a complex genetic aetiology, but these were limited by the lack of uniform diagnostic criteria. The development of validated diagnostic and assessment tools in the early 1990s, most notably the Autism Diagnostic Interview - Revised (ADI-R) and the Autism Diagnostic Observation Schedule (ADOS), addressed these concerns and these tools have proven crucial to the advancement of international research into the ASDs. This work, in concert with important technical advances, made it possible to carry out the first candidate gene association studies and resequencing efforts in the late 1990s. Whole-genome linkage studies followed, and were used to identify additional loci of potential interest. Although the application of genome-wide techniques to assess copy number variation (CNV) has only just begun³⁻⁵, these studies have already identified a large number of potentially important novel candidate loci.

Thus, in contrast to the complete absence of any biological understanding of the ASDs as recently as 30 years ago, we now know that defined mutations, genetic syndromes and *de novo* CNV account for about 10–20% of ASD cases (BOX 2; TABLE 1; Supplementary information S1 (table)). However, the striking finding that none of these known causes accounts for more than 1–2% of cases is reminiscent of mental retardation (MR), an overlapping but distinct neurodevelopmental syndrome for which there is no single major genetic cause, but rather many relatively rare mutations. Despite this heterogeneity in the ASDs, several biological themes, including defective synaptic function⁶ and abnormal brain connectivity⁷ (BOX 3), have been hypothesized to link rare and common variants at the level of biological function. Still, the relative proportion of ASDs that are explained by either rare or common genetic variation (or both) remains to be determined.

In the face of this uncertainty, multiple parallel approaches are necessary to advance our understanding of the genetic factors underlying the ASDs. These approaches include whole-genome and pathway-based association studies, dense resequencing to identify mutations, and the continued collection of large well-characterized patient cohorts and their relatives for genotype–phenotype studies. Here we review this exciting and rapidly evolving field in which diverse genetic findings have begun to define potential biological mechanisms of disease.

Gene association studies

A set of methods that is used to determine the correlation (positive or negative) between a defined genetic variant and a phenotype of interest.

Whole-genome linkage study

A statistical evaluation of genetic variation throughout the genome that is used to identify polymorphic loci that segregate with a phenotype of interest.

Copy number variation

(CNV). The insertion or deletion of a relatively large DNA fragment (>50 kb).

ASD as a complex genetic trait

Autism has a strong genetic basis

Several lines of evidence support genetic factors as a predominant cause of the ASDs. First is the growing body of literature demonstrating that mutations or structural variation in any of several genes can dramatically increase disease risk. Second, the relative risk of a child being diagnosed with autism is increased at least 25-fold over the population prevalence in families in which a sibling is affected⁸. Third, siblings and parents of an affected child are more likely than controls to show subtle cognitive or behavioural features that are qualitatively similar to

those observed in probands^{9,10} (the broader autism phenotype); this is consistent with the segregation of quantitative sub-threshold traits within these families. Fourth, independent twin studies, although small, indicate that concordance rates for monozygotic twins (70–90%) are several-fold higher than the corresponding values for dizygotic twins (0–10%)^{11,12}. An important question for future work will be to clarify how environmental and genetic factors interact to influence risk and presentation (BOX 1).

Box 1

Classification and prevalence of ASDs

Specific impairments in each of three core domains before age three are required for a diagnosis of autistic disorder (13 per 10,000). Within the social domain, impaired use of nonverbal communication (facial expressions or body language) or a reduction in spontaneous attempts to share interests with others are common. Features in the language domain manifest as delayed or absent speech or difficulties initiating or sustaining a conversation. Abnormalities in the restricted and/or repetitive domain can present as abnormal preoccupations, inflexible adherence to routines or rituals, or repetitive motor behaviours. Males are over-represented compared with females (approximately 4:1), an effect that does not seem to be driven by X chromosomal loci. Interestingly, this male-to-female ratio approaches 1:1 when only severe cases of autistic disorder are considered.

Additional terms are useful for describing affected children on the basis of phenotypic presentation, although one should note that diagnosis in the autism spectrum disorders (ASDs) is in many cases complicated by the presence of severe cognitive delay. Individuals with Asperger syndrome (2.6 per 10,000) show impairments in the social and restricted and/or repetitive domains, but most use language in an age-appropriate manner and are not mentally retarded. Males are also over-represented among these cases (approximately 8:1). Individuals with pervasive developmental disorder - not otherwise specified (PDD-NOS; 20.8 per 10,000) show marked impairment in each core domain but do not meet diagnostic criteria for autistic disorder proper. Rett disorder (see main text; TABLE 1; Supplementary information S1 (table)) and childhood disintegrative disorder (normal development until age two with subsequent regression) are less common but are also listed among the ASDs in the current version of the Diagnostic and Statistical Manual of Mental Disorders.

Other important terms worth noting here include the concept of ‘broad-spectrum cases’, a classification typically encompassing a range of presentations, including autistic disorder, Asperger syndrome and PDD-NOS. Likewise, the term idiopathic is used to describe the large number of cases with no known aetiology. Although methodological problems make it difficult to accurately assess how prevalence rates change over time, evidence exists for as much as a twofold increased prevalence in the ASDs in recent years. Most attribute this increase to heightened awareness and the use of broader diagnostic criteria but this does not exclude the involvement of environmental factors in the modulation of ASD risk. Prenatal and perinatal complications are elevated in cases⁸⁵, and viral exposures — particularly rubella — are thought to elevate risk. It is also recognized that paternal age is increased among the fathers of affected children⁸⁶, a finding that might be related to elevated rates of *de novo* copy number variation in the ASDs⁴. Unpublished estimates for concordance rates for autistic disorder among dizygotic twins may be as high as 25% (J. Hallmayer, personal communication). If this figure is confirmed, it would allow for the involvement of *in utero* factors while still supporting the high heritability value of 0.7. The contribution of epigenetic modifications have also been championed^{87,88} but, although they are probably important, the manner and extent of their involvement remains to be defined. As additional

genetic ASD risk factors are identified, the way by which these molecules interact with the environment can be addressed formally.

Genetic models of ASDs

Central to this question of how genetic variation comes to influence phenotypic presentation is whether distinct aspects of ASDs are subject to independent genetic modulation or, alternatively, they are sensitive to largely overlapping risk factors. Recent work in a community-based cohort revealed that, despite high heritability values (>0.64) for social, communication and repetitive and/or restrictive domains¹³, only modest co-variation was observed between them. Similarly, individuals with extreme scores in one domain did not necessarily have extreme scores in others. Additional support for this oligogenic model, in which disease results from the combined action of multiple interacting genes, comes from linkage studies that have identified distinct loci for endophenotypes that are related to different core domains¹⁴⁻¹⁶. Such results are also in keeping with the view that several risk alleles act together to modulate risk in families with multiple affected siblings⁸.

At the same time, it should be recognized that the relationship between core domains in the ASDs might not be properly reflected in community-based samples. For example, within samples ascertained for ASDs, data-mining techniques such as hierarchical clustering and principal components analysis identify a single continuously distributed factor that contributes to multiple aspects of disease¹⁷. Similarly, statistical analysis of ASD family data suggests that a significant proportion of ASD cases may be the result of dominantly acting *de novo* mutations that have a reduced penetrance in females¹⁸. Further support for the idea that autism might be a single continuum comes from a growing list of single genetic lesions, each of which seems to be largely sufficient to cause an ASD.

Together, these observations put into relief two contrasting but valid and potentially compatible paradigms that dominate current thinking regarding the role of genetic variation in ASD susceptibility. The independent heritability of distinct ASD core domains supports the importance of common variation in disease risk and phenotypic presentation. At the same time, the fact that functional disruption of single molecules seems to be sufficient to cause disease suggests that the identification of rare variants is also important. The primary technical approaches used in ASD research are largely rooted in one of these two models, as discussed in the following sections.

Relative risk

The ratio of disease incidence in two groups of individuals that differ with regards to any associated factor (such as genetic polymorphism, environmental exposure or perinatal insult).

Community-based cohort

A group of individuals that have been selected randomly from a population (as opposed to those showing a specific phenotype of interest).

Rare mutations

Cytogenetics

Chromosomal abnormalities offered the first glimpse at the potential role of rare variants in ASD susceptibility¹⁹. Mutation detection in candidate genes and identification of *de novo* CNV are more recent approaches, but are nevertheless rooted in a rare-variant framework. It is

estimated that cytogenetically identified lesions are present in 6–7% of ASDs²⁰, although this proportion is higher in dysmorphic populations with MR. Inherited duplications involving the chromosomal region 15q11–15q13 are among the most common cytogenetic abnormalities in the ASDs, accounting for 1–2% of cases, with maternal interstitial duplications and isodicentric marker chromosomes observed in most cases. As with all cytogenetics work, only large regions (typically containing fifty or more genes) are initially identified. Isolation of the molecules that are contributory requires the serendipitous recovery of overlapping rearrangements in unrelated individuals or the discovery of point mutations within individual genes.

