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A Novel Analytical Framework for Dissecting the Genetic Architecture of Behavioral Symptoms in Neuropsychiatric Disorders

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Abstract

Background: For diagnosis of neuropsychiatric disorders, a categorical classification system is often utilized as a simple way for conceptualizing an often complex clinical picture. This approach provides an unsatisfactory model of mental illness, since in practice patients do not conform to these prototypical diagnostic categories. Family studies show notable familial co-aggregation between schizophrenia and bipolar illness and between schizoaffective disorders and both bipolar disorder and schizophrenia, revealing that mental illness does not conform to such categorical models and is likely to follow a continuum encompassing a spectrum of behavioral symptoms.

Results and Methodology: We introduce an analytic framework to dissect the phenotypic heterogeneity present in complex psychiatric disorders based on the conceptual paradigm of a continuum of psychosis. The approach identifies subgroups of behavioral symptoms that are likely to be phenotypically and genetically homogenous. We have evaluated this approach through analysis of simulated data with simulated behavioral traits and predisposing genetic factors. We also apply this approach to a psychiatric dataset of a genome scan for schizophrenia for which extensive behavioral information was collected for each individual patient and their families. With this approach, we identified significant evidence for linkage among depressed individuals with two distinct symptom profiles, that is individuals with sleep disturbance symptoms with linkage on chromosome 2q13 and also a mutually exclusive group of individuals with symptoms of concentration problems with linkage on chromosome 2q35. In addition we identified a subset of individuals with schizophrenia defined by language disturbances with linkage to chromosome 2p25.1 and a group of patients with a phenotype intermediate between those of schizophrenia and schizoaffective disorder with linkage to chromosome 2p21.

Conclusions: The findings presented are novel and demonstrate the efficacy of this approach in detection of genes underlying such complex human disorders as schizophrenia and depression.

Introduction

Emil Kraepelin’s descriptions of psychiatric diagnoses at the turn of the 20th century were groundbreaking and remain influential to this day. Kraepelin’s dichotomous classification of manic-depressive insanity (bipolar disorder) and dementia praecox (schizophrenia) provides a simple way for conceptualizing an often complex clinical picture and has been extended to include a categorical classification system utilized for a vast array of psychiatric illnesses [1]. The validity of such a categorical classification system has been challenged, as providing an unsatisfactory model of mental illness [2,3,4,5]. In clinical practice, many patients with psychiatric illness do not conform to a prototypical diagnostic category. Findings emerging from many psychiatric research areas and in particular psychiatric genetics are not consistent with the traditional categorical model. For example, family studies reveal notable familial co-aggregation between schizophrenia and bipolar illness and between schizoaffective disorders and both bipolar disorder and schizophrenia [6,7,8]. This points to the arbitrary nature of diagnostic boundaries that do not reflect the underlying pathology. Further, linkage and association studies demonstrate shared genetic susceptibility in
with both schizophrenia and bipolar disorder [6]. Candidate gene studies whose variants were shown to be associated with linkage to common chromosomal regions [6,7], as well as schizophrenia and bipolar disorder. This has been shown through the individual groupings from clustering of individuals with an overlap of clinical symptoms within diagnostic categories. This form of shared behavioral symptoms without regard to the diagnostic category might be more informative for examination of the individual's behavioral symptoms without possessing symptoms of these disorders [12]. As such, direct determinants underlying a specific cluster of symptoms that define a clinical sub-phenotype may be detected. This framework was especially developed for analysis of data from genetic studies of neuropsychiatric disorders with a wide spectrum of clinical symptoms. With this in mind, we applied this method to analysis of schizophrenia data, where we demonstrate the efficacy of this approach in refining the findings from a previous schizophrenia genome scan [13]. As a proof of principle, we also used a published simulated dataset from the Genetic Analysis Workshop 14 [14] that was designed to model the genetic influences on a complex psychiatric disorder.

