

Complement Gene Expression Correlates with Superior Frontal Cortical Thickness in Humans

Dana M Allswede^{*,1}, Amanda B Zheutlin¹, Yoonho Chung¹, Kevin Anderson¹, Christina M Hultman², Martin Ingvar³ and Tyrone D Cannon^{1,4}

¹Department of Psychology, Yale University; ²Department of Medical Epidemiology and Biostatistics, Karolinska Institutet, Sweden; ³Department of Clinical Neuroscience, Karolinska Institutet, Sweden; ⁴Department of Psychiatry, Yale University, New Haven, CT, USA

Recent work suggests that genes encoding complement proteins that are active in the innate immune system may confer risk for schizophrenia by disrupting typical synaptic pruning in late adolescence. Alterations in the complement pathway may contribute to aberrant cortical thinning in schizophrenia prodromes and reduced prefrontal cortical thickness in chronic schizophrenia patients; however, this theory needs to be translated to humans. We conducted a series of analyses in a sample of adult Swedish twins enriched for schizophrenia ($N = 129$) to assess the plausibility of a relationship between complement gene expression and cortical thickness that could go awry in the etiology of schizophrenia. First, we identified that peripheral mRNA expression levels of two complement genes (C5, SERPING1) made unique contributions to the variance in superior frontal cortical thickness among all participants. Vertex-wise maps of the association between gene expression levels and thickness across the cortex suggested that this relationship was especially strong with SERPING1 in the superior frontal region, consistent with the pattern of disruption in cortical thickness observed in schizophrenia. Additional analyses identified that these genes are expressed in the human superior frontal cortex, that heritable genetic factors influence SERPING1 gene expression levels, and that these associations are observed regardless of case status. These findings provide initial evidence linking the complement system with cortical thinning in humans, a process potentially involved in the pathogenesis of schizophrenia.

Neuropsychopharmacology (2018) **43**, 525–533; doi:10.1038/npp.2017.164; published online 23 August 2017

INTRODUCTION

Investigations of individuals at clinically high risk for psychosis have found that the onset of the disorder is preceded by reductions in cortical gray matter thickness, particularly in the superior frontal cortex (Cannon *et al*, 2015). Post-mortem studies suggest that this may be influenced by excessive reduction of synaptic connections between cortical neurons (Bennett, 2011; Glausier and Lewis, 2013). This could lead to reduced integrity of the superior frontal cortex, disrupt cognitive processes that involve this region (Paus, 2005) such as source memory (Dobbins and Wagner, 2005), and ultimately contribute to the development of psychosis (Cannon, 2015). However, potential mechanisms underlying reductions in cortical synaptic density have not been clearly established. As both risk for schizophrenia (Sullivan *et al*, 2003) and measures of superior frontal cortical thickness (Goldman *et al*, 2013) are strongly influenced by genetic factors, examining genes associated with these phenomena may yield insight into underlying pathological processes of the disorder.

The strongest genomic region implicated in genome-wide association studies of risk for schizophrenia is the major histocompatibility complex locus (Ripke *et al*, 2014), which encodes many genes in signaling pathways involved in the immune response to pathogens (Horton *et al*, 2004). One immune pathway associated with this locus that has been increasingly linked with both synaptic pruning and risk for schizophrenia is the complement pathway (Sekar *et al*, 2016). This pathway is known to ‘tag’ both pathogens and damaged human cells for elimination by macrophage cells (Mayilyan *et al*, 2008), and emerging evidence from *in vitro* and rodent studies suggests that complement proteins also tags synapses for elimination (ie, synaptic pruning) in the developing visual cortex (Chu *et al*, 2010; Schafer *et al*, 2012). Synaptic pruning is a neurodevelopmental process that may peak during adolescence (Tamnes *et al*, 2010), coinciding with the typical onset of schizophrenia (Cannon *et al*, 2015). It is possible that overactivation of the complement pathway during this period could increase risk for schizophrenia via exacerbated synaptic elimination. In support of this theory, Sekar *et al* (2016) identified schizophrenia-associated genetic variants within the complement system that increased complement activation in mice, disrupting synaptic pruning. Though synaptic pruning cannot be directly measured in living humans, structural MRI measures of cortical thickness may be a somewhat sensitive proxy (Bourgeois and Goldman-Rakic, 1994; Glausier and Lewis, 2013). A link

*Correspondence: D Allswede, Department of Psychology, Yale University, 2 Hillhouse Ave., PO Box 208205, New Haven, CT 06520, USA, Tel: +1 517 614 3906, E-mail: dana.allswede@yale.edu
Received 20 December 2016; revised 10 July 2017; accepted 13 July 2017; accepted article preview online 31 July 2017

between the complement pathway and cortical thickness would provide a first step towards assessing the plausibility of a connection between genetic variants in the complement system and cortical thickness, with potential implications for understanding schizophrenia.

We assessed whether complement gene mRNA expression levels in peripheral blood leukocytes correlated with superior frontal cortical thickness in a sample of adult twins from Sweden enriched for schizophrenia cases. Further analyses were conducted to assess the plausibility of the proposed pathway, including mapping correlations between complement gene expression and thickness across the entire cortex, assessing complement gene expression in post-mortem human superior frontal cortical samples, examining whether heritable genetic factors influence variance in complement expression, and determining the influence of case status.