Heritability

The proportion of phenotypic variation that is attributable to inherited genetic factors (in contrast to environmental ones).

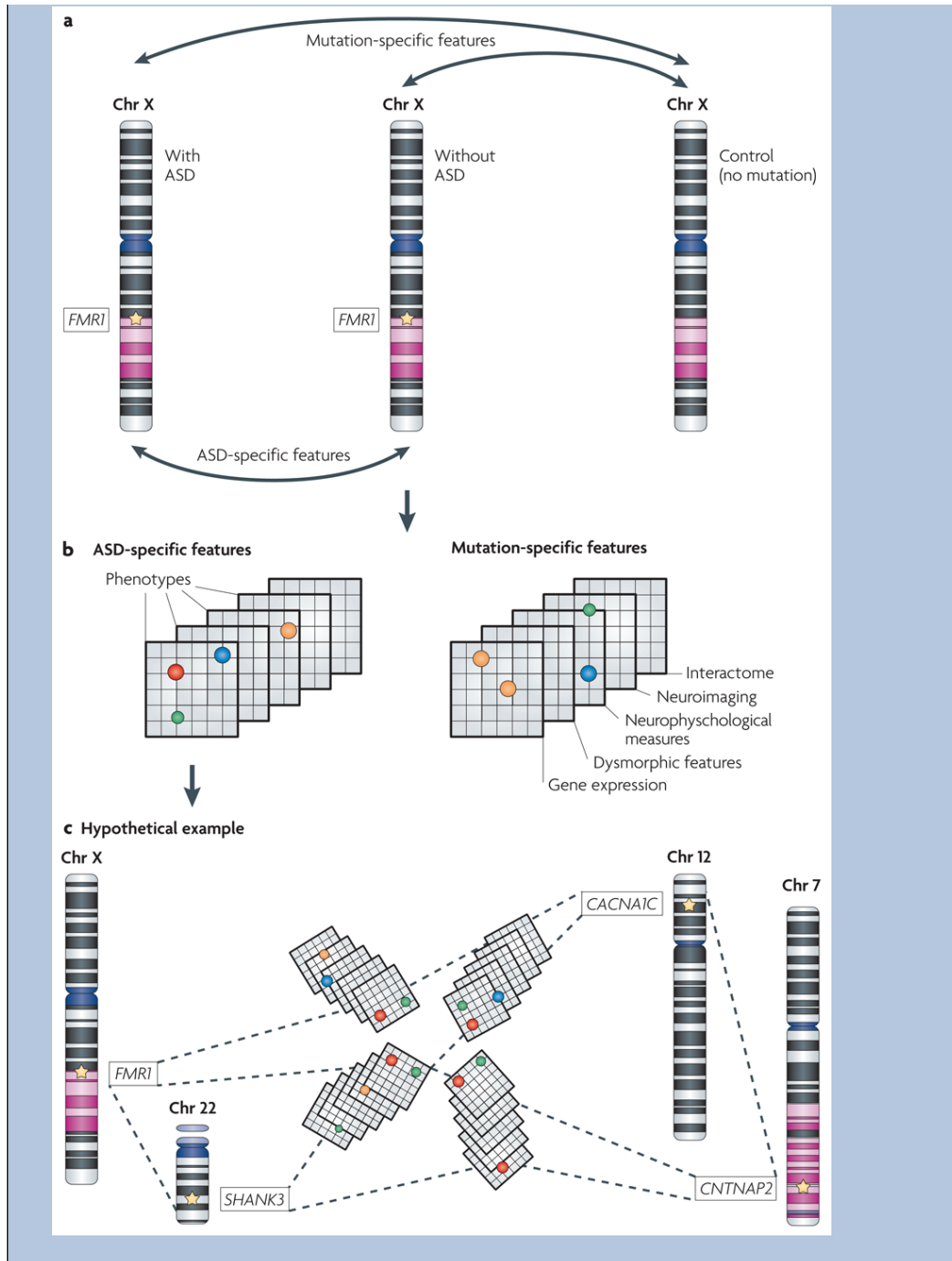
Box 2

Exploiting heterogeneity in the ASDs

Available data suggest that autism spectrum disorder (ASD)-related syndromes individually account for no more than 1–2% of ASD cases (see TABLE 1). This is compared with unclassified cytogenetic lesions visible by G-banding (~6–7% of cases) and unclassified *de novo* copy number variation (CNV) visible by molecular techniques (~2–10% of cases). Taken together it is likely that known syndromes, observable cytogenetics lesions and rare *de novo* mutations account for between 10–20% of cases. It might be possible to leverage this heterogeneity to identify core features that are shared across autism types and are thus central to pathogenesis.

For instance, within etiologically defined subgroups (for example, fragile X syndrome), the phenotypes under investigation would be contrasted not only between mutation carriers and typically developing controls (mutation-specific features in panel **a**) but also between carriers with and without an ASD (ASD-specific features in panel **a**). Comparisons between fragile X mutation carriers and mutation-free controls will identify phenotypes that are related to mutation status but that do not inform us about ASDs *per se*. By contrast, comparisons between fragile X mutation carriers with and without an ASD should highlight factors that are more directly related to risk and presentation. Similarly, this same approach might be used to identify factors within fragile X carriers that modulate presentation or performance on any quantitative trait.

Given this experimental design (see panel **a**) — and sufficiently detailed characterization (see panel **b**) — one might expect such contrasts to identify phenotypic ‘signatures’ that define each of mutation-specific features and ASD-specific features. Mutation-specific signatures will be important to our understanding of gene function (not shown). ASD-specific signatures will clarify the relationship between ASD subtypes. Panel **c** illustrates hypothetical relationships between distinct syndromic ASDs, where coloured circles represent shared phenotypes. *CACNA1C*, calcium channel voltage-dependent L type alpha 1C subunit; Chr, chromosome; *CNTNAP2*, contactin associated protein-like 2; *FMRI*, fragile X mental retardation 1; *SHANK3*, SH3 and multiple ankyrin repeat domains 3.



The clues obtained by these studies have proven important in our understanding of ASD aetiology. Within the 15q11–15q13 locus, ubiquitin protein ligase E3A (*UBE3A*) and gamma-aminobutyric acid A receptor beta 3 (*GABRB3*; an inhibitory neurotransmitter receptor) are currently thought to be central. Similarly, deletions involving 22q13 have been recognized for some time, but the important role of SH3 and multiple ankyrin repeat domains 3 (*SHANK3*; a synaptic adaptor protein) was appreciated only after resequencing and CNV analysis^{21,22}. Deletions involving 2q37 are also common, having been observed in more than 70 cases. Although it is less clear which gene or genes within this region are contributory, patient-specific missense substitutions and positive linkage results highlight the potential involvement of

centaurin gamma 2 (*CENTG2*; a GTPase-activating protein)²³. Other regions that are implicated in the ASDs by chromosomal abnormalities in multiple patients include 5p15, 17p11 and Xp22 (Ref. 19). As a result of the large regions that are typically isolated by analysis of chromosomal anomalies, these methods cannot alone inform us about particular molecular functions that might be impaired in the ASDs.

ASD-related syndromes

Considerable insight into potential candidate genes was obtained from the study of molecularly defined syndromes in which ASD was observed at higher than expected frequencies. Several of these conditions, such as fragile X syndrome and Rett syndrome, suggest synaptic dysfunction as a unifying aetiology⁶, whereas others, such as tuberous sclerosis, highlight the diversity of signalling pathways that seem to be related to the ASDs. Note that not all ASD-related syndromes are limited to the brain. For example, in Timothy syndrome, mutations in the calcium channel voltage-dependent L type alpha 1C subunit gene (*CACNA1C*) cause a multisystem disorder presenting with cardiac arrhythmia, webbing of digits, MR and an ASD in ~70% of patients²⁴. Syndromes such as this — with prominent features outside the central nervous system — reinforce the notion of pleiotropy and argue for caution in the pursuit of candidates on the basis of tissue-restricted gene expression.