**Materials and Methods**

**Ethics Statement**

The recruitment and diagnosis of patients and their family members are described elsewhere [13]. In brief, this clinical cohort was previously examined and published using the behavioral and genetic data utilized in this study in a genome scan of schizophrenia [13]. As described previously [13] subjects were recruited from five geographic centers beginning in 1985: 213 families from the United States (based at Stony Brook, N.Y.), 50 from the United Kingdom (Oxford), 33 from Italy (Milan), 11 from Chile (Santiago), and two from Belgium (Leuven). Recruitment included catchment area screening, recruitment by health professionals at hospital and outpatient facilities, and advertisement through organizations which support families of mentally ill individuals. Written consent was obtained from all participants in the study after receiving an explanation of the study procedures and their implications. Consent was obtained using the same procedures in all five countries, and each center was granted approval with Single Project Assurance status by the Office of Protection From Research Risks of the U.S. Department of Health and Human Services. This study was conducted according to the principles expressed in the Declaration of Helsinki. Individual Institutional Review Board approval from the institutions to which the authors are affiliated were not obtained as this was a reanalysis of a previously published de-identified dataset.

**Samples and Subjects**

**Simulated Data (GAW14).** The GAW14 data was designed to model the genetic influences on a complex psychiatric disorder [14]. The made-up disorder termed Kofendred Personality Disorder (KPD) could be subcategorized into three distinct latent phenotypes denoted as P1, P2, and P3. These latent phenotypes were in turn defined by 12 behavioral traits labeled a-to-l. The genetic architecture of this disorder involves four disease gene loci D1, D2, D3, and D4 (Figure 1A). The genes interact in an epistatic fashion together with two modifier genes, D5 and D6 (Figure 1B). For the purposes of evaluating our methodology we assumed that the latent phenotypes were unknown, instead all analyses were based directly on the 12 behavioral traits.

In each population the families were ascertained based on the following criterion assuming a family contains at least one latent phenotype in order to be considered for inclusion in the study: for the Aipotu population at least two family members must have either P1, P2 or P3; for the Karangar population at least two family members must have P2 or P3; for the Danacaa population at least two family members must have P1. In this way, 100 families were ascertained from each population, constituting a single replicate (Replicate #1 was used in this study). A total of 300 families were analyzed, consisting of 2,077 individuals of which 781 were affected with KPD and 1,296 were unaffected. All genotype data for the 10 simulated chromosomes were examined,
with 416 microsatellite markers approximately 7.5 centimorgans (cM) apart.

**Real Data (Schizophrenia).** Reviewing the findings from the genome scan, we identified those chromosomes with moderate to significant linkage evidence[13]. The schizophrenia study included 1,779 subjects with probands and their relatives, who were previously examined and assigned to one of the following major diagnostic categories: schizophrenia, major depression, depression not otherwise specified, schizoaffective disorder, bipolar disorder, schizotypal personality disorder, psychosis not otherwise specified, or unaffected according to DSM-IV criteria [13] (with some individuals having been assigned an unknown diagnosis). Families with at least two members with diagnosis of schizophrenia were included in the study. In addition, 178 behavioral symptoms, as part of a Lifetime Symptom Checklist, were scored from the combined structured interviews, family informant information and medical records [13] across 1,779 individuals including both patients and family members. From these 178 behavioral symptoms, 158 were utilized in this study comprised of 154 dichotomous traits and four traits with four states (absent and minimally, moderately and severely affected). We then focused our efforts in analyzing these chromosomes in an effort to identify subsets of behavioral symptoms that may strengthen previous linkage findings, which were strictly based on major clinical diagnoses. To this end, 91 microsatellite markers were identified for this analysis (39 markers on chromosome 2, 30 markers on chromosome 10 and 22 markers on chromosome 22).

