



Whole-Genome Sequencing in Autism Identifies Hot Spots for De Novo Germline Mutation

Jacob J. Michaelson,^{1,2,14} Yujian Shi,^{5,14} Madhusudan Gujral,^{1,2,14} Hancheng Zheng,^{5,14} Dheeraj Malhotra,^{1,2,14} Xin Jin,^{5,6,14} Minghan Jian,⁵ Guangming Liu,^{7,8} Douglas Greer,^{1,2} Abhishek Bhandari,^{1,2} Wenting Wu,^{1,2} Roser Corominas,² Aine Peoples,^{1,2,9} Amnon Koren,¹⁰ Athurva Gore,⁴ Shuli Kang,² Guan Ning Lin,² Jasper Estabillo,² Therese Gadomski,² Balvinder Singh,^{1,2} Kun Zhang,⁴ Natacha Akshoomoff,² Christina Corsello,¹¹ Steven McCarroll,¹⁰ Lilia M. Iakoucheva,² Yingrui Li,⁵ Jun Wang,^{5,12,13,*} and Jonathan Sebat^{1,2,3,*}

¹Beyster Center for Genomics of Psychiatric Diseases

²Department of Psychiatry

³Department of Cellular Molecular Medicine

⁴Department of Bioengineering

University of California, San Diego, La Jolla, CA 92093, USA

⁵BGI-Shenzhen, Shenzhen 518083, China

⁶School of Bioscience and Biotechnology, South China University of Technology, Guangzhou 510006, China

⁷School of Computer Science, National University of Defense Technology, Changsha, Hunan 410073, China

⁸National Supercomputer Center, Tianjin 300450, China

⁹Trinity College Dublin, College Green, Dublin 2, Ireland

¹⁰Department of Genetics, Harvard Medical School, Boston, MA 2115, USA

¹¹Rady Children's Hospital, San Diego, CA 92123, USA

¹²Department of Biology

¹³The Novo Nordisk Foundation Center for Basic Metabolic Research

University of Copenhagen, 1165 Copenhagen, Denmark

¹⁴These authors contributed equally to this work

*Correspondence: wangj@genomics.org.cn (J.W.), jsebat@ucsd.edu (J.S.)

<http://dx.doi.org/10.1016/j.cell.2012.11.019>

SUMMARY

De novo mutation plays an important role in autism spectrum disorders (ASDs). Notably, pathogenic copy number variants (CNVs) are characterized by high mutation rates. We hypothesize that hypermutability is a property of ASD genes and may also include nucleotide-substitution hot spots. We investigated global patterns of germline mutation by whole-genome sequencing of monozygotic twins concordant for ASD and their parents. Mutation rates varied widely throughout the genome (by 100-fold) and could be explained by intrinsic characteristics of DNA sequence and chromatin structure. Dense clusters of mutations within individual genomes were attributable to compound mutation or gene conversion. Hypermutability was a characteristic of genes involved in ASD and other diseases. In addition, genes impacted by mutations in this study were associated with ASD in independent exome-sequencing data sets. Our findings suggest that regional hypermutation is a significant factor shaping patterns of genetic variation and disease risk in humans.

INTRODUCTION

Spontaneous germline mutation plays an important role in human disease. For severe neurodevelopmental disorders such as autism spectrum disorders (ASDs), highly penetrant alleles are under strong negative selection (Uher, 2009). Such alleles segregate in the population over few generations or can frequently be observed as de novo mutations (DNMs) in affected individuals. Thus, in order to understand this aspect of the genetics of ASD and other human diseases, we must understand the mutational processes that give rise to human genetic diversity and the intrinsic and extrinsic forces that shape patterns of variation in the genome.

Mutation is a random process. However, the probability of mutation at a given site is not uniform throughout the genome. Regional mutation rates are subject to a variety of intrinsic characteristics (Ellegren et al., 2003) and extrinsic factors such as parental age (Crow, 2000). This is particularly evident for structural variation (SV). Rates of structural mutation can vary between 10^{-4} and 10^{-6} (Lupski, 2007), and there are numerous examples of hot spots for structural mutation where recurrent mutations are mediated by nonallelic homologous recombination (NAHR) between tandem segmental duplications (Lupski, 1998; Malhotra and Sebat, 2012).

Regional rates of nucleotide substitution are also variable (Ellegren et al., 2003); however, the factors that influence

regional mutability are not well understood. In contrast to the SV hot spots described above that are predominantly driven by meiotic recombination, nucleotide substitution can occur by a variety of mechanisms, and the mutation rate is influenced to a much greater extent by mitotic mechanisms (Crow, 2000). Comparisons of genomes from the human and chimpanzee have found evidence that regional mutability is influenced by G+C content (Chimpanzee Sequencing and Analysis Consortium, 2005; Coulondre et al., 1978), recombination rate (Hardison et al., 2003; Hellmann et al., 2005; Lercher and Hurst, 2002), and chromosome-banding patterns (Chimpanzee Sequencing and Analysis Consortium, 2005). These studies indicate that regional mutation rates are influenced by various properties of the genome and that no single factor can explain the observed patterns of genetic diversity and divergence in humans. However, previous studies do not represent a complete and unbiased view of germline mutation. The full extent of variation in mutation rates genome wide remains unclear (Francino and Ochman, 1999; Nelis et al., 1996; Webster et al., 2003), and the relevance of hypermutability to common diseases such as ASD is not known.

We have investigated global and regional rates of nucleotide substitution by direct detection of germline mutations in monozygotic (MZ) twins concordant for ASD and their parents. We show that the distribution of mutations in the genome is nonrandom. Wide variation in regional mutation rates can be explained by intrinsic characteristics of the genome. Furthermore, we find significant evidence that genes impacted by DNMs in twins are associated with autism in independent cohorts.

RESULTS

Detection of Germline Mutations by Whole-Genome Sequencing in MZ Twins

We applied a whole-genome sequencing (WGS) strategy to characterizing patterns of germline mutation (Figure S1 available online). Central to our approach was the selection of a MZ twin-family sample and the development of a custom machine-learning-based method for DNM calling.

Cell line-derived genomic DNAs from ten MZ twin pairs concordant for ASD and their parents were obtained from the NIMH genetics initiative biorepository (<http://www.nimhgenetics.org>). Concordant MZ twins afford significant advantages to this study. Disease risk can be more directly attributed to risk factors in the germline. In addition, having complete genome sequences on identical twins allows us to readily distinguish germline mutation from somatic and cell line mutations. To improve our power to account for paternal age effects on mutation rate, half of the twin pairs were selected to have younger fathers (16–29 years old), and half were selected to have older fathers (38–41 years old).

Deep (40×) WGS was performed at BGI using the Illumina HiSeq platform. Raw sequence files were processed at UCSD with a WGS pipeline consisting of automated tools for alignment and variant calling (see Experimental Procedures).

DNM detection was performed using a machine-learning-based tool as described in Experimental Procedures. Using an internal “gold standard” set generated by exhaustive validation

of putative DNM calls in one quad family (family 74-0352, see Experimental Procedures), we trained a Random Forest classifier (forestDNM) that discriminates validated DNMs from invalidated putative DNMs, based on combinations of the associated quality metrics. When presented with new sites and quality metrics, the trained classifier could discriminate true DNMs from false positives with high sensitivity and low false discovery rate (FDR). Based on misclassification error on the internal test set, we estimated that sensitivity was 91% (67 of 74 recovered), and FDR was 11.8% (9 false positives out of 76 called positives). Software specifications and validation studies are described in the Supplemental Information.

We applied forestDNM to the detection of DNMs in quads and adapted forestDNM further to mutation detection of DNMs in trios. Mutations that were shared by MZ twins constitute germline mutations. Mutations that were not shared by MZ twins constitute somatic or cell line mutations (Koren et al., 2012).

A total of 668 putative germline DNMs were detected and subject to comprehensive validation studies by Sanger sequencing and Sequenom genotyping. Validation results on mother, father, and offspring were obtained for 652 sites, and incomplete data were obtained for 16 sites (Table S1). DNMs were confirmed for 565 sites (87%), and 87 DNM calls were invalidated, of which 34 (6%) were false-positive variant calls, and 53 (9%) were true-positive-inherited SNPs falsely called as negative in one parent. Thus, we confirm the high accuracy of forestDNM on new data. After excluding invalidated DNMs, subsequent analyses were performed on the remaining set of 581 DNM calls.

Base composition of DNMs detected in this study was similar to the base composition of segregating SNPs and DNMs reported in previous studies by Conrad et al. (2011) and Lynch (2010) (see Extended Experimental Procedures). In addition, DNM calls were similar in depth and quality to variant calls for segregating SNPs (Table S1). Phred-like quality scores and alternate allele counts were slightly higher on average for validated DNM calls as compared to randomly sampled heterozygous SNPs (by one additional alternate allele read on average). This subtle skewing toward higher-quality SNP calls had no effect on the overall genomic distribution of variants (Extended Experimental Procedures).