Although these ASD-associated syndromes involve genes with multiple molecular functions, it seems increasingly plausible that they converge on common biological pathways or brain circuits to give rise to ASDs⁷. In support of this notion, links between these syndromes are beginning to emerge. Levels of *UBE3A* and *GABRB3*, for example, are reduced in each of Angelman syndrome, Rett syndrome and idiopathic autism²⁵. Further evidence for molecular overlap between different forms of syndromic ASDs comes from a subset of clinically identified ‘Angelman cases’ that are due to mutations in the Rett Syndrome gene, methyl CpG binding protein 2 (*MECP2*) (Ref. 26). Comparative study of these rare syndromes should be useful in identifying molecular features common to a variety of ASDs. Within disorders, contrasting cases with and without ASD-like features is also likely to prove informative (BOX 2; TABLE 1), although such studies have seldom been performed. As discussed below, support for such an approach comes from significant overlap in differentially expressed genes between each of fragile X syndrome and 15q duplication patients and controls²⁷. Unlike common variants that may subtly modulate ASD-related phenotypes, the more pronounced effects that are typical of syndromic mutations allow for clearer assessment of causality, greatly facilitating downstream functional analysis. A potentially important observation is that a substantial proportion of these syndromic cases (TABLE 1; Supplementary information S1 (table)) are associated with seizures (8 out of 12) and/or congenital cardiovascular anomalies (7 out of 12). This observation is consistent with the idea that defects in electrical conduction and neural transmission might be important in ASD pathogenesis. These data also suggest that genes known to modulate such properties merit careful consideration in candidate gene studies. Furthermore, although motor delay is not recognized as a core feature among ASDs, it is noteworthy that such abnormalities are observed in 9 out of 12 of these ASD-linked syndromes.

Endophenotype

A measurable trait that is both heritable and related to a specific aspect of a condition under investigation.

Hierarchical clustering

A statistical method in which a collection of objects (observations, individuals or risk loci) are grouped into subsets, such that those within each cluster are more closely related to one another than objects that are assigned to different clusters.

Principal components analysis

A statistical method used to simplify data sets by transforming a series of correlated variables into a smaller number of uncorrelated factors.

Penetrance

The frequency with which individuals that carry an allele of a given gene will show the manifestations associated with the variant. If the penetrance of a disease allele is 100% then all individuals carrying that allele will express the associated disorder.

Dysmorphic

Showing a structural abnormality of a body part or facial feature.

Interstitial

A chromosomal segment that is located between the centromere and telomere.

Isodicentric

A genetic abnormality characterized by the presence of two additional and identical DNA segment copies that are joined end to end to form a forty-seventh chromosome.

Syndromic ASD

An ASD case that is observed in the context of a recognized syndrome (for example, fragile X syndrome).

Box 3**Neurobiological hypotheses in the ASDs**

No single neurobiology currently dominates the autism spectrum disorders (ASDs), an observation that is presumably reflective of both the heterogeneity of the mechanisms at play and the short history of molecular work in the study of these disorders. Despite the general consensus regarding a developmental onset, little agreement exists around the primary nature of the insult(s). Although varied, dominant hypotheses can be attributed to cellular, regional or systemic dysfunction.

Among the cellular explanations, those involving the synapse currently dominate the field, although the manner by which generalized synaptic dysfunction might lead to specific behavioural impairments while largely sparing many aspects of cognition remains an important question. One hypothesis suggests a unifying role for glutamatergic neurotransmission⁸⁹, a theory that is bolstered by the observation that reduction of GluR5 gene dosage can ameliorate ASD-like features in fragile X mice⁹⁰. Others have posited that the defect lies at the inhibitory synapse³¹; this model could also account for the seizures that are observed in a subset of patients with ASDs. At the same time, strong arguments exist for the involvement of serotonin⁹¹, potentially accounting for abnormalities both in the brain and outside the central nervous system. Abnormal calcium signalling has likewise been suggested as a possible mechanism⁹². In support of this hypothesis several of the molecules underlying syndromic ASDs are known to act through intracellular signalling pathways. An important question that needs to be answered by any single unifying molecular hypothesis, synaptic or otherwise, is how cognitive and behavioural specificity is attained. The broad functional categories of genes identified thus far suggest that no single molecular explanation will suffice.

Histological abnormalities, particularly those involving the cerebellum, are among the earliest regional hypotheses, although such findings have not been observed consistently

among cases. Reduced hemispheric asymmetry⁹³, blunted mirror neuron activity⁹⁴ and aberrant connectivity⁷ are alternative regional hypotheses that have emerged more recently. An area of convergence from pathological⁹⁵ and imaging studies⁹⁶ involves frontal and anterior temporal regions of the brain and their long-distance reciprocal and parietal connections⁷, presumably focusing on brain regions involved in joint attention, an early social behaviour and important precursor of pragmatic language⁹⁷.

Layered over the top of these two paradigms are systemic abnormalities that are thought to have a role in the ASDs. The differential effects of maternal and paternal gains of 15q11, for example, are an important example of epigenetics at work. Although the role of epigenetic factors in the ASDs is still in its infancy, a handful of careful studies provides concrete molecular links between pervasive developmental disorders^{87,88}.

Hypocholesterolaemia⁹⁸, exposure to prenatal testosterone⁹⁹ and hyperactivation of the immune system¹⁰⁰ have also been offered as explanations for the ASDs. The relative merits of these hypotheses will be tested as gene-finding efforts move forward and aspects of the ASDs are modelled in cells and in animal systems. Approaches that are rooted in network biology will be crucial for understanding how these diverse molecular pathways act together at the systems level. One potential way to reconcile the known molecular abnormalities (which include those that affect synaptic transmission, cell–cell interactions and intracellular signalling pathways (TABLE 2; TABLE 4)) with histological and anatomical systems findings is to suggest that they cause a developmental disconnection between higher-order association areas⁷.

Candidate resequencing

The introduction of cost-effective resequencing has made it possible to build on cytogenetic studies and obtain evidence for the involvement of specific candidate genes in the ASDs. The identification of rare ASD-linked mutations in neuroligin 3 (*NLGN3*) and neuroligin 4 X-linked (*NLGN4X*) was an important advance linking the ASDs to specific molecules that are involved in synaptic function²⁸. Although coding variants in these genes do not seem to be a common explanation for ASDs²⁹, the neuroligins provide a salient example of how the study of rare disease-linked variants can inform our understanding of disease mechanisms. For example, the presence of the disease-linked R451C mutation in *NLGN3* interferes with cell-surface localization and appropriate protein–protein interactions³⁰. Similarly, subsequent characterization of mice harbouring this same mutation in *Nlgn3* highlights a possible role for excess inhibitory neurotransmission in disease³¹.

Mutations in *SHANK3*, the product of which interacts with neuroligins³², were identified by a similar route, and provide further evidence for the potential role of defective synaptogenesis in ASDs. This work also demonstrates the successful use of patients with structural chromosomal variation to guide gene choice in resequencing in large case–control cohorts. Three genetic lesions were identified in probands in three separate families from among the several hundred analysed²¹, and a follow-up screen for *SHANK3* mutations in 400 non-overlapping ASD probands identified rare *de novo* variants in nearly 1% of cases, most of whom were female²².

Mirror neuron

A neuron that is active when a subject is observing or imagining a motor movement; mirror neurons are thought to underlie imitation.

Joint attention

Sharing interest or experience with another person by pointing or following gaze.

Pragmatic language

Practical, social use of language.

Neuroigin

A member of a family of postsynaptic cell-adhesion molecules that is important in regulating the balance of inhibitory and excitatory neurotransmission.

Beta-neurexins also interact with neuroligins³³ and as such are compelling candidates for involvement in the ASDs. Identification of *de novo* deletions overlapping with neurexin 1 (*NRXN1*) in affected sisters⁵, along with rare missense mutations in other cases³⁴, provides strong support for the involvement of this molecule in the ASDs. That *NRXN1* deletions can be inherited from unaffected parents and are sometimes found in only a subset of affected siblings³⁵ also suggests incomplete penetrance, consistent with the notion of substantial complexity. A recessive frameshift mutation was also identified in contactin associated protein-like 2 (*CNTNAP2*), a member of the neurexin family³⁶, in Amish individuals presenting with cortical dysplasia-focal epilepsy syndrome, a congenital disorder characterized by seizures and language regression³⁷. Notably, two-thirds of affected individuals also met the criteria for an ASD. Other recent work demonstrates that both rare single-base-pair mutations³⁸ and common variation in *CNTNAP2* (Refs 39,40) could also contribute to ASD risk. Although *CNTNAP2* is best known for clustering potassium channels along myelinated axons, data from the human fetal brain indicate expression at high levels before myelination⁴¹. Along with evidence for abnormalities in neuronal migration in Amish patients who are homozygous for the frameshift mutation, these data suggest additional unappreciated functionality and an important role for this gene in the development of brain regions that are likely to be important for autism.