**Algorithm for Behavioral and Genetic Network Analysis**

The hierarchical behavioral network representing phenotypic relatedness is obtained through the use of a character-based analysis. This approach optimizes the change of behavioral traits, where a change is defined by the loss (1→0) or gain (0→1) of the presence of a behavioral trait as the network is traversed from one individual to another[16]. This scoring system allows for the separation of clinical symptoms within diagnostic categories and for overlap between diagnostic categories. The structure of this network is then utilized to create increasingly more inclusive or nested sets of individuals based on phenotypic similarity each of which is tested via traditional linkage and/or association analyses. As such, the nesting of individuals based on the structure of the behavioral network allows for the identification of genetic loci that have both local and global influences on clusters of symptoms. Each group of individuals, defined by the nesting group derived from the behavioral network structure, is then considered as a candidate behavioral endophenotype (or a candidate phenotypic model) that is adopted for subsequent genetic linkage or association testing. If significant evidence for linkage or association is detected for a particular behavioral endophenotype, the symptom profile of that group can then be examined to identify those symptoms shared by the majority of individuals. Since the behavioral network algorithm maximizes the traits that individuals close to one another on the network share, the majority of individuals in a group with significant linkage or association are likely to all share one or more behavioral traits in common. In this way, relationships between specific endophenotypes and genotypes may be established.

The character-based algorithm described here, which generates a behavioral network based on individual symptoms, accounts for phenotypic heterogeneity. The goal is to identify genetically meaningful phenotypic groups. Since an optimal arrangement of shared behavioral symptoms was used to build the phenotypic network, the symptoms defining a phenotypic group of interest can easily be determined. As phenotypic groups are analyzed at multiple, increasingly inclusive levels, genetic loci that show linkage or association within small or large groups of individuals with particular symptoms can be detected (denoted as local or global affects respectively). This provides a direct means of detecting genetic loci that can potentially modulate behavioral symptoms.

Specifically, our algorithm consists of four distinct components including (1) estimating a behavioral network, (2) nesting the behavioral network into inclusive groups/clades[17], (3) performing genetic analysis, and (4) evaluating statistical significance of behavioral symptoms (see Figure 2 for an outline of the algorithm, and Figure S1 for an example of network estimation). The statistical evaluation of behavioral symptoms involves comparing symptom distributions of individuals belonging to a given nested group to the symptom distribution within the diagnostic category to which they were assigned. To this end, we adopt a likelihood-based approach to test for significant differences in the symptom distributions in these groups. The likelihood ratio test is formulated as follows,
Estimate behavioral network

Group individuals sharing behavioral symptoms (character-based approach):
- Code symptoms into discrete character states (1: present; 0: absent)
- Determine hierarchical arrangement of individuals with unique symptom profiles, while minimizing total character state changes in network
- Apply parsimony optimality criterion to optimize minimum change in symptoms, where change is loss (1→0) or gain (0→1) of a symptom
- Result: hierarchical arrangement of individuals by phenotypic relatedness (Lipscomb 1992)

The likelihoods for the null and alternative hypotheses (H₀ and Hₐ respectively) are straightforward, where

$L(H₀) = (1-p_2)^{x_2} (1-p_3)^{x_3} \max_{p_1, p_2} L(p_1, p_2) = (1-p_2)^{x_2} (1-p_3)^{x_3}$

$L(Hₐ) = (1-p_2)^{x_2} (1-p_3)^{x_3} (1-p_4)^{x_4} \max_{p_1, p_2, p_3} L(p_1, p_2, p_3) = (1-p_2)^{x_2} (1-p_3)^{x_3} (1-p_4)^{x_4}$

The likelihoods thus formulated are evaluated for each trait of interest and assessed via the likelihood ratio test at the parameter’s maximum likelihood estimates. Furthermore, for assessment of statistical significance, empirical p-values were estimated using 10,000 permutations of the data.

Data Analysis

Generating a network from the behavioral symptoms of individuals in the dataset involves examination of the entire “tree space”. This requires that all possible network configurations, which group individuals with respect to their shared symptom profiles must be enumerated and evaluated. This is not computationally feasible. Instead we used a heuristic ratchet search algorithm that has been developed for applications of exceptionally large datasets [18]. The ratchet search algorithm assumes that there are islands of
local optimality in the search space for the shortest network [19],
that is, a network with an arrangement of individuals and their
shared symptoms that minimize the number of character state
changes. However, such heuristic algorithms typically produce
multiple equally parsimonious trees. A solution to this problem is to
adopt a majority rule consensus tree, where a resolution among
individual nodes on the tree is arrived at if it is supported by the
majority of trees in the tree space. In this application, 51% is the
minimum allowable support. For this analysis, all parsimony based
ratchet searches were conducted using TNT v 1.0 [20]. All trees
were visualized and all symptoms were mapped onto trees using
MACCLADE v 4.08 [21]. To improve our tree resolution for a
specific clade, we performed a tree search using the SPR branch
swapping in PAUP v 4.0b10 [22].