Variation in Genome-wide Rates of Germline Mutation

A total of 581 germline DNMs were detected in ten MZ twin pairs. A mean of 58 DNMs per offspring suggests that the average genome-wide mutation rate in humans is 1×10^{-8} per generation. Our estimate is lower than theoretical estimates by a factor of two (Haldane, 2004; Kondrashov and Crow, 1993) but consistent with empirical estimates from other WGS studies (Conrad et al., 2011). Total mutation burden varied between 42 and 75 DNMs per offspring, consistent with previous observations of mutation rate variation (Conrad et al., 2011). Paternal age accounted for a substantial proportion of the variability in mutation burden in offspring ($p = 0.004$; $R^2 = 0.44$; see Figure 1), whereas maternal age was not significant. To account for any unforeseen deviations from the assumptions of the Poisson regression model, we also applied a permutation-based test: the one-sided p value for the effect of paternal age on mutation rate

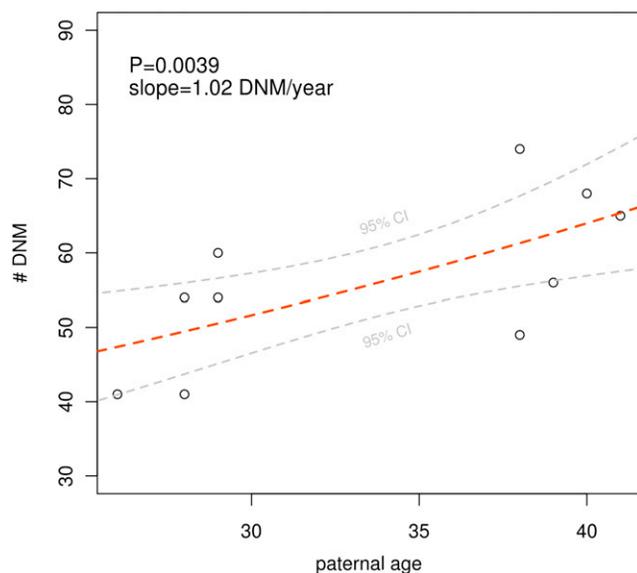


Figure 1. Paternal Age Effect Explains 44% of Variation in Genome-wide Mutation Rates

Data points represent the total number of autosomal DNMs detected in offspring. 95% CI, 95% confidence interval. See also [Figure S1](#) and [Table S1](#).

was 0.0226. These results allow us to quantify the accumulation of nucleotide substitutions in spermatogonial cells, which occurs at an average rate of one new mutation per year. Parent of origin was determined for 131 DNMs, of which 97 (74%) originated from the father ([Table S1](#)).

Global Patterns of Germline Mutation

Germline DNMs displayed a remarkably nonrandom positioning in the genome ($p = 4.4 \times 10^{-5}$, KS test). Compared to a random mutation model (uniform probability across the assembled genome; see [Experimental Procedures](#) for details), there was an overrepresentation of DNM pairs spaced more closely than the expectation ([Figure 2](#)). The effect is significant when considering only the distribution within the individual (intra-individual DNM spacing) and when considering only the distribution across individuals (inter-individual DNM spacing).

The observed distribution of DNMs reflects the underlying patterns of mutation and does not reflect nonuniformity in our ascertainment or validation of DNMs, as mentioned previously (see [Extended Experimental Procedures](#)). As we describe in the following sections, the distribution of mutations can be explained by intrinsic characteristics of the genome.

Mutation Clusters

As evident from [Figure 2](#), within individual genomes, we observed striking enrichment of very closely spaced DNMs (inter-DNM distance <100 kb). Where parent of origin information was known for three loci (chr16:1823255–chr16:1823256, chr3:90077648–chr3:90077664, chr8:3872643–chr8:3892698), closely spaced pairs of DNMs had a single parent of origin. These results are consistent with very closely spaced mutations arising as part of a single mutation event ([Wang et al., 2007](#))

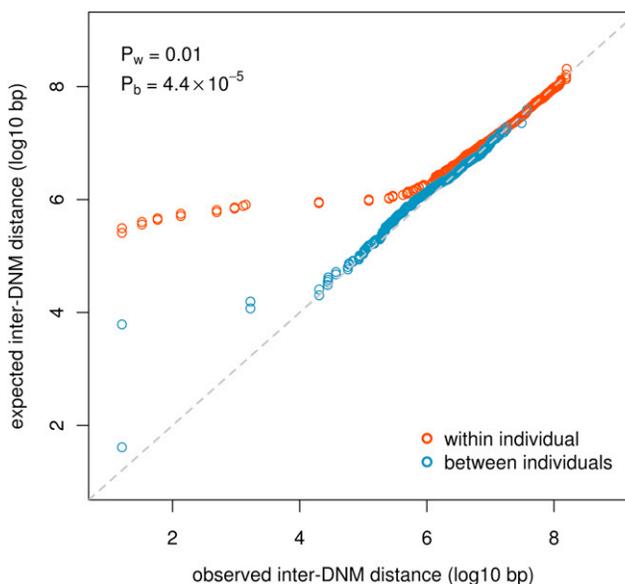


Figure 2. Nonrandom Distribution of DNMs in the Genome

Quantile-quantile plots of the observed distribution of inter-DNM distances within and between individuals and the expected distribution based on a random mutation model. Differences are statistically significant at $\alpha = 0.05$ by the KS test. See also [Figure S4](#) and [Table S2](#).

within a narrow region of a chromosome. Defining a “cluster” as two or more DNMs located within a 100 kb span, a total of ten mutation clusters were identified on eight chromosomes (see [Table S2](#)), suggesting that mutation clusters occur at a rate of approximately one per generation. One mutation cluster in subject 75-0355 is evident in the 8p23 region illustrated in [Figure 5](#). The observation of ten dense clusters of DNMs was statistically significant by permutation test ($p < 0.001$).

Multiple mutational mechanisms could explain these findings, including compound mutation ([Schridder et al., 2011](#)) or gene conversion ([Chen et al., 2007](#)). Nonallelic gene conversion, which requires the presence of a paralogous sequence variant elsewhere in the genome, could be ruled out for a majority (eight of ten) of clusters (see [Extended Experimental Procedures](#)). Clusters could instead be explained by compound mutation or by de novo nucleotide substitutions that occur during allelic gene conversion events ([Hurles, 2002](#); [Ratray et al., 2002](#)). In all cases, we could rule out the possibility that mutation clusters are a spurious observation due to the mismapping of reads containing a paralogous sequence variant (see [Extended Experimental Procedures](#)).

Determining Intrinsic Properties of the Genome that Influence Mutability

Regional mutation rates are subject to a combination of influences. In order to investigate the effect of intrinsic properties of the genome, we used logistic regression to discriminate DNMs from random genome background sites, based on the characteristics of the genome at these sites (and not relative or absolute genomic positions of DNMs). See [Extended Experimental Procedures](#) for details on the genomic features used.

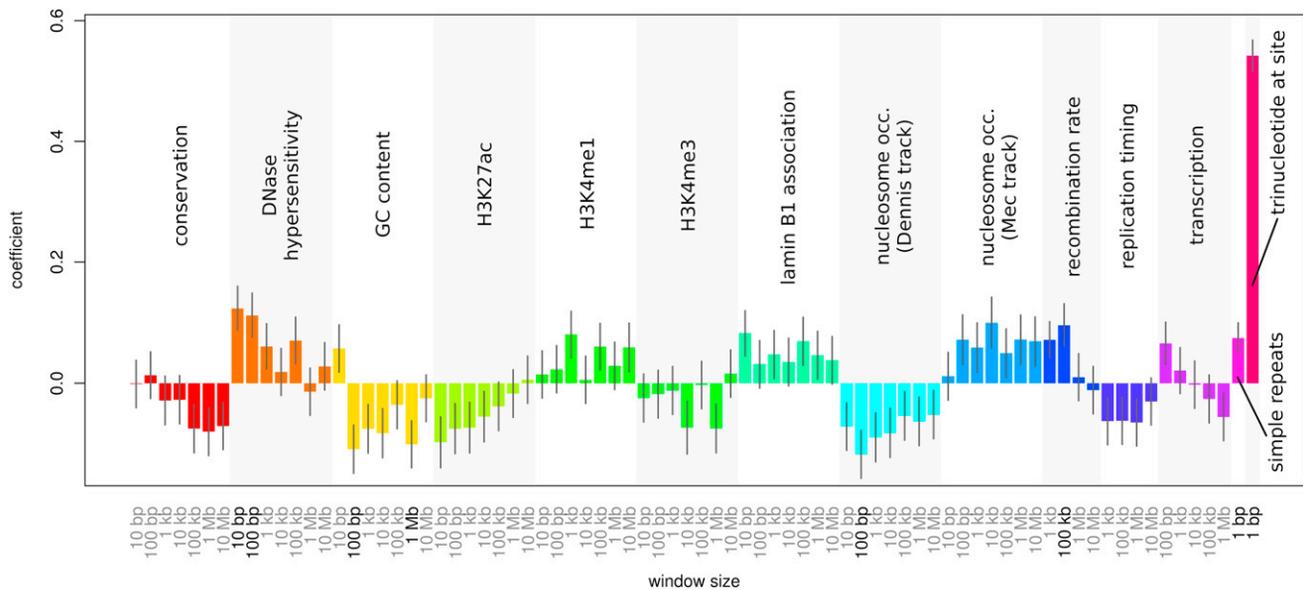


Figure 3. Individual Associations of Genome Features with DNM

Predisposition to DNM is influenced by sequence and chromatin characteristics. A variety of quantitative genome data was tested for associations with DNM sites, including conservation, DNase hypersensitivity, GC content, histone marks, lamin B1 association, nucleosome occupancy (occ.), recombination rate, replication timing, transcription in human embryonic stem cells, simple repeats at the site of DNM, and the particular trinucleotide sequence centered at the site of DNM. The data were tested for association at different scales (i.e., window sizes at which the genome data were averaged), indicated on the x axis. The strength and direction of association between the features and DNM are indicated by logistic regression coefficients (y axis), which are shown with their SEs. Significant associations (FDR < 0.10) are indicated in bold type. A summary of the relationship between these features and the PCs used in the predictive model is provided in Figure S6. A detailed legend of the feature names and their descriptions is provided in Table S6, and further details relating to the origin and construction of the features can be found in Experimental Procedures.