Copy number variation

The identification of CNV in addition to single-base-pair polymorphisms has opened a new window on human genetic variation⁴². *De novo* and inherited CNV are emerging as important causes of ASDs, either as rare variants that strongly modulate risk or as potentially new syndromes linked to the ASDs (see the autism chromosome rearrangement database for an extensive compilation)³⁻⁵. The concept of structural variation is not entirely new, as chromosomal disorders were among the earliest identified genetic abnormalities leading to ASDs. However, the increased resolution of array-based approaches suggests that the proportion of cases that might ultimately be attributable to rare structural variants is probably much higher than the 6–7% identified by standard cytogenetics. In addition to the identification of novel loci that are important for our understanding of the ASDs (FIG. 1; TABLE 2), observed differences in the extent of *de novo* variation between controls (1%), multiplex ASD families (2–3%) and simplex ASD families (7–10%)^{4,20} are consistent with other complex inherited diseases in which different genetic mechanisms are observed in sporadic compared with familial cases. These results are also relevant to the notion of the broader autism phenotype that is observed in the general population. The manyfold higher frequency of *de novo* CNV in simplex versus multiplex families would predict that ‘unaffected’ individuals from multiplex families would be more likely to harbour these lesser disease-related phenotypes than comparable individuals in simplex families (in whom the disease is more likely to arise *de novo*), as has been recently observed⁴³.

With regards to individual loci, the recent discovery of a recurrent *de novo* deletion involving an estimated 30 genes across 500 kb on chromosomal region 16p11 is of particular importance⁴⁴ as it is present in about 1% of cases in several sizeable cohorts^{20,35,44}. Importantly, a large population-based analysis³⁵ indicates that, whereas the deletion is observed in controls, it is enriched 100-fold in ASD cases. Understanding the contribution of

individual genes within this deletion, and the corresponding duplication that is also observed in cases, is an important question for future work. Another interesting CNV is a 750 kb *de novo* deletion involving the Ca²⁺-dependent activator protein for secretion 2 gene (*CADPS2*) and 7 other genes at 7q31, a replicated linkage region⁵ (see FIG. 1, item 7.7). This result, together with abnormalities in *Cadps2* knockout mice and rare missense variants in patients⁴⁵, supports a potential role for this positional candidate in disease. Similarly, a *de novo* loss at 20p13 (including the arginine vasopressin gene, the oxytocin gene and an additional 30 genes⁴) is intriguing given the associations between the variation in each of the corresponding receptors and ASDs (see later section on association studies) as well as the well-established role of both molecules in the modulation of social behaviour.

At the same time, it must be emphasized that the presence of a rare variant in a patient with a common disease need not always be meaningful⁴⁶, a point underscored by the 1% frequency of *de novo* CNV detected in controls⁴. Empirical determination of how a CNV or any rare mutation affects gene function or expression — as was done in a patient with a deletion in the neuronal specific splicing factor ataxin 2-binding protein 1 (*A2BPI*)⁴⁷ — will be important. Given that many of these rare variants span many genes and have only been observed in a single proband, much work is required to determine the subset causally related to disease. For some of the very rare, virtually unique, mutations even large sample sizes will not be sufficient to demonstrate statistical association, although the biological significance of the mutation may be clear.

Multiplex

Multiplex families are those in which multiple individuals have a clinically diagnosed ASD.

Simplex

Simplex families are those in which only a single individual has a clinically diagnosed ASD.

Specificity of rare variants

Overall, none of the molecules or syndromes currently linked to the ASDs have been shown to selectively cause autism. Instead, each seems to result in an array of abnormal neurobehavioural phenotypes, including autism, Asperger syndrome, non-syndromic MR and other neurodevelopmental abnormalities. For example, within a large French family harbouring a truncating mutation in *NLGN4X*, most male carriers presented with non-specific MR (10 out of 13), with only the remaining minority showing additional features consistent with an ASD⁴⁸. Given that mutations in *NLGN4X* seem to cause MR more frequently than ASDs, a different consensus regarding involvement and specificity might have emerged had this paper been published earlier than the original autism paper. A similar range of phenotypes is observed for each of *SHANK3*, *NRXN1* and *CNTNAP2* mutations. Lastly, an extensive study of the 16p11 CNV in multiple clinical populations showed that it is at least as prevalent in a clinical population with global developmental delay or language delay as it is in autism³⁵. Given this apparent lack of specificity for the ASDs, it will not be surprising if variation in some of these genes contribute to other neuropsychiatric disorders. As we discuss below, an understanding of the contribution of common variation — and the manner by which rare variants could modulate presentation even in cases with rare ‘major’ mutations — is an important future step.

Linkage studies

Substantial effort in autism genetics over the last 10 years has been focused on genetic linkage analysis using an affected sibling-pair design in multiplex families. Most studies have identified linkage regions reaching the threshold of suggestive linkage at best (see Ref. 49 for a recent review). Despite large increases in patient cohorts, linkage signals have not increased concomitantly with sample size. Loci on most chromosomes have been suggested to harbour ASD risk loci, but only a minority have been independently identified (FIG. 1; TABLE 3). To date, only loci on 17q11–17q21 and 7q have been replicated at levels that could be considered genome-wide significant^{50–52}.

The lack of genome-wide significant results in most published linkage studies is probably a consequence of the small effect size that is attributable to any particular gene. Early recognition of substantial genetic heterogeneity in the ASDs, and the need for large patient cohorts, led to the development of the Autism Genetic Resource Exchange (AGRE)⁵³. AGRE is a publicly available resource of phenotypic data and bio-materials that has been widely used in these and other genetic studies of ASDs. Despite the replication of the chromosome 17q locus in the AGRE sample⁵¹, this signal has not been observed in every subsequent study¹⁵. Even the linkage scan published by the Autism Genome Project Consortium⁵, a large collaborative effort containing approximately 1,400 families, showed only minor overlap with previous genome scans. This might be because samples were contributed from multiple groups throughout the world, increasing the genetic heterogeneity in this cohort. Similarly, diagnostic differences used by participating groups might have increased phenotypic heterogeneity.

Subsetting cohorts to increase homogeneity

It is therefore not surprising that efforts to reduce heterogeneity by subsetting the sample according to specific phenotypes^{54,55} and refining phenotype definitions, have improved linkage signals. For example, subsetting by sex of proband^{51,54,56}, language⁵⁷ or other neurobehavioural features such as autistic regression or behavioural inflexibility^{55,58,59} has increased signals relative to non-stratified samples, including identification of genome-wide significant loci^{51,54}. Given these successes, additional heritable phenotypes such as macrocephaly, structural features defined by magnetic resonance imaging, or the presence of seizures or electroencephalographic abnormalities might offer promise in defining subgroups of probands with autism.

Endophenotypes and mapping QTLs

In QTL mapping, autism endophenotypes are studied as opposed to affection status. The premise underlying a QTL approach complements models in which key aspects of the ASDs might be at one end of a continuum of normal behaviour and cognition⁶⁰. Such work also recognizes that the diagnostic categories used in clinical practice might not properly represent underlying genetic risk. That subtle ASD-like symptoms are elevated in frequency in siblings and parents of cases relative to controls^{9,10} makes the use of a QTL-based approach reasonable. Moreover, because many of these traits — including aspects of social behaviour, language and repetitive and/or restricted behaviours — vary within populations^{61,62} mapping efforts can be extended to large community-based cohorts. Important studies within diabetes⁶³, psychiatric genetics^{64,65} and other human disorders^{66,67} highlight the power of this approach. As such, identification of refined quantitative end-points within the ASDs should be seen as a high priority.

Because a significant percentage of the non-autistic siblings of probands have a history of speech and language delay⁹, Alarcon *et al.* used a measure of language delay to identify a QTL on 7q34–7q36 (Ref. 14). Subsequent attempts at replication did not yield genome-wide

significant results, but did provide suggestive support for linkage of language delay to this locus in ASDs as well as evidence for substantial genetic heterogeneity⁶⁸. Schellenberg and colleagues¹⁵ identified a locus at 9q34 using the same age-at-first-word measure, taken from the ADI-R. Loci underlying quantitative assessment of non-verbal communication have also been identified¹⁶, and similar advances have been obtained through analysis of quantitative aspects of social behaviour, a core feature of the ASD diagnosis; this identified several regions already linked with ASDs, including a locus on chromosome 11 (Ref. 69). These preliminary QTL studies hold promise as a means of increasing power in linkage and association studies. Such methods will become more useful as our knowledge of ASD-related endophenotypes grows through twin, family and case-control studies.

The fact that linkage studies have not identified ‘the ASD gene’ is not a failure of these methods but rather an accurate reflection of the complexity of this group of disorders and the need for larger sample sizes. Although refined quantitative end points should improve the power of these approaches, insights that have already been obtained from these studies are important and should not be underestimated. Our identification of an association between common variation in *CNTNAP2* and age at first word, for example, was the direct result of high-density SNP genotyping across the entire 7q34–7q36 linkage region. In a two-stage analysis, only variation in this gene survived correction for multiple comparisons. In this context, it is interesting to speculate about how many of the other ASD candidate genes in the more proximal 7q region (FIG. 1) might have been missed were it not for the well-replicated linkage to this region.