The behavioral networks thus generated were examined and
nested groups/clades were identified for genetic analysis. Since the
datasets considered consist of family data, we performed genetic
linkage analysis using the program MILINK from the LINKAGE
software package [23,24]. Heterogeneity LOD scores (HLOD)
were computed based on an admixture likelihood model that
jointly tests for linkage and heterogeneity (i.e., the maximum
HLOD is compared with the log-likelihood under a null hypothesis of “no linkage and no heterogeneity” rather than with
the maximum homogeneity LOD) [25,26]. Linkage analyses were
performed on those clades that were comprised of individuals from
at least 40 families. This clade constraint was applied, a priori,
before conducting the linkage analyses. This limited the number of
tests performed for small samples with potentially little power to
detect linkage. Of all nested groups considered, 6 clades met this
criteria in the simulated dataset and 39 clades in the schizophrenia
dataset. For each nested clade, LOD scores maximized over
multiple models were calculated with corresponding estimated
empirical p-values adjusting for the testing of multiple phenotypic
and genotypic models as well as multiple marker loci. LOD scores
were calculated under models of both homogeneity (LOD) and
heterogeneity (HLOD)[26]. Four genetic models were considered
including (1) a fully penetrant dominant model (Dom-1) and
disease allele frequency of 0.01, (2) fully penetrant recessive model
(Rec-1) and disease allele frequency of 0.09, (3) a dominant model
with 55% penetrance (Dom-2) and phenocopy rate of 0.0005, and
disease allele frequency of 0.01, and (4) a recessive model with
55% penetrance (Rec-2), phenocopy rate of 0.0005, and disease
allele frequency of 0.09. The first two models (Dom-1 and Rec-1),
though the simplest and perhaps overly optimistic, were chosen
because they provide the greatest power to detect linkage [27].
The latter two models (Dom-2 and Rec-2) were based on a
previously published analysis of this schizophrenia dataset[28]. In
the absence of any knowledge regarding the mode of inheritance
of the disease, as is typically the case for complex diseases,
application of a limited set of simple genetic models have been
shown to work well when testing for linkage [29].

To account for multiple testing, we estimated empirical p
values, allowing for multiple phenotypic and genetic models, as
well as multiple marker loci tested. To this end, we randomly
assigned genotypes to the founders within each family while
conditioning on the observed allele frequency and intermarker
distances in the data and then mating individuals within families
according to the pedigree structure using the program SIMU-
LATE [30]. In this way, 100 randomized replicates of the data
were generated. These replicates were used to estimate both the
model-based and the global empirical p-values. The model-based
p value (pM) is calculated by making comparisons to the maximum LOD
scores from randomized replicates across all genotypic and
phenotypic models (clades) and marker loci tested. This approach
accounts for multiple testing of all combinations of genetic-
phenotypic models as well as genetic markers tested.

Results

Simulated Data (GAW14)

Behavioral traits from all family members were analyzed to
generate a behavioral network. The network correctly grouped the
three latent phenotypes, as shown in Figure 1C. Within these
groups, referred to as clades, the proportions of individuals with
each of the behavioral traits were examined and found to concur
with the simulated models relating the behavioral traits with the
latent phenotypes (Figure 1C). Furthermore, genetic linkage
analysis of these key clades identified the major disease loci
contributing to KPD. In contrast to the findings observed from
conducting a traditional genome scan (where KPD is used as the
major diagnosis for defining affectedness), the observed linkage
signals from this analysis were more significant (with the exception
of one locus), and combinations of loci contributing to specific
latent phenotypes were identified (Table S2). This analysis
indicates that our algorithm is able to identify the genetic factors
underlying each of the latent phenotypes. Indeed, this degree of
resolution in detecting the contribution of genetic loci to specific
sub-phenotypes in a complex trait model is not attainable using
existing approaches.