Numerous features were found to influence site mutability. The most significant features were DNase hypersensitivity, GC content, nucleosome occupancy, recombination rate, simple repeats, and the trinucleotide sequence surrounding the site (Figure 3). We note that the UCSC Dennis and MEC nucleosome occupancy tracks (Gupta et al., 2008) use scores opposite in direction to indicate nucleosome occupancy. For both tracks, nucleosome occupancy was associated with suppressed mutation.

In addition to testing marginal associations, we investigated whether interactions between these genome features were predictive of mutation rate. This was done by performing two-way ANOVA for all possible combinations of features. After correcting for multiple testing, no two-way interactions were significant.

We next sought to construct a predictive model that could estimate nucleotide level mutation rates, based on information contained in all the features. This was accomplished by performing principal components analysis (PCA) on the features and then using the principal components (PCs) as predictors in a regularized logistic regression model (again using “observed DNM” and “genome background” as the class labels). The output of the model is a measure of mutability that we call the mutability index (MI). MI is an estimate of relative mutation rate at single-nucleotide resolution (see Experimental Procedures for details). Throughout, we use the term “mutability” to refer to the MI, and we use the term “mutation rate” to refer to the observed rate of DNMs for a given site or region.

Wide Variation in Site-Specific and Regional Mutation Rates

MI was highly predictive of site-specific (1 bp resolution) mutation rates (Figure 4) and could explain ~90% of the variability in mutation rates at sites across the genome. As expected, mutability was greatest for CpG dinucleotides. However, our model was highly predictive of mutation rate independent of this phenomenon. CpG sites and non-CpG sites varied widely in their mutability (10- and 100-fold, respectively), and the range of CpG mutability overlapped considerably with the range for non-CpG sites (Figure S2).

The validity of MI was confirmed in independent data sets of DNM. MI was highly correlated with mutation rate variation in a genome-wide data set from two trios (Conrad et al., 2011) (Figure 4B) and exome data sets from four independent trio-based studies of autism (Iossifov et al., 2012; Neale et al., 2012; O’Roak et al., 2011, 2012; Sanders et al., 2012) (Figures 4C and 4D). In all data sets examined, observed mutation rates varied consistently by greater than two orders of magnitude ranging from $10^{-8.5}$ to $10^{-6.5}$. MI explained ~90% of variation of the observed mutation rates in these studies. We conclude that our statistical model of mutability can explain a majority of the variance in site-specific mutation rates. Having confirmed the validity and accuracy of the MI, we apply this measure to the analysis of regional mutability.

We examined the landscape of mutability throughout the genome. Mean MI (in nonoverlapping 1 kb windows) revealed broad genomic regions of hypermutability, generally

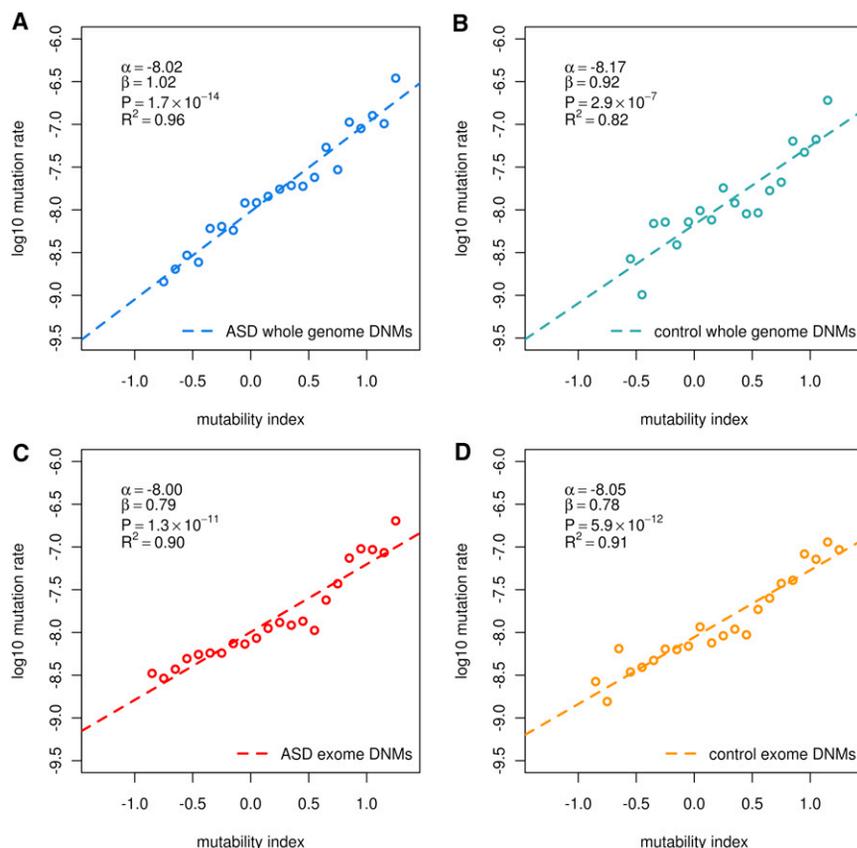


Figure 4. Intrinsic Characteristics of the Genome Explain Variation in Observed Mutation Rates

(A–D) MI at the site level (1 bp) is highly predictive of the mutation rate in (A) ASD genomes in this study, (B) control genomes in Conrad et al. (2011), and in ASD cases (C) and controls (D) of previous exome studies (combined data from O’Roak et al., 2011, 2012; lossifov et al., 2012; Sanders et al., 2012; Neale et al., 2012). MI explains a majority of the variability in site-specific mutation rates, and the degree of mutation rate variation was similar in cases and controls. CpG sites and non-CpG sites varied widely in their mutability, and the range of CpG mutability overlapped considerably with the range for non-CpG sites (Figure S2). MI was also predictive of regional mutation rates (Figure S3).

Considering that our statistical model was developed based on a data set of genomes largely derived from individuals diagnosed with ASD, we examined whether the mutation rate variation we observe is related to autism. We compared the predictive value of MI in cases and controls in the exome data sets. MI was equivalently predictive of mutation rate in healthy individuals ($R^2 = 0.91$, slope = 0.78) and in ASD cases ($R^2 = 0.90$, slope = 0.79) (Figures 4C and 4D). Likewise, we compared the total burden

tens to hundreds of kilobases in size. These included “hot spots” with highly elevated mutability (≥ 7 -fold) and “warm spots” with moderately increased mutability (2- to 3-fold) (Figure 5).

Genomic regions of hypermutability were then defined by segmenting the MI scores using a five-state hidden Markov model (HMM). Parameters of the HMM were derived through numerical optimization by fitting a five component Gaussian mixture to the overall distribution of mean MI of 1 kb windows of the genome. The sequence of hidden states along each chromosome was calculated using the Viterbi algorithm. Altogether, approximately 9% and 0.02% of the genome were defined as “warm” and “hot,” respectively, with 54%, 37%, and 0.5% being segmented as “baseline,” “cool,” and “cold.”

Hypermutability of these genomic regions was confirmed in this study and in five independent mutation data sets. The observed rate of DNMs in genomic segments was positively correlated with the mean MI of segments (Figures S3A and S3B). Likewise, exonic mutation rates were highly correlated with the mean MI of exons (Figures S3C and S3D).

These results confirm that the landscape of mutability, like other characteristics of the genome, is highly nonrandom, in part explaining the distribution of DNMs that we originally observed. When we sampled a null model such that representation of sites was consistent with predicted mutability, the observed inter-DNM distances were closer to this null distribution (Figure S4).

of DNMs in hypermutable genes (average exonic log₁₀ MI >0.5), in cases and controls and observed no association with ASD (OR = 0.73; $p = 0.227$). Therefore, the mutation rate variation that we observe cannot be attributable only to a subset of disease-associated mutations that is present in autism genomes.

A U-Shaped Relationship between Genome Mutability and Evolutionary Conservation

We examined the relationship between regional rates of mutation, evolutionary change and genetic diversity in the human genome. Our results confirm that some hot spots have undergone rapid evolutionary change, consistent with previous studies by the Chimpanzee Sequencing and Analysis Consortium (2005). However, patterns of germline mutation, particularly within the exome, reveal many highly mutable regions that change little over evolutionary time, an observation that challenges the common definition of the “evolutionary hot spot.”

A plot of mutability, divergence, and diversity reveals a distinctly U-shaped relationship between mutability and sequence conservation (Figure 6A). In regions that are less conserved (the left arm of the “U”), there is a clear correlation of hypermutability, hyperdivergence, and hyperdiversity, consistent with such regions undergoing rapid evolutionary change. Surprisingly, in highly conserved regions (the right arm of the “U”), the opposite trend is evident: hypermutability is correlated with highly conserved sequence and low genetic diversity.