Association studies

Although several large whole-genome association studies are underway, including work in the AGR sample, not one of these studies has yet been published. Numerous studies have, however, evaluated common variation in biological and positional candidates for association with ASDs or ASD-related phenotypes. A summary of findings for genes with the strongest support is provided in TABLE 4. The fact that most of these associated SNPs appear to be intronic — the met proto-oncogene (*MET*) promoter variant⁷⁰ is an important exception — suggests that substantial work will be required to understand how disease-linked variants modulate clinical phenotypes.

Genes for which rare ASD-linked mutations have been identified have not been shown to modulate risk through common variants. However, this is a potentially promising area and some interesting exceptions — including *CNTNAP2* (Refs 39,40) and the Abelson helper integration site 1 gene (*AHII*; A. Alvarez-Retuerto and D. G., unpublished results), in which mutations cause 6q23-linked Joubert syndrome⁷¹ — are emerging. At the same time, comprehensive evaluation of the genome-wide significant chromosome 17q locus by high-density SNP analysis⁷² did not reveal any single common variant that survived correction for multiple comparisons. Similarly, the *CNTNAP2* variant, recently found to be associated with age at first word⁴⁰, does not fully account for the linkage signal across the 7q34–7q36 interval¹⁴. Together, these data suggest that other variants, yet to be identified, might contribute to both peaks, necessitating much larger cohorts as has been necessary in other common diseases. These data also suggest that rare mutations are more important than previously anticipated.

At this point, it is perhaps reasonable to question whether any of the common variants identified thus far, each only subtly modulating risk, have added anything other than confusion to an otherwise productive field. In most cases, the true functional variant remains unidentified. Similarly, there is no case in which independent groups consistently replicated any of the existing associations. At the same time, such arguments belie the truth. None of the known

mutations consistently results in autistic disorder, Asperger syndrome or any other defined spectrum disorders, necessitating the involvement of other factors. Moreover, given the heterogeneity in the ASDs it is not surprising that associations are not always replicated in each population evaluated. Holding associations to a standard of 100% replication would be similar to dismissing the role of a particular mutation after not seeing it in a small case series. Additional support for the common variant approach comes from data indicating that mice with mutations in genes for which association is well established (for example, *reelin* and *Gabrb3*) show ASD-like abnormalities^{73,74}. Not only should rare and common variant approaches be pursued in parallel, but an integration of the results from both methods will also be necessary. Larger cohorts will also be needed to identify more definitive associations.

Autistic regression

Normal development until the age of two with a subsequent loss of skills within core ASD domains.

Macrocephaly

Head circumference greater than two standard deviations above the mean (the ninety fifth percentile).

Multiple comparisons

Refers to the problem that arises when many null hypotheses are tested and 'significant' differences are observed when in reality there are no differences.

Array analyses — from genes to pathways

Microarray studies are beginning to provide important insights into molecules and pathways that might be dysregulated across the ASDs and within individual subtypes of pervasive developmental disorders. Early work using cDNA arrays and subtraction strategies contrasted cerebellar cortex from cases and controls and identified expression changes in genes relating to glutamatergic neurotransmission⁷⁵. Interestingly, among the most differentially expressed genes identified by subtraction was erythrocyte membrane protein band 4.1-like 3 (*EPB41L3*; also known as *4.1B*), a known interactor of *CNTNAP2*. Identification of molecules that might be central to the aetiology in fragile X syndrome — and, by extension, the ASDs — comes from other work identifying mRNAs that are associated with fragile X syndrome *in vivo* and a subset that seem to be dysregulated in patient-derived lymphoblastoid cells⁷⁶.

Nishimura and colleagues²⁷ showed that gene expression can distinguish among ASD cases caused by known genetic lesions and identify common pathways that were validated both in neural tissues and cases of idiopathic autism. This work defined 68 molecules that are differentially expressed in cells from fragile X syndrome and 15q duplication patients with an ASD relative to controls and identified cytoplasmic FMR1 interacting protein 1 (*CYFIP1*; an interactor of fragile X protein) and janus kinase and microtubule interacting protein 1 (*JAKMIP1*, also known as *MARLIN1*, which traffics gamma-aminobutyric acid receptors) as providing a direct molecular link between the two conditions. Several other studies have profiled gene expression in peripheral blood⁷⁷⁻⁸⁰ to identify biomarkers or pathophysiological pathways in ASDs and related neurodevelopmental disorders; these await validation using independent methods and samples.

It is notable that although less than 1% of the ~900 unique genes collectively identified by these array studies were independently identified in separate experiments, among this set are several genes within the 15q interval (*CYFIP1*, non imprinted in Prader-Willi/Angelman syndrome 2 (*NIPA2*) and *UBE3A*). Additionally, several ontological categories are strongly

over-represented across the entire data set, including ubiquitin conjugation ($n = 18$, $p = 2.7 \times 10^{-5}$), SH3 domain-containing proteins ($n = 28$, $p = 8.7 \times 10^{-9}$), GTPase regulator activity ($n = 41$, $p = 4.0 \times 10^{-11}$), α -protocadherin genes ($n = 14$, $p = 1.2 \times 10^{-15}$) and alternative splicing ($n = 272$, $p = 4.0 \times 10^{-34}$), raising these pathways as potential candidates for future mutation screening and association studies.

The use of gene expression data will increase as sample sizes grow, as additional molecularly defined syndromes are characterized by expression arrays^{37,44} and as expression information is better integrated with comprehensive phenotypic data⁸¹. It is also likely that the integration of expression studies with high-density SNP arrays will ultimately come to elucidate how disease-associated variants affect cellular function⁸². Furthermore, such expression QTL analysis might offer more power than traditional phenotypes, as the genotype relative risk associated with levels of specific transcripts might be higher than that associated with a complex neurobehavioural phenotype, such as social behaviour.

Looking forward

The identification of multiple rare mutations has implicated numerous genes of diverse function in the aetiology of the ASDs. Although causality remains to be demonstrated in most cases, a substantial subset seems to be important in modulating disease risk. These *de novo* mutations, together with those inherited in the context of a rare syndrome, each represent no more than 1–2% of cases individually, but account for at least 10–20% of the ASDs (TABLE 1; Supplementary information S1 (table)). The proportion of ASDs that might eventually come to be explained in terms of such major gene effects (as opposed to multigene interactions) should be clarified within the next year or two.

Given variable expressivity and incomplete penetrance among individuals carrying the same rare mutation, understanding the manner by which these rare variants interact with common alleles remains important. Similarly, the normal distribution of ASD-like features in populations⁶² as well as the elevated frequency of the broader autism phenotypes in close relatives of probands^{9,10} argues for an important role of common variation. That several common variants have now been independently shown to modulate risk and/or presentation is also evidence of important progress. A significant challenge here, however, is a continued focus on categorical measures (such as whether an individual is affected or not). Instead, quantitative endophenotypes will be necessary to properly identify risk alleles and understand the manner by which variation contributes to pathology. From a biological perspective, common variants are likely to have much greater salience when studied with regards to more specific phenotypes, including measures of gene expression, brain structure and quantitative aspects of social behaviour or communication. Use of quantitative end-points will also allow evaluation of whether genes that modulate ASD risk can contribute to aspects of normal phenotypic variation. For example, the association of variation in *CNTNAP2* with language onset raises the possibility that variation in this gene might also modulate language-related cognitive phenotypes in both the general population and other clinically distinct, but related, disorders.

Also important, and immediately tractable, is the question of whether ASDs of different etiologies share common molecular mechanisms or pathways, and, if they do, whether the relationship between the underlying genes be understood^{83,84}. Given the observed heterogeneity, an understanding of how risk factors interact functionally is an important step towards therapeutic interventions. Although this etiological heterogeneity will complicate substantially the translation of genetic findings from the laboratory to the clinic, it might prove useful in the identification of common targets for clinical intervention (BOX 2). Related to the heterogeneity in the ASDs, and discussed above, is the absence of clarity surrounding the

specifics of the relationship between the ASDs, MR and other neuropsychiatric conditions. Although each can appear together, that they are also seen independently provides an opportunity to understand the overlap between MR and autism at the level of brain structure and function. Other co-morbid disorders observed in families with ASD probands also provide an important entry-point for exploring the genetic and biological boundaries of these conditions. For example, some of the language deficits observed in the ASDs are also seen in other disorders such as specific language impairment. Similarly, aspects of frontal executive and social dysfunction seem to overlap with other childhood neurodevelopmental conditions such as attention deficit hyperactivity disorder. These concepts reinforce the idea that current clinical notions of boundaries between neuropsychiatric disorders need not be representative of the underlying genetic or biological etiologies. At a practical level, these data support evaluation of putative ASD-linked variants in unaffected family members, typically developing controls and cohorts with other neurodevelopmental disorders (for example, nonspecific MR, schizophrenia and bipolar disorder). Also helpful here could be the use of rare disease subtypes to define the relationships between ASDs, as well as links to clinically distinct disorders with overlapping features.