Real Data (Schizophrenia)

Analysis of schizophrenia samples identified four distinct
behavioral groups (clades) with corresponding evidence for genetic
linkage. The salient clinical features of these groups were similar to
major depression and schizophrenia with two groups resembling
“depression” (clades 6_4 and 4_28) and two “schizophrenia” (clades
6_6 and 6_1). These clades can be represented in a behavioral
network (Figure 3). In this network representation, the most
inclusive nesting level contains two clades (8_0 and 8_1) that
encase the four clades noted above, where these clades become smaller and less inclusive as the network is traversed from
left to right (Figure 3). In this way, individuals with shared
behavioral symptoms are grouped through successive nesting
levels, in that specific symptom(s) are shown to define specific
classes (Figure 3). The significance of these specific symptom
profiles was further evaluated (Figure 4). Those behavioral
symptoms that were observed in >70% of the individuals within
each clade were identified, and the relative proportion of these
symptoms were compared to the assigned diagnostic categories.
Specifically, those symptoms that occur in a significantly greater
number of individuals in the clade under consideration were
compared to the diagnostic category (e.g., depression or
schizophrenia) to which the majority of the individuals in the
clade were assigned. In this way, statistically significant symptom
profiles were identified that characterize each clade (Figure 4).

The depression group [depression] is characterized by the
symptom “difficulty concentrating” (Figure 4), since the majority
of individuals belonging to this clade share this symptom. In
contrast, the second clade, [depression] is characterized by a
spectrum of symptoms, that include “trouble getting to sleep”,
“trouble staying asleep” and “early morning wakening”, and
“severely poor adaptation to school with poor scholastic perfor-
Such symptoms appear in significantly greater proportions of individuals in these clades than those with the assigned diagnosis of major depression (Figure 4). Further, these individuals belong to mutually exclusive groups accounting for 83 of the 139 patients with major depression in the total dataset (Table 1), identifying two depression sub-phenotypes with distinct symptom profiles.

Linkage analysis of these depression clades provided significant evidence for linkage on chromosome 2 (Table 1). Individuals with behavioral symptoms in each of the depression groups were designated as affected and their family members who did not share these defining symptoms were designated as unaffected for consideration in the linkage analyses. We observed significant linkage signal for the depression clade with loss of concentration as the defining symptom on chromosome 2q35 (heterogeneity LOD score HLOD = 4.07 at marker D2S2248). We also observed suggestive evidence for linkage on 2q13 for the second depression clade (HLOD of 2.86), where the dominating symptoms were those of sleep disturbances. Comparatively, analysis of families in the total dataset using the diagnosis of major depression to define affectedness yielded lower linkage analysis of families in the total dataset using the diagnosis of major depression (Figure 4). Further, these individuals belong to two mutually exclusive groups accounting for 83 of the 139 patients with major depression in the total dataset (Table 1), identifying two depression sub-phenotypes with distinct symptom profiles.