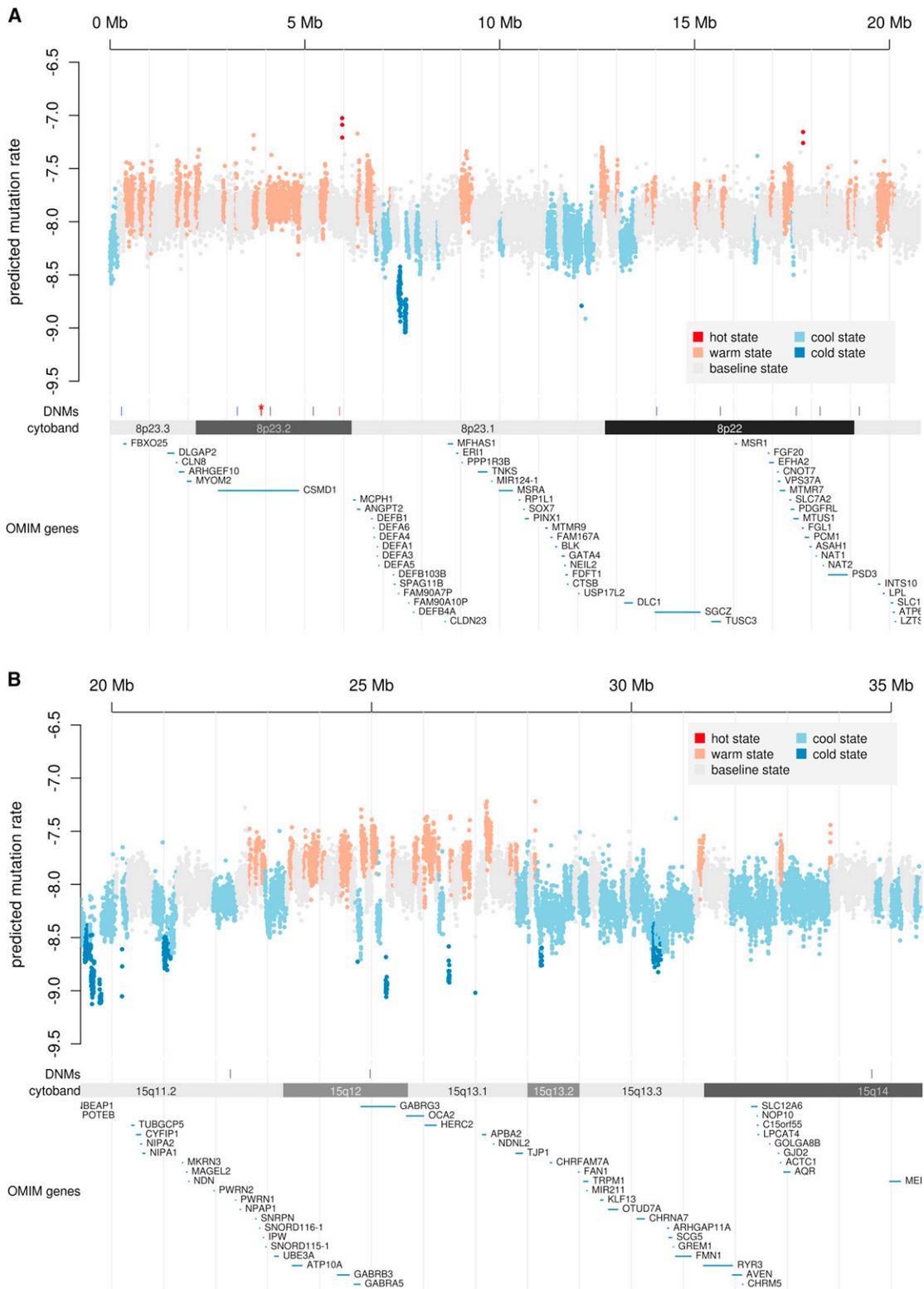


Figure 5. Landscape of Mutability in the Genome

(A) The 1 kb average MI across a 20 Mb genomic region of chromosome 8p21-23 indicates the existence of extended regions of hypermutability. “Hot spots” (red), “warm spots” (orange), as well as “cold spots” were defined by segmenting the MI scores using a five-state HMM (see Table S7). Predicted mutation rates (y axis) were computed by multiplying the arithmetic mean MI by the baseline mutation rate of 10^{-8} , then transforming to the \log_{10} scale. The genome- and (legend continued on next page)

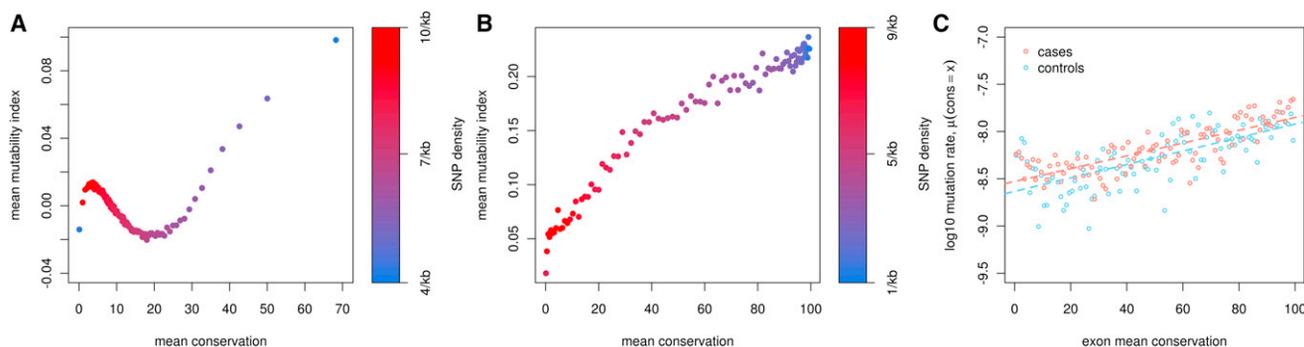


Figure 6. U-Shaped Relationship of Mutability and Evolutionary Conservation

(A) Throughout the genome, we observe a correlation of hypermutability, hyperdivergence, and hyperdiversity, consistent with previous studies. By contrast, in highly conserved regions, the opposite trend is evident. MI and conservation were averaged in 1 kb windows genome wide. Windows were then binned according to percentiles of conservation.

(B) Specifically within exons, there is a strong positive correlation of mutability and evolutionary conservation (also binned by percentiles of conservation).

(C) The positive correlation between mutation rate and average exon conservation was confirmed by data from exome studies. Note that the positive relationship exists for both cases and controls. Under the null hypothesis, in which exons are hit with probability proportional to their length, this relationship is not observed.

We performed a similar analysis of exons and confirmed a strong positive correlation between MI and conservation (Figure 6B). However, the right arm of the “U” (Figure 6A) could not be entirely explained by exonic sequences. We repeated the analysis in Figure 6A after excluding all exons, and the same U-shaped relationship was observed (data not shown). Finally, we confirmed a positive correlation of conservation and mutation rate in protein-coding exons in exome data sets of ASD (Figure 6C). Notably, the positive correlation between mutation rate and conservation was similar in cases and in controls. Therefore, this trend does not appear to reflect patterns that are unique to mutations that are detected in subjects with ASD. The aforementioned results suggest that mutability in the genome is, to some extent, coupled with functionality.

There are multiple genomic features that vary with evolutionary conservation in a similar fashion, most notably GC content. However, this feature alone does not explain patterns of mutability (see Figure 3). Importantly, genotype quality of SNPs and DNMs was not correlated with conservation (data not shown); hence, these observations do not appear to be an artifact of variable ascertainment.

Hypermutability Is Common among Disease Genes

Genes that are subject to high mutation rates and strong purifying selection could be of particular importance to human disease. Mutability was significantly elevated for essential genes derived from the Online GENE Essentiality (OGEE) database (Chen et al., 2012) and human disease genes derived from the Online Mendelian Inheritance in Man (OMIM) database and varied by the modes of inheritance (Figures 7A and 7B). Mutability was highest for essential genes and genes associated with dominant disorders. Mutability was elevated to a lesser extent for genes involved in recessive or polygenic traits.

Of relevance to our disease of interest, mutability of genes preferentially expressed in the brain was significantly higher on average. In addition, mutability was elevated in a literature-based set of genes that have been implicated in ASD and in a set of genes that are associated with “syndromic” forms of autism (Figures 7C and 7D). Examples of hypermutable ASD-associated genes include *NRXN1*, *AUTS2*, *GABRB3*, *SHANK2*, and *KCNMA1*, which have one or more exons that rank among the top 20% most highly mutable in the exome (Tables S3 and S4). Another particularly striking example of a disease-associated hot spot (see Figure 5B) is the 15q11-13 region. This region is well known for having an elevated structural mutation rate due to its local segmental duplication architecture, where recurrent duplications are associated with ASD, and deletions are associated with Prader Willi/Angelman syndrome (Ledbetter et al., 1981). As we observe here, mutability of the DNA sequence within 15q11-13 is also predicted to be highly independent of the local duplication architecture, suggesting that rates of nucleotide substitution are also elevated in this region.

Exonic Mutations in MZ Twins Are Significantly Associated with ASD

DNMs detected in our MZ twin samples impacted a total of 34 genes (Table S1), including 29 protein-coding genes and 5 noncoding RNAs. We hypothesize that genetic risk in our patient population is explained in part by DNMs in some of the aforementioned genes. We investigated the frequency of DNMs in protein-coding genes in larger exome data sets on 962 cases and 590 controls from recent studies of ASD (1,035 mutations in 969 genes in cases, 564 mutations in 536 genes in controls) (Iossifov et al., 2012; Neale et al., 2012; O’Roak et al., 2011, 2012; Sanders et al., 2012).

exome-wide distributions of MI are depicted in Figure S7. The locations of DNMs are also shown and include a dense cluster of DNMs from individual 74-0355 (red, DNMs <100 kb apart marked by asterisk).