Finally, we must aim to integrate existing and emerging genetic candidates into our understanding of human brain function. Such efforts are likely to provide important insights not only into ASD but also into related disorders in which behaviour is compromised through impaired function of overlapping regions and circuits. Because genes modulate behaviour through complex temporal and positional expression, analyses of candidate genes both through development⁴¹ and in patient material (for example, the [Autism Tissue Program](#)) will be important. Advances in systems biology should provide an important platform on which to integrate the modulatory effects of multiple interacting genes with functional data compiled from many levels of analysis^{83,84}.

From the dominance of psychodynamic theories of autism as recently as 1970 to the awareness of upwards of 20 *bona fide* risk genes today, it must be concluded that substantial progress has been made in a relatively short time. That the identification of virtually every ASD-related gene and syndrome occurred within the last 5–10 years is particularly telling. Linkage studies have not found ‘the autism gene’ but have unequivocally demonstrated that more sophisticated solutions will be required to explain this group of disorders. The availability of new technology — particularly the ability to engage families in research through the internet — will permit the initiation of population-based strategies that are likely to provide more satisfying answers. Despite the immense amount of work implied in this agenda, the landscape for the future study of the ASDs is coming into view and has never looked as promising.

Frontal executive

Frontal executive function describes broad aspects of higher cognition (for example, attention, working memory and relational reasoning) that are mediated by the frontal lobe and interconnected subcortical circuitry.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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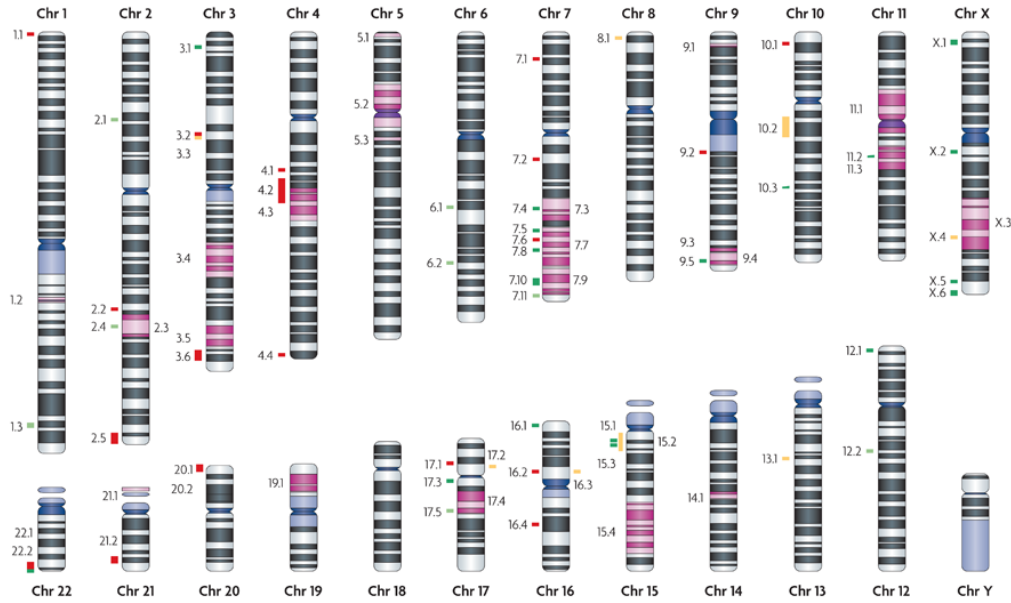
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ID	Feature	Position	Refs	ID	Feature	Position	Refs	ID	Feature	Position	Refs
1.1	Loss	1p36	3	7.4	<i>RELN</i>	7q22	117-121	15.3	Gain	15q11-15q13	4
1.2	Linkage	1q21-1q23	116	7.5	<i>MET</i>	7q31	70,123	15.4	Linkage	15q22-15q26	5
1.3	<i>DISC1</i>	1q42	122	7.6	Loss	7q31	5	16.1	<i>TSC2</i>	16p13	110
2.1	<i>NRXN1</i>	2p16	5,34	7.7	Linkage	7q32-7q34	15	16.2	Loss	16p11	4,20,35,44
2.2	Loss	2q24	4	7.8	<i>CADPS2</i>	7q31	5,45	16.3	Gain	16p11	20,35,44
2.3	Linkage	2q24-2q31	57,58,112	7.9	Linkage	7q34-7q36	14,52,68	16.4	Loss	16q21	5
2.4	<i>SLC25A12</i>	2q24	124-126	7.10	<i>CNTNAP2</i>	7q35-7q36	37-40	17.1	Loss	17p12	5
2.5	Loss	2q37	4	7.11	<i>EN2</i>	7q36	129,130	17.2	Gain	17p12	107
3.1	<i>OTXR</i>	3p25	127,128	8.1	Gain	8p23	5	17.3	<i>SLC6A4</i>	17q11	131-134
3.2	Loss	3p14	4	9.1	Linkage	9p24	5	17.4	Linkage	17q11-17q21	51,54,135
3.3	Gain	3p14	4	9.2	Loss	9q12	5	17.5	<i>ITGB3</i>	17q21	136,137
3.4	Linkage	3q22	15	9.3	Linkage	9q33	5	19.1	Linkage	19p13	140
3.5	Linkage	3q25-3q27	138,139	9.4	Linkage	9q34	15	20.1	Loss	20p13	5
3.6	Loss	3q27-3q28	3	9.5	<i>TSC1</i>	9q34	110	20.2	Loss	20p13	5
4.1	Loss	4q21	3	10.1	Loss	10p14-10p15	4	21.1	Linkage	21q11	55
4.2	Loss	4q21-23	3	10.2	Gain	10q11-10q21	4	21.2	Loss	21q22	3
4.3	Linkage	4q22-4q25	15	10.3	<i>PTEN</i>	10q23	141	22.1	Loss	22q13	4
4.4	Loss	4q35	5	11.1	Linkage	11p12-11p13	5	22.2	<i>SHANK3</i>	22q13	21,22,142,143
5.1	Linkage	5p15	5	11.2	<i>DHCR7</i>	11q13	108	X.1	<i>NLGN4X</i>	Xp22	28
5.2	Linkage	5p13-5q11	140	11.3	Linkage	11q13-11q14	15	X.2	<i>NLGN3</i>	Xq13	28
5.3	Linkage	5q12	5	12.1	<i>CACNA1C</i>	12p13	24	X.3	Linkage	Xq21-Xq25	140
6.1	<i>GRIK2</i>	6q21	144-146	12.2	<i>AVPR1A</i>	12q14-12q15	147	X.4	Gain	Xq24	3
6.2	<i>AHII</i>	6q23	106	13.1	Gain	13q14	5	X.5	<i>FMRI</i>	Xq27	105,148
7.1	Loss	7p21	4	14.1	Linkage	14q23	149	X.6	<i>MECP2</i>	Xq28	109
7.2	Loss	7q11	3	15.1	<i>UBE3A</i>	15q11	102,103				
7.3	Linkage	7q22-7q32	52,111-113	15.2	<i>GABRB3</i>	15q12	25,114,115				

Figure 1. Loci implicated in ASD etiology

Entries in the ID column of the table map link entries to the ideograms of individual chromosomes. Red and yellow bars correspond to *de novo* losses and gains, respectively, that are observed in cases but not in controls. Green bars correspond to genes that are observed to modulate autism spectrum disorder (ASD) risk (either through a rare syndrome or genetic association): light green and dark green bars represent promising or probable candidate genes, respectively, as defined in TABLE 2. Regions shaded in purple correspond to linkage peaks. Only human data were considered in the assembly of the table. *AHII*, Abelson helper intergration site 1; *AVPR1A*, arginine vasopressin receptor 1A; *CACNA1C*, calcium channel voltage-dependent L type alpha 1C subunit; *CADPS2*, Ca²⁺-dependent activator protein for

secretion 2; *CNTNAP2*, contactin associated protein-like 2; *DHCR7*, 7-dehydrocholesterol reductase; *DISC1*, disrupted in schizophrenia 1; *EN2*, engrailed homeobox 2; *FMR1*, fragile X mental retardation 1; *GABRB3*, gamma-aminobutyric acid (GABA) A receptor beta 3; *GRIK2*, glutamate receptor ionotropic kainate 2; *ITGB3*, integrin beta 3; *MECP2*, methyl CpG binding protein 2; *MET*, met proto-oncogene; *NLGN3*, neuroligin 3; *NLGN4X*, neuroligin 4 X-linked; *NRXN1*, neurexin 1; *OXTR*, oxytocin receptor; *PTEN*, phosphatase and tensin homologue; *RELN*, reelin; *SHANK3*, SH3 and multiple ankyrin repeat domains protein 3; *SLC25A12*, solute carrier family 25 (mitochondrial carrier, Aralar) member 12; *SLC6A4*, solute carrier family 6 (neurotransmitter transporter, serotonin) member 4; *TSC1*, tuberous sclerosis 1; *TSC2*, tuberous sclerosis 2; *UBE3A*, ubiquitin protein ligase E3A.