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Figure 4. The spectrum of behavioral symptoms defining the depression and schizophrenia clades. Symptoms present in greater than 70% of individuals with the diagnosis of depression, schizophrenia, or schizoaffective disorder are depicted as filled-in circles with depression (in blue), schizophrenia (in purple) and schizoaffective (in gray). Significant differences in symptom distributions within clades compared to the diagnostic categories of depression (Dep), schizophrenia (Schiz), and schizoaffective (Schizaf) are depicted with a “*” (with statistical significance reported at the 0.05 level). Unfilled circles with a “**” imply statistically significant differences between the clade and diagnostic category but that less than 70% of individuals in that clade have that symptom. Boxes which encompass the circles in the three columns of depression, schizophrenia and schizoaffective disorder are shaded when that symptom appears in greater than 70% of the individuals in that diagnostic category. Five symptoms distinguish the depression4-28 clade from the diagnostic category of depression, which include trouble getting to sleep, trouble staying asleep, early morning awakening, severe impairment in both childhood and adolescent adaptation to school. The depression4-28 clade is distinguished by one symptom, mainly difficulty concentrating. These depression clades are mutually exclusive. Further, language disorder symptoms distinguish the schizophrenia6-6 clade from the diagnostic category schizophrenia (i.e., circumstantial speech and excess details) as well as an increased incidence of violence and aggression. The schizophrenia6-1 clade is distinguished from both diagnostic categories schizophrenia and schizoaffective disorder by more than 70% of individuals in that clade have that symptom. Boxes which encompass the circles in the three columns of depression, schizophrenia and schizoaffective disorder are shaded when that symptom appears in greater than 70% of the individuals in that diagnostic category. Five symptoms distinguish the depression4-28 clade from the diagnostic category of depression, which include trouble getting to sleep, trouble staying asleep, early morning awakening, severe impairment in both childhood and adolescent adaptation to school. The depression4-28 clade is distinguished by one symptom, mainly difficulty concentrating. These depression clades are mutually exclusive. Further, language disorder symptoms distinguish the schizophrenia6-6 clade from the diagnostic category schizophrenia (i.e., circumstantial speech and excess details) as well as an increased incidence of violence and aggression. The schizophrenia6-1 clade is distinguished from both diagnostic categories schizophrenia and schizoaffective disorder by three symptoms, including thoughts inserted into one’s head that are not one’s own, thoughts stopping or withdrawn, and thoughts being read by others. However, this clade shares behavioral symptoms characteristic of both of these diagnostic categories.

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5_15, which has no defining symptom profile and encompasses a collection of individuals from many diagnostic categories with the largest represented group being the unaffected. Many of these individuals have very few symptoms, which is why they cluster more closely with the unaffected individuals. However, closer examination of their symptom distribution revealed that approximately 57% of all individuals carry at least one symptom of a personality disorder (data not shown), including paranoid, schizoid, schizotypal and borderline traits (with significant evidence for linkage, HILOD of 3.4 proximal to D2S391 approximately 4 cM from the peak LOD in schizophrenia4-6 clade see Table S1). This result captures the notion of a continuum of psychosis. As expected, unaffected family members of the mentally ill often share some symptoms with their affected family members.

Discussion

In this study, we have developed an analytical framework for the characterization of behavioral symptoms with shared genetic contribution. This method is a departure from the traditional approaches to analysis of neuropsychiatric disorders in that it does not rely on a priori assignment of individuals to specific diagnostic categories. We have demonstrated the effectiveness of this approach in identifying the genetic factors involved in the etiology of complex phenotypic models using simulated data. Application of this method to our schizophrenia data revealed groupings of patients whose characteristic symptoms are novel with potential involvement of gene(s) contributing to these symptoms. With this method, we further refined previous linkage findings in this dataset, providing improvements in the linkage results by limiting potential phenotypic heterogeneity. Analysis of individuals with shared behavioral symptoms is a powerful and straightforward approach to identify the genetic factors underlying such symptom profiles and will lead to discovery of endophenotypes that are likely to be more biologically meaningful than standard diagnostic categories.

Our results clearly demonstrate the separation of individuals with major depression on the basis of whether they exhibit sleep

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<th>Table 1. Diagnostic and LOD score statistics for clades.</th>
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For the four significant depression and schizophrenia clades, the number of individuals from each diagnostic group that are present in each clade and corresponding LOD scores are reported. The clades are separated into two groups, consisting of individuals with symptoms typical of depression and those with individuals with symptoms typical of schizophrenia. The maximum LOD score is reported for each clade, maximized over all genetic models and analysis schemes examined. The term HILOD denotes the maximum heterogeneity LOD score and s is the corresponding heterogeneity parameter. Model refers to the genetic model as described in the text. $P_{M}$ and $P_{G}$ are the estimated model-based and global empirical p values respectively.