(B) The lower panel displays segmentation results for a second genomic region at 15q11-13. This region is notable for having a high rate of recurrent structural mutation. In the same region, the predicted rate of nucleotide substitutions is highly elevated.

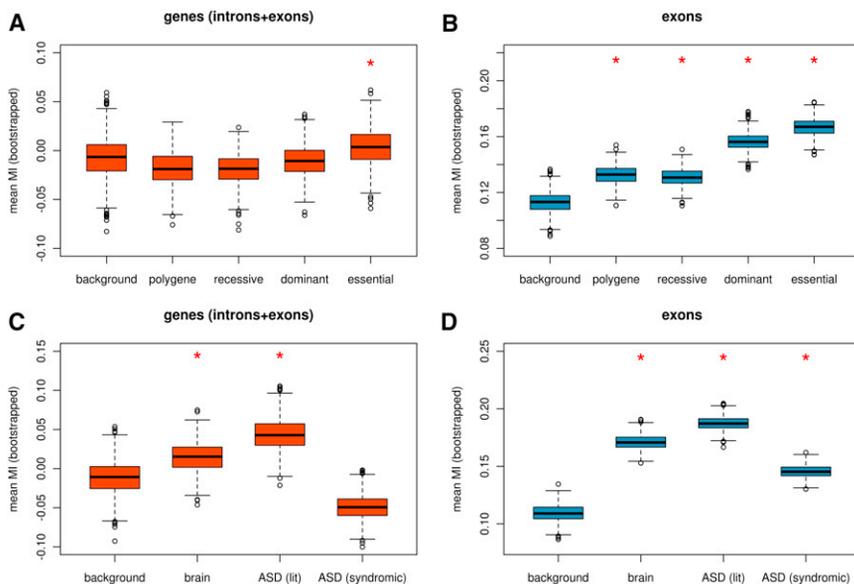


Figure 7. Disease Genes Are Characterized by High Mutability

(A–D) Disease genes are more mutable than non-disease genes (A) within genes and (B) within exons. In both cases, mutability is highest for genes involved in dominant disorders, and mutability is increased to a lesser extent for genes involved in recessive and polygenic traits. Mutability is significantly elevated for genes preferentially expressed in the brain (C and D) as well as genes involved in ASD (see [Experimental Procedures](#) for details). An asterisk indicates a significant difference compared to the respective background set (at $\alpha = 0.01$ by a two-sided t test). See also [Tables S3](#) and [S4](#) for the mean MI of exons and genes, respectively.

In our set of 29 genes, zero exonic hits were reported in controls, consistent with the low probability of observing an overlapping gene by chance. By contrast, seven de novo-coding mutations of five genes were detected in cases, and two genes (*KIRREL3* and *GPR98*) were hit twice. This constitutes a significant genetic overlap between genes mutated in concordant MZ twins and sporadic ASD cases for total number of hits ($p = 0.006$), number of double hits ($p = 0.005$), and number of genes ($p = 0.04$). See [Extended Experimental Procedures](#) for details on the calculation of these empirical p values.

DISCUSSION

Our model of intrinsic mutability, based on the unbiased ascertainment of germline mutations in families, reveals wide variation in mutation rates throughout the genome. The results of our study provide a global view of this landscape of mutability and its corresponding influence on genetic diversity and susceptibility to disease in humans. We show that hypermutability is a characteristic of disease genes, including genes that have been implicated in autism.

Mutability is explained by multiple influences acting in combination. For instance, a specific di- or trinucleotide motif may have an elevated mutation rate. However, mutability of the site can be further modulated by other factors, including factors acting on larger scales such as nucleosome occupancy ($\sim 10^2$ bp), recombination rate ($\sim 10^4$ bp), and replication timing ($\sim 10^6$ bp). Mutation rate variation in somatic cells ([Koren et al., 2012](#)) and cancer ([Schuster-Böckler and Lehner, 2012](#)) is also influenced by aspects of chromatin structure, consistent with partially overlapping mutational mechanisms acting in germ cells and somatic cells.

The patterns of mutability that we have uncovered provide new insights into the relationship between mutation, genetic diversity and disease that were not evident from studies of segregating genetic variation ([Ellegren et al., 2003](#)). We demon-

strate that genome mutability and evolutionary conservation have a U-shaped relationship. Paradoxically, some of the mostly highly mutable sequences in the genome are in fact highly conserved.

The correlation of hypermutability and high evolutionary conservation is surprising and could not have been predicted from previous studies based on segregating variation in humans. We consider three possible theories to explain this finding. The first is the hypothesis that regional hypermutability itself is a trait that could be selected for under certain conditions, for instance, where greater genetic diversity at a specific locus provides a fitness advantage. This hypothesis is reminiscent of the classic concept of “adaptive mutation” ([Delbrück and Bailey, 1946](#); [Rosenberg, 2001](#)), a process by which genome-wide mutation rates in bacteria increase in response to selective pressure. The second is the hypothesis that certain functional and highly conserved elements originated from ancient mutation hot spots and have since been subject to intense purifying selection. The third is the hypothesis that conserved hot spots could be explained simply by the fact that some DNA repair mechanisms are coupled with gene regulation ([van Attikum and Gasser, 2005](#)) or transcription ([Svejstrup, 2002](#)). Thus, the most highly transcribed regions in a given tissue could be the most susceptible to mutation. Further studies are needed to determine the underlying mutational and evolutionary mechanisms, but these findings have a significant implication regardless: patterns of mutation in the human genome appear to favor genetic changes that influence biological function.

Hypermutability in the genome has implications for human disease. Mutability is highest for essential genes and genes involved in dominant disorders. To a lesser extent, mutability is elevated for genes primarily involved in recessive disorders or polygenic traits (polygenes). Likewise, hypermutable loci are likely to be important in neurodevelopmental disorders. Mutability was significantly elevated for a large set of genes that are preferentially expressed in the brain and genes that have been implicated in ASD. Our results are consistent with a prominent role for recurrent DNMs in autism and in other traits that have a contribution from dominant-acting alleles. We view these results, and the previous observation that mutation occurs at

higher rates in highly conserved elements, as possibly two sides of the same coin. Presumably, the selective pressures that constrain evolutionary divergence and nucleotide diversity in mutational hot spots are acting upon disease phenotypes such as ASD.

The genome-wide rate of mutation in individuals with ASD was not high. The average mutation rate in the genomes of patients in this study was 1×10^{-8} . While the present study was under review, three studies were published using WGS to estimate the human mutation rate. These studies yielded estimates in the same range as ours ($0.89\text{--}2.3 \times 10^{-8}$) (Campbell et al., 2012; Kong et al., 2012; Sun et al., 2012). Also, one study documented the occurrence of compound mutations and gene conversion events (Campbell et al., 2012). A second study also documented a paternal age effect on germline mutation rates (Kong et al., 2012). Collectively, these studies suggest that the true mutation rate in humans is lower than previous theoretical estimates by Haldane (2004), Kondrashov and Crow (1993), and Nachman and Crowell (2000), possibly by as much as a factor of two. This knowledge has led some to consider a recalibration of the timescales of human evolution and the divergence of human populations (Scally and Durbin, 2012). These results also suggest that, after accounting for any effects due to paternal age, genome-wide rate of mutation in most individuals with autism is not significantly elevated.

The mutation rate variation that we observed in this study reflects patterns of mutation in a sample of subjects with ASD. This fact raises the possibility that disease mutations in our data set could have an influence on the overall distribution of DNMs and estimates of site-specific mutability. When we compared mutation rates in exomes of cases and controls, we did not find evidence that mutation rate variation differs between affected and unaffected individuals. However, due to a paucity of available genome-wide data on controls, we are not able to compare regional mutation rates of intronic and intergenic regions in cases and controls. Thus, we cannot rule out the possibility that the distribution of DNMs in individuals with ASD might tend to exhibit a higher level of clustering around disease genes.

The set of genes impacted by DNMs in concordant MZ twins demonstrated a significant association with autism in independent samples, a result that was equally surprising and tantalizing. Given that the majority of exonic DNMs in autism cohorts are likely to be unrelated to disease (Neale et al., 2012; Sanders et al., 2012), we anticipated the same to be true for DNMs in our MZ twin pairs. To the contrary, a set of independent exome-sequencing studies (962 cases and 590 controls) detected seven exonic mutations in five genes exclusively in cases, a result that is unlikely to occur by chance. This result suggests that exonic mutations in our MZ twin sample may be enriched in causal variants as compared to DNMs in the more typical sporadic/simplex cases.

These results do not provide conclusive evidence implicating individual genes in autism. However, mutations detected in our concordant twin sample and in independent studies highlight some intriguing candidates. These include *GPR98* and *KIRREL3*, where three de novo point mutations of each have been detected exclusively in cases, and a balanced translocation disrupting

KIRREL3 has been reported in a recent study by Talkowski et al. (2011). In addition, the *TCF4* gene is a strong candidate given the documented involvement of this gene in Pitt Hopkins syndrome (Amiel et al., 2007; Zweier et al., 2007) and intellectual disability (Hamdan et al., 2012; Need et al., 2012), and the observation of multiple DNMs of *TCF4* in ASD (this study; O'Roak et al., 2012).

As exemplified by early success from the preceding waves of copy number variant (CNV) (Sebat et al., 2007) and exome-sequencing (Iossifov et al., 2012; Neale et al., 2012; O'Roak et al., 2012; Sanders et al., 2012) studies in ASD, new technologies for detection of mutations in the genome hold promise for understanding the genetic basis of this disorder. WGS provides another major boost to our ability to ascertain point mutations and CNVs (Michaelson and Sebat, 2012). This considerable improvement in mutation discovery comes at a relatively modest increase in sequencing cost. As the field continues its rapid transition toward incorporating comprehensive data on genomic variation and DNMs into genetic studies, we anticipate progress toward a deeper understanding of the underlying mechanisms of genome evolution and disease.