Table 1

ASD-related syndromes

Syndrome	Gene(s) associated with the syndrome	Proportion of patients with the syndrome that have an ASD	Proportion of patients with an ASD that have the syndrome	Refs
15q duplication — Angelman syndrome	<i>UBE3A</i> (and others)	>40%	1–2%	101–103
16p11 deletion	Unknown	High	~1%	20, 35, 44
22q deletion	<i>SHANK3</i>	High	~1%	21, 22, 104
Cortical dysplasia-focal epilepsy syndrome	<i>CNTNAP2</i>	~70%	Rare	37
Fragile X syndrome	<i>FMRI</i>	25% of males; 6% of females	1–2%	105
Joubert syndrome	Several loci	25%	Rare	106
Potocki–Lupski syndrome	Chromosome position 17p11	~90%	Unknown	107
Smith–Lemli–Optiz syndrome	<i>DHCR7</i>	50%	Rare	108
Rett syndrome	<i>MECP2</i>	All individuals have Rett syndrome	~0.5%	109
Timothy syndrome	<i>CACNA1C</i>	60–80%	Unknown	24
Tuberous sclerosis	<i>TSC1</i> and <i>TSC2</i>	20%	~1%	110

The rates quoted in the table depend on the population that is being evaluated. For example, rates are higher in individuals from simplex families compared with multiplex families, and are higher in dysmorphic and mental retardation populations compared with idiopathic populations. ‘High’ is used for syndromes in which no good estimates exist (that is, only a handful of individuals with the syndrome in question have been identified). It should also be noted that none of the studies cited here indicates that assessment for the autism spectrum disorder (ASD) was performed blind to a patient's primary diagnosis. An expanded version of the table with additional variables can be found in Supplementary information S1 (table). *CACNA1C*, calcium channel voltage-dependent L type alpha 1C subunit; *CNTNAP2*, contactin associated protein-like 2; *DHCR7*, 7-dehydrocholesterol reductase; *FMRI*, fragile X mental retardation 1; *MECP2*, methyl CpG binding protein 2; *SHANK3*, SH3 and multiple ankyrin repeat domains 3; *TSC1*, tuberous sclerosis 1; *TSC2*, tuberous sclerosis 2; *UBE3A*, ubiquitin protein ligase E3A.

Table 2

Evidence scores for ASD gene candidates

Gene	Syndrome or mutation(s)	Replicated association	Analysis of variant	Mouse model	Other evidence	Total score
Promising						
<i>AVPR1A</i>	0	0	0	1	0	1
<i>DISC1</i>	0	0	0	1	0	1
<i>ITGB3</i>	0	1	0	0	0	1
<i>AH11</i>	2	0	0	0	0	2
<i>EN2</i>	0	1	0	1	0	2
<i>GRIK2</i>	0	1	0	0	1; homozygous mutation results in non-syndromic mental retardation	2
<i>NRXN1</i>	2	0	0	0	0	2
<i>SLC25A12</i>	0	1	0	0	1; associated with neurite outgrowth, expression is upregulated in ASD brain	2
Probable						
<i>CACNA1C</i>	2	0	1	0	0	3
<i>CNTNAP2</i>	2	1	0	0	0	3
<i>MET</i>	0	1	1	0	1; expression reduced in brains of cases versus controls	3
<i>OXTR</i>	0	1	0	1	1; expression reduced in blood of cases versus controls	3
<i>SHANK3</i>	2	0	0	0	1; modulates glutamate-dependent reconfiguration of dendritic spines	3
<i>SLC6A4</i>	0	1	1	0	1; clinical benefit from inhibitors, variation linked to gray-matter volume	3
<i>CADPS2</i>	2	0	1	1	0	4
<i>DHCR7</i>	2	0	1	0	1; hypocholesterolaemia in a proportion of probands	4
<i>FMRI</i>	2	0	1	1	0	4
<i>NLGN3</i>	2	0	1	1	0	4
<i>NLGN4X</i>	2	0	1	1	0	4
<i>PTEN</i>	2	0	0	1	1; mutations result in abnormal structure and function of the synapse	4
<i>TSC2</i>	2	0	1	0	1; regulates dendrite morphology and function of glutamatergic synapses	4
<i>GABRB3</i>	2	1	0	1	1; expression is dysregulated in pervasive developmental disorders	5

Gene	Syndrome or mutation(s)	Replicated association	Analysis of variant	Mouse model	Other evidence	Total score
<i>MECP2</i>	2	0	1	1	1; <i>MECP2</i> deficiency causes reduced expression of <i>UBE3A</i> and <i>GABRB3</i>	5
<i>TSC1</i>	2	0	1	1	1; regulates dendrite morphology and function of glutamatergic synapses	5
<i>UBE3A</i>	2	0	1	1	1; expression is dysregulated in pervasive developmental disorders	5
<i>RELN</i>	2	1	1	1	1; levels reduced in brains of cases versus controls	6

Because the relationship to disease is most clear for rare variants, we biased our scoring accordingly. Genes associated with an autism spectrum disorder (ASD)-linked syndrome or mutation resulted in 2 points, whereas other lines of evidence resulted in 1 point. To qualify as a mouse model, 2 out of 3 core features were required to be present. The mean and standard deviation for evidence scores are 3.3 and 1.4, respectively. We assigned genes with scores greater than 3 as probable. Although we have done our best to systematically and comprehensively evaluate available data for each of the different molecules discussed, we recognize that these evidence scores are largely arbitrary. Together with unintended omissions of genes that are likely to be important in the ASDs, we hope that this table might serve as a useful starting point for discussion. *AH11*, Abelson helper integration site 1; *AVPR1A*, arginine vasopressin receptor 1A; *CACNA1C*, calcium channel voltage-dependent L-type alpha 1C subunit; *CADPS2*, Ca^{2+} -dependent activator protein for secretion 2; *CNTNAP2*, contactin associated protein-like 2; *DHCR7*, 7-dehydrocholesterol reductase; *DISC1*, disrupted in schizophrenia 1; *EN2*, engrailed homeobox 2; *FMRI*, fragile X mental retardation 1; *GABRB3*, gamma-aminobutyric acid (GABA) A receptor beta 3; *GRIK2*, glutamate receptor ionotropic kainate 2 precursor; *ITGB3*, integrin beta 3; *MECP2*, methyl CpG binding protein 2; *MET*, met proto-oncogene; *NLGN3*, neuroligin 3; *NLGN4X*, neuroligin 4 X-linked; *NRXN1*, neuroligin 1; *OXTR*, oxytocin receptor; *PTEN*, phosphatase and tensin homologue; *RELN*, reelin; *SHANK3*, SH3 and multiple ankyrin repeat domains 3; *SLC25A12*, solute carrier family 25 (mitochondrial carrier, Aralar) member 12; *SLC6A4*, solute carrier family 6 (neurotransmitter transporter, serotonin) member 4; *TSC1*, tuberous sclerosis 1; *TSC2*, tuberous sclerosis 2; *UBE3A*, ubiquitin protein ligase E3A.