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disturbance symptoms. These physiological symptoms may distinguish the etiological factors for the disorder in each group. Further, the separation of the two linkage peaks for major depression on chromosome 2 based on two primary behavioral symptoms (i.e., sleep disturbances and difficulty concentrating) may indicate the identification of two groups of patients whose symptoms have two distinctly different genetic origins. The individuals in the group suffering from sleep disturbances appear to have more severe symptoms during childhood, indicating a possible prodrome or an earlier age of onset. This increases the likelihood that these symptoms may have high genetic loading, consistent with epidemiological studies, suggesting a strong correlation between the diagnosis of depression and sleep disturbances [32,33,34]. The second depression group is comprised of individuals that have difficulty concentrating, confirming previous findings [35,36,37]. This group provided the strongest linkage evidence in our study, where the linkage signal spans the genomic region containing the gene cAMP responsive element binding protein 1 (CREB1) which has been implicated as a candidate gene for depression [38,39].

The most striking schizophrenia finding involved the group of individuals with language disorders, considered central to the symptom pathology of schizophrenia [40,41]. It has been suggested that these symptoms are related to cognitive deficits in schizophrenia [42]. We observed one group with over 95% of individuals defined by specific symptoms of language disorders, such as circumstantial speech and excess details. These could represent a core set of symptoms for a specific subtype of schizophrenia with a distinct genetic pathway that might be targeted with specific pharmacological and cognitive treatments. While there have been numerous studies reporting linkage to schizophrenia on chromosome 2 [31,43,44,45,46,47,48,49,50] none have specifically reported linkage at the sites identified in the analysis of our two subgroups of schizophrenia patients at chromosomal regions 2p25.1 and 2p21. The region 2p25.1 contains the gene neurotensin receptor 2, which has an important physiological role in sensory perception [31]. Additionally, the region 2p21 contains the gene protein kinase C epsilon, which has been shown to be involved in neuronal channel activation and may be involved in emotional learning and memory [52]. These results demonstrate the efficacy of our approach, however they are subject to replication in future studies using the wealth of genetic and behavioral data collected in other linkage and association studies.

While grouped individuals based primarily on shared behavioral symptoms, it is also possible to include physiological trait measurements, as well as non-genetic or environmental factors. In future analyses, the relative importance of traits can be weighted when building the network based on the heritability of the trait. Traits with high heritability would contribute more to the structure of the network defining phenotypic relationships. The analytical procedure is also easily extendable to association studies using a case-control study design by simply performing association tests on phenotypic groups instead of linkage analyses. This method is ideally suited for application to diseases where clinical heterogeneity of phenotypes is suspected and multiple symptoms are recorded for study subjects, as is typically the case for most neuropsychiatric disorders.

Our study shows that reconsideration and refinement of phenotypic definitions will reveal a myriad of new phenotypic and genotypic relationships. Although the representation of behavioral symptoms among individuals is not likely to be hierarchical, with some genes affecting multiple symptoms and multiple genes having an effect on an individual symptom, our method aims to generate hypotheses regarding specific subgroups of individuals with shared symptoms and to delineate the genetic basis of such behavioral symptoms. In this way, individuals with shared symptom profiles will be grouped together and genes with effects on these symptoms will be detected, generating novel phenotype-genotype relationships.

Supporting Information

Figure S1 Simplified example of a network representing relationships between patient’s behavioral phenotypes. This shows how behavioral symptoms of individuals in the dataset are used to group patients together into a hierarchical network. (A) Depiction of eight patients each scored for the presence (1) or absence (0) of ten behavioral symptoms. (B) Network representing the grouping of patients based on phenotypic relatedness. Patients who share more behavioral symptoms in common are grouped together, where the closest neighbors in a network are binned together into a more inclusive group (referred to as nesting level). Found at: doi:10.1371/journal.pone.0009714.s001 (8.21 MB TIF)

Figure S2 Depression LOD score plots. This demonstrates the separation and amplification of linkage peaks in the two mutually exclusive depression groups as compared to the overall diagnoses of depression. The LOD score peak at approximately 122 cM circled for the depression diagnoses (panel A) is significantly amplified in the depression4,28 clade (panel B), which also lacks a LOD score peak at ~218 cM position. In contrast, the depression6,4 clade shows amplification of the peak at ~218 cM (panel C), corresponding to the second peak for the depression diagnoses (panel A). Interestingly, the depression6,4 clade lacks the peak at approximately 122 cM, present in the depression4,28 clade (panels B and C). These two depression clades are mutually exclusive, indicating a potential separation of two genetically distinct groups of individuals within the diagnostic category major depression who can be distinguished phenotypically by the presence/absence of sleep disturbance symptoms. Found at: doi:10.1371/journal.pone.0009714.s002 (9.47 MB TIF)