EXPERIMENTAL PROCEDURES

WGS

Genomic DNAs from ten identical twin pairs and their parents were obtained from the NIMH genetics initiative biorepository (<http://www.nimhgenetics.org>). All DNA samples were derived from EBV-immortalized lymphoblastoid cell lines. A list of the 40 samples is provided in the [Extended Experimental Procedures](#). Deep (40×) WGS was performed at BGI using the Illumina HiSeq Platform (500 bp library, 90 bp reads). Prior to sequencing, samples were randomized to minimize batch effects. Genomes were aligned to hg18 with BWA (Li and Durbin, 2009), and all subsequent analyses were performed with hg18 as the reference unless otherwise stated.

Alignment and Variant Calling

Alignment and variant (SNP) calls were generated on quad families using our WGS analysis pipeline implemented on the Triton compute cluster at UCSD (<http://tritonresource.sdsc.edu/>). Short reads were mapped to hg18 reference genome by BWA version 0.59 with the following parameters: "aln -o 1 -e 63 -i 15 -l -l 31 -k 2 -t 6." Subsequent processing was carried out using SAMtools version 0.18, GATK version 1.2-52 (DePristo et al., 2011), and Picard tools version 1.52, which consisted of the following steps: sorting and merging of the BAM files, indel realignment, fixing mate pairs, removal of duplicate reads, base quality score recalibration for each individual. Variant calls for each family were made (in "trio" mode) by running the unified genotyper for all four family members.

DNM Detection

Based on experience from our earlier CNV-based studies of DNM (Malhotra et al., 2011; Nord et al., 2011; Sebat et al., 2007), an unfiltered set of putative DNMs is highly enriched for errors. In order to accurately distinguish true de novo variants from errors, we employed a custom machine-learning pipeline we call forestDNM. A detailed description of the development and validation of this software is provided in [Extended Experimental Procedures](#). Briefly, a Random Forest (RF) classifier was trained using quality metrics (see [Table S5](#)) on an initial set of positive and negative training examples obtained by comprehensive validation of unfiltered putative DNMs from a single family (family 74-0352). See [Figure S5](#) for a depiction of the predictive importance of each quality metric. The trained classifier had an estimated sensitivity of 91% (67 of 74 recovered) and an estimated specificity of 11.8% (9 false positives out of 76 called positives). We used this trained RF classifier to predict the

validation status of the putative DNMs in all families. In total, we predicted 668 DNMs in the ten families.

Experimental Validation

Putative DNMs were validated by genotyping offspring using two independent validation methods: Sanger sequencing and Sequenom MassArray genotyping technologies (see [Extended Experimental Procedures](#)). Parental genotypes were obtained using the Sequenom platform and additionally by Sanger sequencing if an informative Sequenom assay could not be designed. A total of 565 of 668 putative DNMs sites were validated, and 87 sites were invalidated (34 as false heterozygous calls in the twins, 53 as inherited variants), corresponding to an overall observed FDR of 13%. In all subsequent analyses, we combine sites with complete validation data (565) with sites with incomplete validation data (16) for a total of 581 DNMs. Given the demonstrated low FDR of the classifier, we only expect 2 of the 16 incompletely validated sites to be false positives, so their inclusion is justifiable.

Parental Age Effect

We used Poisson regression to test the relationship between paternal and maternal age and DNM burden ([Figure 1](#); [Table S1](#)). In a fit using both paternal and maternal age as covariates, paternal age was significant ($p = 0.01$), but maternal age was not ($p = 0.6$). We thus discarded maternal age and fit a model using only paternal age, which had a significant effect ($p = 0.0039$) and a slope of approximately one DNM/year.

Analysis of the Effect of DNA and Chromatin Features on DNM

We investigated whether quantitative genomic features (see [Extended Experimental Procedures](#) for details on training data and features) had individual associations to DNM by fitting logistic regression models (classes: observed DNM or genome background site), using each of the genome features as covariates. The coefficients and their SEs are shown in [Figure 3](#), and those features with significant (FDR < 0.10) associations have been noted in bold-faced type. Positive coefficients indicate a positive association between the value of the feature and DNM as the predicted class, whereas negative coefficients indicate a negative association.

Modeling Intrinsic Mutability of the Genome

With an unbiased set of germline mutations as training data, we used regularized logistic regression to predict mutability of sites based on intrinsic characteristics of the genome (see [Extended Experimental Procedures](#) for details). We assembled quantitative genome features (conservation, transcription, GC content, simple repeat entropy, replication timing, recombination rate, DNase hypersensitivity, histone marks, nucleosome occupancy, lamin B1 association) and summarized them at several scales by taking the mean value in windows of 10 bp, 100 bp, 1 kb, 10 kb, 100 kb, 1 Mb, and 10 Mb. The bulk of these data was derived from UCSC Genome Browser tracks (<http://genome.ucsc.edu>), and their provenance is outlined in detail in [Table S6](#). In addition to these features, we included a numerical variable that indicated predisposition to DNM, based on the trinucleotide sequence centered at the site (see [Extended Experimental Procedures](#) for details).

Using these genomic features directly in the model would be problematic because they are highly correlated, with large-scale variation in GC content being one major source of the correlations. In order to more fully exploit the information carried in the features, we performed PCA, to produce 78 decorrelated features (i.e., the PCs).

PCs represent the unique signals in the data and were used in place of the genome features as predictors in the model. Using these, we fit the model to the training data and defined a linear relationship between the class membership probability and the logarithm of the fold DNM excess at that probability. The relationship among genomic features, the PCs, and the model coefficients is shown in [Figure S6](#). We define the MI as the \log_{10} of the fold excess of training set DNMs observed for a given predicted class probability. This fold excess is an estimate of relative mutation rate. Using the model, we determined MI for every position in the genome. The genome and exome-wide distribution of MI at the single-nucleotide level is given in [Figure S7](#).

To define regional patterns of mutability, we segmented the genome-wide map of mutability with a five-state (cold, cool, baseline, warm, hot) HMM (see [Table S7](#)). In all analyses involving exons, the exon boundaries were used to define regions, and the mean MI over the exon was used as the representative mutability.

Genomic Distribution of DNMs

We computed two types of inter-DNM distance, considering first the nearest neighboring DNM within an offspring (i.e., a twin pair) and then the nearest neighboring DNM in another unrelated offspring. We call these the within-individual inter-DNM distance and the between-individuals inter-DNM distance, respectively. We then computed null distributions by sampling random positions from the genome (excluding assembly gaps) while maintaining the number and family-wise allocation per chromosome of DNMs, then calculating both inter-DNM distances as described. Using the KS test, we found that both observed distributions were significantly enriched (at $\alpha = 0.05$) for smaller inter-DNM distances compared to the simulated null distributions ([Figure 2](#)), suggesting that observed DNMs are spaced more closely than expected by chance.

In light of our exploration of genome-wide mutability, we hypothesized that if the null distributions were sampled such that a site's probability of inclusion in the sample was proportional to its MI, the deviation of the observed inter-DNM distance distribution from the expectation would be attenuated. This was indeed the case for both inter-DNM distance measures ([Figure S4](#)), as shown by the difference in p values where both uniform sampling and weighted (i.e., by MI) sampling were used to construct the null distributions.

Correlation of MI with Mutation rate

Site-Level Analysis

The genome was binned with respect to nucleotide-resolution MI in increments of 0.1 on the \log_{10} scale, and both the proportion of the genome scored within that bin, as well as the diploid mutation rate of sites scored within that bin, were calculated. We used sites from this work, [Conrad et al. \(2011\)](#), [Iossifov et al. \(2012\)](#), [Neale et al. \(2012\)](#), [O'Roak et al. \(2011, 2012\)](#), and [Sanders et al. \(2012\)](#), which were lifted over from hg19 to hg18 coordinates, in the calculation of these mutation rates ([Figure 4](#)).

Regional Analysis

We examined whether the trend of increasing mutation rate with increasing MI also held when looking at a regional scale. For WGS studies (this study; [Conrad et al., 2011](#)), we used the previously described HMM segments, with their mean MI as the representation of regional mutability. We then binned such that each bin contained an equivalent number of DNMs (10%) and then calculated the diploid mutation rate ([Figures S3A and S3B](#)). For exome studies ([Figures S3C–S3F](#)), we used the mean MI of exons as the measure of regional mutability, again binned the exons such that each bin contained 10% of DNMs from the respective study, and finally calculated the diploid mutation rate. Linear regression models were fit for each study independently, and all studies showed a positive correlation between MI and mutation rate (all slopes were significant at $\alpha = 0.01$ except [Conrad et al., 2011](#), which had the fewest DNMs).

Conservation, Segregating Variation, and Mutability

We investigated the relationship among MI, segregating variation, and evolutionary conservation ([Figure 6](#)) by first binning regions (genomic HMM segments and exons) according to the percentiles of their mean conservation values (yielding 100 bins). We then calculated the bin's mean MI, mean conservation, and SNP density. SNPs were compiled from the families in this study, and the total number of observed SNPs was counted per bin, rather than the number of polymorphic sites (this places more emphasis on common variation).