Table 3

Linkage peaks with support from independent studies*

Locus	Endpoint	Statistics	Cohort (subsetting)	Best marker	Candidate genes	Refs
1q21–1q23	Asperger diagnosis	Z _{max} = 3.6 (p = 0.0002)	30 extended families of Finnish origin	D1S484	–	150
	ASD diagnosis	MLS = 2.6 (p = 0.002)	38 extended families (strict autism in 21)	D1S1653	–	138
2q24–2q31	ASD diagnosis	MLS = 4.8 (p = 2 × 10 ⁻⁵)	152 IMGSAC families (strict autism in 127)	D2S2188	<i>CENTG2</i>	112
	ASD diagnosis	NPL = 3.3 (p = 0.0005)	100 families (speech delay in 49)	D2S364	–	57
3q25–3q27	ASD diagnosis	MLS = 4.8 (p = 2 × 10 ⁻⁵)	38 extended families	D3S3037	–	138
	ASD diagnosis	NPL = 3.5 (p = 0.0003)	Large Utah pedigree with 7 affected children	rs1402229	–	139
5p13–5p14	ASD diagnosis	Z = 3.4 (p = 0.0003)	1181 AGP families (194 FC families with ≥2 children with strictly defined autism)	rs1968011	–	5
	ASD diagnosis	MLS = 2.5 (p = 0.003)	110 AGRE families	D5S2494	–	140
	ASD diagnosis	MLS = 2.5 (p = 0.003)	345 AGRE families	D5S1473	–	135
7q22–7q31	ASD diagnosis	MLS = 3.2 (p = 0.0006)	152 IMGSAC families	D7S477	<i>RELN, MET, CADPS2</i>	70:112:117-121:123
	ASD diagnosis	MLS = 3.1 (p = 0.0008)	170 IMGSAC families	D7S477	–	45:111
7q34–7q36	Age at first word	Z _{max} = 3.0 (p = 0.001)	152 AGRE families	D7S1824 to D7S3058	<i>GNTNAP2, EN2</i>	14:39:40:129, 130:151:152
	Age at first word	Z _{max} = 2.1 (p = 0.02)	291 AGRE families (including the 152 from above)	D7S2426	–	68
9q33–9q34	Age at first word	Z = 3.5 (p = 0.0002)	222 CPEA families	D9S164	–	15
	ASD diagnosis	Z = 3.3 (p = 0.0005)	1181 AGP families (741 male only)	rs536861	–	5
11p12–11p13	ASD diagnosis	Z = 4.0 (p = 3 × 10 ⁻⁵)	1181 AGP families (335 FC; batch CNV ²)	rs1358054	–	5
	Social responsiveness score	Z _{max} = 3.2 (p = 0.0007)	99 AGRE families	ATA34E08	–	69
17q11–17q21	ASD diagnosis	MLS = 4.3 (p = 5 × 10 ⁻⁵)	257 AGRE families (148 male only)	D17S1294	<i>ITGB3, SLC6A4</i>	54:131:133, 136:137
	ASD diagnosis	MLS = 4.1 (p = 8 × 10 ⁻⁵)	91 AGRE families (48 male only)	D17S2180	–	51
	ASD diagnosis	MLS = 2.8 (p = 0.002)	345 AGRE families	D17S1800	–	135

Locus	Endpoint	Statistics	Cohort (subsetting)	Best marker	Candidate genes	Refs
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* An attempt has been made to include all linkage peaks for which at least one study obtained a \log_{10} of odds (LOD) score > 3.0 and a second obtained a $\text{LOD} > 2.0$. LOD is a measure of significance given by the logarithm of the odds under the null (no linkage) and alternative (linkage present) hypotheses. P values for Z scores were obtained in R using the formula $\text{pnorm}(-\text{abs}(Z))$; pnorm refers to normal distribution with a mean of 0 and a standard deviation of 1 and abs refers to absolute value. Values for LOD scores were obtained in R using the formula $1/10^{\text{LOD}}$.

[‡]Batch CNV refers to the analytic method that was used to identify and remove families with copy number variation (CNV). The candidate genes in the table are: *CADPS2*, Ca^{2+} -dependent activator protein for secretion 2; *CENPG2*, centaurin gamma 2; *CNTNAP2*, contactin associated protein-like 2; *EN2*, engrailed homeobox 2; *ITGB3*, integrin beta 3; *MET*, met proto-oncogene; *RELN*, reelin; *SLC6A4*, solute carrier family 6 (neurotransmitter transporter, serotonin) member 4. Other abbreviations: AGP, Autism Genome Project; AGRE, Autism Genetic Resource Exchange; ASD, autism spectrum disorder; CPEA, Collaborative Programs of Excellence in Autism Network at the National Institutes of Health; FC, female containing; IMGSAC, International Molecular Genetic Study of Autism Consortium; MLS, multipoint LOD score; NPL, nonparametric LOD score.

Table 4

Association studies in the ASDs*

Gene (map position)	Relevant findings [‡]	Replication of results	Refs
<i>AVPR1A</i> (12q14–12q15)	A positional candidate for ASD and important in rodent social behaviour. Interacts with <i>OXTR</i> . Association with affection status ($p = 0.004$) and a quantitative trait — Vineland Subscale Score ($p = 0.007$)	No replication	147
<i>CNTNAP2</i> (7q35)	A positional candidate gene with observed mutations. mRNA distribution markedly different in human versus rodent species. Association with affection status ($p = 2 \times 10^{-3}$) and a quantitative trait — age at first word ($p = 0.05$)	Independent replication	37-41
<i>DISC1</i> (1q42)	A key gene in psychiatric disorders and functionally linked to neuroligin signalling. Associated with ASD in a Finnish isolate by family-based association ($p = 0.0007$) and a case-control analysis ($p = 9 \times 10^{-5}$)	No replication	122
<i>EN2</i> (7q36)	A positional candidate that is linked to cerebellar abnormalities in mutant mice. SNP and haplotype-based associations to affection in multiple cohorts ($p = 5 \times 10^{-6}$, 0.001 and 0.04)	Independent replication	129-130
<i>GABRB3</i> (15q11–15q12)	A positional candidate; dysregulated in Rett syndrome, Angelman syndrome and autism brain ²⁵ . Association with autism in multiple cohorts ($p = 0.0014$ and 0.0011)	Independent replication	25-114, 115
<i>GRIK2</i> (6q21)	A positional candidate that is linked to neuroligin signalling by PSD95. A rare homozygous mutation in an Iranian pedigree results in non-syndromic mental retardation. Association with autism in Caucasian ($p = 0.0002$) and Chinese populations ($p = 0.01$)	Independent replication	144-145
<i>ITGB3</i> (17q21)	Positional candidate involved in regulation of serotonin. Evidence for functional interaction with <i>SLC6A4</i> . Association with whole-blood serotonin levels in multiple populations ($p = 0.01$ and 0.0055) and autism ($p = 0.00076$)	Serotonin QTL replicated	136-137
<i>MET</i> (7q31)	Positional candidate and reduced expression in brains of cases versus controls. Association between promoter variant and affection status in two large family-based cohorts ($p = 0.0005$ and 0.001) and a case-control analysis ($p = 0.001$). A function difference was observed between the two alleles of the associated variant	Internal replication	70-123
<i>OXTR</i> (3p25)	Important in rodent social behaviour, reduced in blood of cases versus controls and interacts with <i>AVPR1A</i> . Association with affection status ($p = 0.0094$ and 5×10^{-3}) and a quantitative trait — intelligence quotient ($p = 0.0002$)	Association with affection status has been replicated	127-128
<i>RELN</i> (7q22)	Positional candidate and identification of rare variants among cases. Expression levels are reduced in brains of cases versus controls. Association with affection status by case-control analyses ($p = 0.001$) and family-based analyses ($p = 0.001$ and 0.002)	Independent replication	117-121
<i>SLC25A12</i> (2q24)	A positional candidate that is related to neurite outgrowth and is upregulated in the prefrontal cortex of autistic subjects. Association between affection status and both single SNPs ($p = 0.0094$ and 0.02) and haplotypes ($p = 5 \times 10^{-3}$ and 0.03)	Independent replication	124-126
<i>SLC6A4</i> (17q11)	A positional candidate that is involved in the regulation of serotonin. Variation	Replicated, although complex and	131-134

Gene (map position)	Relevant findings [‡]	Replication of results	Refs
	<p>in <i>SLC6A4</i> is linked to grey matter volume in the cortex. Evidence for functional interaction with <i>ITGB3</i>. Some clinical benefit is seen with <i>SLC6A4</i> inhibitors. Association between promoter variant and both affection status ($p = 0.007$ and 0.007) and cortical grey matter volume ($p = 0.004$). Rare variants transmitted to cases at greater than expected frequency</p>	controversial	

* No single approach was used to identify the genes we highlight here, but there were three factors important in determining which genes were highlighted. First, the extent of statistical support. To limit type II error, we have not required genome-wide significant results for inclusion in the table. Because these genes were tested in either a regional-based or candidate-based fashion, we instead required within-study significance corrected for multiple comparisons. Second, the availability of convergent biological evidence and third, the presence of independent replication. Given the extreme heterogeneity in autism spectrum disorders (ASDs), negative findings were not used as evidence against other positive results and are not included here.

[‡] Statistical significance of the findings is given by a p value; when multiple studies have been reported, the p value from each study is given. *AVPR1A*, arginine vasopressin receptor 1A; *CNTNAP2*, contactin associated protein-like 2; *DISC1*, disrupted in schizophrenia 1; *EN2*, engrailed homeobox 2; *GABRB3*, gamma-aminobutyric acid (GABA) A receptor beta 3; *GRIK2*, glutamate receptor ionotropic kainate 2 precursor; *ITGB3*, integrin beta 3; *MET*, met proto-oncogene; *OXTR*, oxytocin receptor; *RELN*, reelin; *SLC25A12*, solute carrier family 25 (mitochondrial carrier, Aralar) member 12; *SLC6A4*, solute carrier family 6 (neurotransmitter transporter, serotonin) member 4.