Table S1 Diagnostic and LOD score statistics for clade 5_15. For this clade, the number of individuals carrying each diagnosis is provided as well as the number of individuals and families and the relevant linkage statistics. The maximum LOD score is reported maximized over all genetic models and analysis schemes examined with corresponding model parameters. The term HLOD denotes the maximum heterogeneity LOD score and is the corresponding heterogeneity parameter. Marker refers to the genetic marker with the observed maximum HLOD. Model refers to the genetic model as described in the text. PM and PG are the estimated model-based and global empirical p-values respectively. Found at: doi:10.1371/journal.pone.0009714.s003 (0.04 MB DOC)

Table S2 Linkage Results of Simulated GAW14 Data. Clade refers to the clades under consideration, Phenotype refers to the latent phenotypes, HLOD is the maximum heterogeneity LOD score and is the heterogeneity parameter, Model refers to the genetic model as described in the text, and PM and PG are the estimated model-based and global empirical p-values respectively. Chromosome is the chromosome on which this peak occurs, position is the position on the chromosome at which the peak occurs in cM, and disease locus is the disease locus that it identifies. Details of the genetic models and analyses as well as the empirical p-value estimations are given in main text. (A) Linkage analysis of the clade (0,21) containing the latent phenotype P1 showed strong linkage to the disease gene D1 on chromosome 1,
which together with D2 define the underlying genetic contribution for P1. Analysis of clade 0_4 also revealed significant evidence for linkage with the disease genes D3 and D4 contributing to the latent phenotypes P2 and P3. However, the disease locus D2 was not detected in linkage analysis of these clades, which included individuals who harbored the latent phenotypes of interest. This is likely due to the fact that the latent phenotypes P2 and P3 are caused by alternate epistatic interactions between the disease loci D2 and D3, where for P2 the disease loci D2 has a recessive mode of inheritance and D3 has a dominant mode of inheritance, and in contrast for P3 the disease loci D2 has a dominant mode of inheritance and D3 has a recessive mode of inheritance. As for the linkage analysis there was no resolution between the phenotypic groups P2 and P3. Thus, they were analyzed with these opposite modes of inheritance which coupled with the reduced sample size resulting from subdividing this group reduced the potential genetic signal for the disease loci D2. Interestingly, D2 was correctly localized when the clade containing the majority of the unaffected was examined. The disease locus D2 is the genetic determinant for traits e, f and h in unaffected individuals, which acts in a dominant manner with a penetrance of approximately 20%. (B) Whole-genome scan analysis on the entire dataset using Kofendred was examined. The disease locus D2 is the genetic determinant for traits e, f and h in unaffected individuals, which acts in a dominant manner with a penetrance of approximately 20%. (B) Whole-genome scan analysis on the entire dataset using Kofendred Personality Disorder as the major diagnosis (i.e., used to define affectedness status). All the major disease loci were also identified in this analysis, yet with less significant linkage signals. The exception was locus D2 which had a more significant HLOD score in this genome scan. (C) The two clades separated by the presence (P2) or absence (P2) of trait b were examined via linkage analysis, and loci D1, D2 and D4 were successfully isolated within the separated phenotypic groups P2 and P3.

Found at: doi:10.1371/journal.pone.0009714.s004 (0.05 MB DOC)

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Author Contributions

Conceived and designed the experiments: AJD RD FGH. Performed the experiments: AJD RC LED RD. Analyzed the data: AJD RC LED RD FGH. Wrote the paper: AJD RC LED RD FGH. Involved in the conception, design and implementation of the algorithm: FGH AJD RD. Involved in the analysis and interpretation of the data: FGH AJD LED RD. Involved in the drafting and final approval of the manuscript: FGH AJD RC LED RD. Involved in the implementation of the algorithm: RC. Involved in the analysis of the data: RC. Provided the data: LED.

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