Mutability and the Genetic Mode of Disease Genes

We compared trends in mutability when classifying genes according to the genetic basis of their related disease phenotype ([Figures 7A and 7B](#)). For polygenic disease traits, we consulted the NHGRI GWAS catalog ([Hindorf et al., 2009](#)) and selected the most commonly studied diseases: diabetes (types I and II), coronary heart disease, Crohn's disease, ulcerative colitis, multiple sclerosis, and rheumatoid arthritis. We selected genes that had a SNP (i.e., within its boundaries) referenced in the GWAS catalog and classified

them as “polygene” (296 genes). For the recessive and dominant categories, we downloaded the OMIM database (<http://omim.org>) and extracted genes that were connected to diseases with “recessive” and “dominant” in the title, respectively (122 and 86 genes). Essential genes were extracted from the OGEE database (Chen et al., 2012) for a total of 1,394 genes. Together, these sets of genes comprised our “disease genes,” and all remaining genes were considered as the background set. We computed gene and exon mean MI for all genes and compared trends in mutability by performing a t test on each category, with the “background” set of genes as the reference group. To show the trends of enriched mutability in each category, we calculated a bootstrapped group mean. This was accomplished by bootstrap sampling equal numbers (100 and 1,000 for genes and exons, respectively) from the category under consideration (background, polygene, recessive, dominant, or essential) and computing the mean of each sample. This was performed 1,000 times for each group.

Mutability of Brain and Autism Genes

An approach similar to that described above was used for investigating the trend of mutability in brain and autism genes, compared to the background set of all other genes (Figures 7C and 7D). A list of genes preferentially expressed in the brain was assembled (totaling 2,577) according to the approach used in Raychaudhuri et al. (2010). We also assembled two sets of autism genes. The first was an inclusive set of ASD genes based on the strength of their connection to autism in the literature. This was accomplished by using NCBI mappings between Entrez gene IDs and PubMed IDs together with Fisher’s exact test to find genes significantly associated with autism publications. We thresholded the list at FDR <0.01, resulting in 93 literature-supported genes that have been implicated in ASD. The second was a partially overlapping set that included only “syndromic-ASD” genes (*CACNA1C*, *CNTNAP2*, *FMR1*, *MECP2*, *NLGN3*, *NLGN4X*, *PTEN*, *SHANK3*, *TSC1*, *TSC2*, and *UBE3A*) and “ASD-related” genes (*AGTR2*, *ARX*, *ATRX*, *CDKL5*, *FOXP2*, *HOXA1*, *NF1*, and *SLC6A8*) from a previous study by Sakai et al. (2011). We added to this list three additional syndromic ASD genes, including *KCNMA1* (Laumonnier et al., 2006), *AUTS2* (Huang et al., 2010), and *SHANK2* (Berkel et al., 2010). Again, we used t tests and bootstrapped means to compare the distributions of brain and autism-implicated genes against the background set of all other genes.

ACCESSION NUMBERS

The NDAR accession number for the sequence reported in this paper is NDARCOL0002019.

SUPPLEMENTAL INFORMATION

Supplemental Information includes Extended Experimental Procedures, seven figures, and seven tables and can be found with this article online at <http://dx.doi.org/10.1016/j.cell.2012.11.019>.

ACKNOWLEDGMENTS

This manuscript is dedicated in honor of James F. Crow, a pioneer in human genetics. This study was supported by grants to J.S. from the National Institutes of Health (MH076431 and HG005725) and the Simons Foundation Autism Research Initiative (SFARI 178088). L.M.I. was supported by NIH RO1 HD065288 and NIH RO1 MH091350. We wish to thank Joe Gleeson for helpful comments on the manuscript. Special thanks to the San Diego Super-computer Center for providing computing resources. Samples used in this study were provided by the NIMH genetics initiative (<http://www.nimhgenetics.org>). Acknowledgments for autism biomaterials are provided in Supplemental Information.

Received: August 17, 2012

Revised: October 5, 2012

Accepted: October 30, 2012

Published: December 20, 2012

REFERENCES

- Amiel, J., Rio, M., de Pontual, L., Redon, R., Malan, V., Boddart, N., Plouin, P., Carter, N.P., Lyonnet, S., Munnich, A., and Colleaux, L. (2007). Mutations in TCF4, encoding a class I basic helix-loop-helix transcription factor, are responsible for Pitt-Hopkins syndrome, a severe epileptic encephalopathy associated with autonomic dysfunction. *Am. J. Hum. Genet.* **80**, 988–993.
- Berkel, S., Marshall, C.R., Weiss, B., Howe, J., Roeth, R., Moog, U., Endris, V., Roberts, W., Szatmari, P., Pinto, D., et al. (2010). Mutations in the SHANK2 synaptic scaffolding gene in autism spectrum disorder and mental retardation. *Nat. Genet.* **42**, 489–491.
- Campbell, C.D., Chong, J.X., Malig, M., Ko, A., Dumont, B.L., Han, L., Vives, L., O’Roak, B.J., Sudmant, P.H., Shendure, J., et al. (2012). Estimating the human mutation rate using autozygosity in a founder population. *Nat. Genet.* **44**, 1277–1281.
- Chen, J.M., Cooper, D.N., Chuzhanova, N., Férec, C., and Patrinos, G.P. (2007). Gene conversion: mechanisms, evolution and human disease. *Nat. Rev. Genet.* **8**, 762–775.
- Chen, W.H., Minguez, P., Lercher, M.J., and Bork, P. (2012). OGEE: an online gene essentiality database. *Nucleic Acids Res.* **40**(Database issue), D901–D906.
- Chimpanzee Sequencing and Analysis Consortium. (2005). Initial sequence of the chimpanzee genome and comparison with the human genome. *Nature* **437**, 69–87.
- Conrad, D.F., Keebler, J.E., DePristo, M.A., Lindsay, S.J., Zhang, Y., Casals, F., Idaghdour, Y., Hartl, C.L., Torroja, C., Garimella, K.V., et al; 1000 Genomes Project. (2011). Variation in genome-wide mutation rates within and between human families. *Nat. Genet.* **43**, 712–714.
- Coulondre, C., Miller, J.H., Farabaugh, P.J., and Gilbert, W. (1978). Molecular basis of base substitution hotspots in *Escherichia coli*. *Nature* **274**, 775–780.
- Crow, J.F. (2000). The origins, patterns and implications of human spontaneous mutation. *Nat. Rev. Genet.* **1**, 40–47.
- Delbrück, M., and Bailey, W.T. (1946). Induced mutations in bacterial viruses. *Cold Spring Harb. Symp. Quant. Biol.* **11**, 33–37.
- DePristo, M.A., Banks, E., Poplin, R., Garimella, K.V., Maguire, J.R., Hartl, C., Philippakis, A.A., del Angel, G., Rivas, M.A., Hanna, M., et al. (2011). A framework for variation discovery and genotyping using next-generation DNA sequencing data. *Nat. Genet.* **43**, 491–498.
- Ellegren, H., Smith, N.G., and Webster, M.T. (2003). Mutation rate variation in the mammalian genome. *Curr. Opin. Genet. Dev.* **13**, 562–568.
- Francino, M.P., and Ochman, H. (1999). Isochores result from mutation not selection. *Nature* **400**, 30–31.
- Gupta, S., Dennis, J., Thurman, R.E., Kingston, R., Stamatoyannopoulos, J.A., and Noble, W.S. (2008). Predicting human nucleosome occupancy from primary sequence. *PLoS Comput. Biol.* **4**, e1000134.
- Haldane, J.B. (2004). The rate of spontaneous mutation of a human gene. 1935. *J. Genet.* **83**, 235–244.
- Hamdan, F.F., Daoud, H., Patry, L., Dionne-Laporte, A., Spiegelman, D., Dobrzaniecka, S., Rouleau, G.A., and Michaud, J.L. (2012). Parent-child exome sequencing identifies a de novo truncating mutation in TCF4 in non-syndromic intellectual disability. *Clin. Genet.* Published online June 4, 2012. <http://dx.doi.org/10.1111/j.1399-0004.2012.01890.x>.
- Hardison, R.C., Roskin, K.M., Yang, S., Diekhans, M., Kent, W.J., Weber, R., Elnitski, L., Li, J., O’Connor, M., Kolbe, D., et al. (2003). Covariation in frequencies of substitution, deletion, transposition, and recombination during eutherian evolution. *Genome Res.* **13**, 13–26.
- Hellmann, I., Prüfer, K., Ji, H., Zody, M.C., Pääbo, S., and Ptak, S.E. (2005). Why do human diversity levels vary at a megabase scale? *Genome Res.* **15**, 1222–1231.
- Hindorf, L.A., Sethupathy, P., Junkins, H.A., Ramos, E.M., Mehta, J.P., Collins, F.S., and Manolio, T.A. (2009). Potential etiologic and functional implications of genome-wide association loci for human diseases and traits. *Proc. Natl. Acad. Sci. USA* **106**, 9362–9367.

- Huang, X.L., Zou, Y.S., Maher, T.A., Newton, S., and Milunsky, J.M. (2010). A de novo balanced translocation breakpoint truncating the autism susceptibility candidate 2 (AUTS2) gene in a patient with autism. *Am. J. Med. Genet. A* 152A, 2112–2114.
- Hurles, M. (2002). Are 100,000 “SNPs” useless? *Science* 298, 1509.
- Iossifov, I., Ronemus, M., Levy, D., Wang, Z., Hakker, I., Rosenbaum, J., Yamrom, B., Lee, Y.H., Narzisi, G., Leotta, A., et al. (2012). De novo gene disruptions in children on the autistic spectrum. *Neuron* 74, 285–299.
- Kondrashov, A.S., and Crow, J.F. (1993). A molecular approach to estimating the human deleterious mutation rate. *Hum. Mutat.* 2, 229–234.
- Kong, A., Frigge, M.L., Masson, G., Besenbacher, S., Sulem, P., Magnusson, G., Gudjonsson, S.A., Sigurdsson, A., Jonasdottir, A., Jonasdottir, A., et al. (2012). Rate of de novo mutations and the importance of father's age to disease risk. *Nature* 488, 471–475.
- Koren, A., Polak, P., Nemesh, J., Michaelson, J.J., Sebat, J., Sunyaev, S.R., and McCarroll, S.A. (2012). Differential Relationship of DNA Replication Timing to Different Forms of Human Mutation and Variation. *Am. J. Hum. Genet.* 91, 1033–1040.
- Laumonier, F., Roger, S., Guérin, P., Molinari, F., M'rad, R., Cahard, D., Belhadj, A., Halayem, M., Persico, A.M., Elia, M., et al. (2006). Association of a functional deficit of the BKCa channel, a synaptic regulator of neuronal excitability, with autism and mental retardation. *Am. J. Psychiatry* 163, 1622–1629.
- Ledbetter, D.H., Riccardi, V.M., Airhart, S.D., Strobel, R.J., Keenan, B.S., and Crawford, J.D. (1981). Deletions of chromosome 15 as a cause of the Prader-Willi syndrome. *N. Engl. J. Med.* 304, 325–329.
- Lercher, M.J., and Hurst, L.D. (2002). Human SNP variability and mutation rate are higher in regions of high recombination. *Trends Genet.* 18, 337–340.
- Li, H., and Durbin, R. (2009). Fast and accurate short read alignment with Burrows-Wheeler transform. *Bioinformatics* 25, 1754–1760.
- Lupski, J.R. (1998). Genomic disorders: structural features of the genome can lead to DNA rearrangements and human disease traits. *Trends Genet.* 14, 417–422.
- Lupski, J.R. (2007). Genomic rearrangements and sporadic disease. *Nat. Genet.* 39(7, Suppl), S43–S47.
- Lynch, M. (2010). Rate, molecular spectrum, and consequences of human mutation. *Proc. Natl. Acad. Sci. USA* 107, 961–968.
- Malhotra, D., and Sebat, J. (2012). CNVs: harbingers of a rare variant revolution in psychiatric genetics. *Cell* 148, 1223–1241.
- Malhotra, D., McCarthy, S., Michaelson, J.J., Vacic, V., Burdick, K.E., Yoon, S., Cichon, S., Corvin, A., Gary, S., Gershon, E.S., et al. (2011). High frequencies of de novo CNVs in bipolar disorder and schizophrenia. *Neuron* 72, 951–963.
- Michaelson, J.J., and Sebat, J. (2012). forestSV: structural variant discovery through statistical learning. *Nat. Methods* 9, 819–821.
- Nachman, M.W., and Crowell, S.L. (2000). Estimate of the mutation rate per nucleotide in humans. *Genetics* 156, 297–304.
- Neale, B.M., Kou, Y., Liu, L., Ma'ayan, A., Samocha, K.E., Sabo, A., Lin, C.F., Stevens, C., Wang, L.S., Makarov, V., et al. (2012). Patterns and rates of exonic de novo mutations in autism spectrum disorders. *Nature* 485, 242–245.
- Need, A.C., Shashi, V., Hitomi, Y., Schoch, K., Shianna, K.V., McDonald, M.T., Meisler, M.H., and Goldstein, D.B. (2012). Clinical application of exome sequencing in undiagnosed genetic conditions. *J. Med. Genet.* 49, 353–361.
- Nelis, E., Van Broeckhoven, C., De Jonghe, P., Löfgren, A., Vandenbergh, A., Latour, P., Le Guern, E., Brice, A., Mostacciolo, M.L., Schiavon, F., et al. (1996). Estimation of the mutation frequencies in Charcot-Marie-Tooth disease type 1 and hereditary neuropathy with liability to pressure palsies: a European collaborative study. *Eur. J. Hum. Genet.* 4, 25–33.
- Nord, A.S., Roeb, W., Dickel, D.E., Walsh, T., Kusenda, M., O'Connor, K.L., Malhotra, D., McCarthy, S.E., Stray, S.M., Taylor, S.M., et al; STAART Psychopharmacology Network. (2011). Reduced transcript expression of genes affected by inherited and de novo CNVs in autism. *Eur. J. Hum. Genet.* 19, 727–731.
- O'Roak, B.J., Deriziotis, P., Lee, C., Vives, L., Schwartz, J.J., Girirajan, S., Karakoc, E., Mackenzie, A.P., Ng, S.B., Baker, C., et al. (2011). Exome sequencing in sporadic autism spectrum disorders identifies severe de novo mutations. *Nat. Genet.* 43, 585–589.
- O'Roak, B.J., Vives, L., Girirajan, S., Karakoc, E., Krumm, N., Coe, B.P., Levy, R., Ko, A., Lee, C., Smith, J.D., et al. (2012). Sporadic autism exomes reveal a highly interconnected protein network of de novo mutations. *Nature* 485, 246–250.
- Rattray, A.J., Shafer, B.K., McGill, C.B., and Strathern, J.N. (2002). The roles of REV3 and RAD57 in double-strand-break-repair-induced mutagenesis of *Saccharomyces cerevisiae*. *Genetics* 162, 1063–1077.
- Raychaudhuri, S., Korn, J.M., McCarroll, S.A., Altshuler, D., Sklar, P., Purcell, S., and Daly, M.J.; International Schizophrenia Consortium. (2010). Accurately assessing the risk of schizophrenia conferred by rare copy-number variation affecting genes with brain function. *PLoS Genet.* 6, e1001097.
- Rosenberg, S.M. (2001). Evolving responsively: adaptive mutation. *Nat. Rev. Genet.* 2, 504–515.
- Sakai, Y., Shaw, C.A., Dawson, B.C., Dugas, D.V., Al-Mohtaseb, Z., Hill, D.E., and Zoghbi, H.Y. (2011). Protein interactome reveals converging molecular pathways among autism disorders. *Sci. Transl. Med.* 3, 86ra49.
- Sanders, S.J., Murtha, M.T., Gupta, A.R., Murdoch, J.D., Raubeson, M.J., Willsey, A.J., Ercan-Sencicek, A.G., DiLullo, N.M., Parikshak, N.N., Stein, J.L., et al. (2012). De novo mutations revealed by whole-exome sequencing are strongly associated with autism. *Nature* 485, 237–241.
- Scally, A., and Durbin, R. (2012). Revising the human mutation rate: implications for understanding human evolution. *Nat. Rev. Genet.* 13, 745–753.
- Schrider, D.R., Hourmouzi, J.N., and Hahn, M.W. (2011). Pervasive multinucleotide mutational events in eukaryotes. *Curr. Biol.* 21, 1051–1054.
- Schuster-Böckler, B., and Lehner, B. (2012). Chromatin organization is a major influence on regional mutation rates in human cancer cells. *Nature* 488, 504–507.
- Sebat, J., Lakshmi, B., Malhotra, D., Troge, J., Lese-Martin, C., Walsh, T., Yamrom, B., Yoon, S., Krasnitz, A., Kendall, J., et al. (2007). Strong association of de novo copy number mutations with autism. *Science* 316, 445–449.
- Sun, J.X., Helgason, A., Masson, G., Ebenesersdóttir, S.S., Li, H., Mallick, S., Gnerre, S., Patterson, N., Kong, A., Reich, D., and Stefansson, K. (2012). A direct characterization of human mutation based on microsatellites. *Nat. Genet.* 44, 1161–1165.
- Svejstrup, J.Q. (2002). Mechanisms of transcription-coupled DNA repair. *Nat. Rev. Mol. Cell Biol.* 3, 21–29.
- Talkowski, M.E., Ernst, C., Heilbut, A., Chiang, C., Hanscom, C., Lindgren, A., Kirby, A., Liu, S., Muddukrishna, B., Ohsumi, T.K., et al. (2011). Next-generation sequencing strategies enable routine detection of balanced chromosome rearrangements for clinical diagnostics and genetic research. *Am. J. Hum. Genet.* 88, 469–481.
- Uher, R. (2009). The role of genetic variation in the causation of mental illness: an evolution-informed framework. *Mol. Psychiatry* 14, 1072–1082.
- van Attikum, H., and Gasser, S.M. (2005). The histone code at DNA breaks: a guide to repair? *Nat. Rev. Mol. Cell Biol.* 6, 757–765.
- Wang, J., Gonzalez, K.D., Scaringe, W.A., Tsai, K., Liu, N., Gu, D., Li, W., Hill, K.A., and Sommer, S.S. (2007). Evidence for mutation showers. *Proc. Natl. Acad. Sci. USA* 104, 8403–8408.
- Webster, M.T., Smith, N.G., and Ellegren, H. (2003). Compositional evolution of noncoding DNA in the human and chimpanzee genomes. *Mol. Biol. Evol.* 20, 278–286.
- Zweier, C., Peippo, M.M., Hoyer, J., Sousa, S., Bottani, A., Clayton-Smith, J., Reardon, W., Saraiva, J., Cabral, A., Gohring, I., et al. (2007). Haploinsufficiency of TCF4 causes syndromal mental retardation with intermittent hyperventilation (Pitt-Hopkins syndrome). *Am. J. Hum. Genet.* 80, 994–1001.