MATERIALS AND METHODS

Participants

The Swedish Twin Registry was used to identify a national cohort of twins born between 1940 and 1975 (see Supplementary Information). In total, 147 individuals who were interviewed, underwent an MRI scan, and provided blood samples that were assayed for gene expression were included in the present study. Fifteen participants were excluded due to MRI quality (see below) and three participants were excluded due to missing BMI data, yielding a total sample of 129 participants. Across the sample, 43% were male ($n = 56$), average age was 49.1 years (95% CI (29.2, 69.0)), and average BMI was 26.4 (17.0, 35.7). Twenty-two individuals were diagnosed with schizophrenia, 21 were unaffected schizophrenia co-twins, 13 were diagnosed with bipolar disorder, 13 were unaffected bipolar co-twins, and 60 were control twin pairs. As this theory is based on studies of psychosis (Sekar *et al*, 2016) and information about psychotic features was not available for bipolar participants, bipolar participants and their co-twins were included with controls for all primary analyses. This approach parallels Sekar *et al* (2016), in which bipolar cases and controls were grouped when testing for and identifying increased C4 expression in the dorsolateral prefrontal cortex of individuals with schizophrenia. To assess the influence of this grouping, secondary analyses were conducted with schizophrenia and

bipolar cases and co-twins grouped together and with bipolar cases and co-twins excluded entirely (see Supplementary Information). Results did not change appreciably.

RNA Microarray

Gene expression was assayed from peripheral blood mononuclear cells (PBMCs) using the Illumina Human WG6 v3.0 chip. RNA was extracted from PBMCs isolated from a 10 ml blood sample (ABI Tempus System). RNA aliquots of 100 ng/ μ l were analyzed by the UCLA Biological Samples Processing Core. Technical replicates were run on all samples using the Illumina Human WG6 v3.0 chip, and correlations between these samples for each person were evaluated. All samples had a useable quantity of RNA, and all subjects had good correlations between their technical replicate samples (ICCs: 0.902–0.998). Samples were pre-processed using the Illumina Bead Studio package. Technical replicates were averaged to produce one vector per person, and samples were log-transformed to ensure normalization of the sample distributions. The Illumina chip indexed a total of 24 526 markers. After rank normalization and background subtraction, 5967 probes were excluded based on low signal strength (not significantly greater than 0 at a Bonferroni-corrected $\alpha < 0.05$).

Gene Selection and Quality Control

The Gene Ontology (GO) Consortium (geneontology.org) was used to identify *a priori* genes involved in the complement system. A total of 28 unique human genes were annotated with the term ‘regulation of complement activation’, and mRNA levels of 22 of the 28 genes identified in GO were available from the chip assay after quality control (see Supplementary Information). Outliers (> 2 SD) gene expression values were winsorized (ie extreme values set to a value two standard deviations from the mean expression level) using the R package ‘robustHD’ (Alfonso, 2016). Winsorization did not significantly influence results (see Supplementary Information).

Magnetic Resonance Imaging

MRIs were acquired on a 1.5-T scanner (GE Healthcare, Little Chalfont, Buckinghamshire, UK) using a 3D T1-

Table 1 Demographic Characteristics of the Sample

	SZ ($n = 22$)	SZ co-twin ($n = 21$)	Control ($n = 86$)	Effect size	df	p
Age (years)	50.29 (31.65, 68.92)	48.77 (28.76, 68.77)	48.86 (28.53, 69.18)	$F = 0.19$	2126	0.826
Sex (% male)	14 (63.6%)	11 (52.4%)	31 (36.0%)	$\chi^2 = 6.25$	2	0.044
BMI	27.43 (19.48, 35.38)	25.30 (14.70, 35.89)	26.37 (17.01, 35.73)	$F = 1.12$	2126	0.328
Smoking (% yes)	11 (50%)	7 (33.3%)	23 (26.7%)	$\chi^2 = 4.40$	2	0.111
Antipsychotics (% yes) ^a	14 (63.6%)	1 (7.1%)	3 (4.3%)	$\chi^2 = 42.42$	2	0.001
Zygosity (% MZ)	8 (36.4%)	7 (33.3%)	44 (51.2%)	$\chi^2 = 3.10$	2	0.212
Superior frontal thickness (mm ³) ^b	2.64 (2.21, 3.07)	2.68 (2.37, 2.99)	2.64 (2.31, 2.98)	$F = 0.43$	2	0.654

95% confidence intervals listed in brackets.

^aMissing data: co-twin ($n = 14$), control ($n = 69$).

^bSee Supplementary Table 3 for superior frontal thickness of schizophrenia and bipolar cases, their co-twins, and controls.

weighted IRSPGR sequence acquired sagittally (TE = 6 ms, flip angle = 35°, and no interslice gap) in the Department of Clinical Neuroscience, Karolinska Institutet. The matrix size was 256 × 256 × 256 pixels, which corresponded to a resolution of 1 mm³. All MRI images were processed using FreeSurfer version 5.3 (<http://surfer.nmr.mgh.harvard.edu/>) (see Chung *et al*, 2015). Unrecoverable artifacts (eg motion, poor contrast) in scans led to the exclusion of 14 subjects (4 cases, 2 co-twins, 8 controls). An additional control was excluded due to abnormally large ventricles (potential undiagnosed neurological condition).

Statistical Analyses

Sample characteristics are compared by case status in Table 1. Expression levels did not differ by case status for any complement genes (see Supplementary Information). See Supplementary Information for a flow chart of analyses (Supplementary Information Figure S2).

Prescreening

There was not sufficient power to account for expression levels of all 22 complement genes simultaneously in a model predicting superior frontal cortical thickness. As we did not have an external replication sample for this data set, we needed to nominate predictors for further investigation in a simultaneous model. To protect against Type I error, a parameter reduction selection approach was taken at a univariate level to identify transcripts that were most consistently associated with superior frontal cortical thickness across 1000 subsets of the data. Subsets were created by randomly selecting 85% of participants ($N=105$) without replacement (ie, resampling). The association between expression levels of a gene and superior frontal cortical thickness was examined in each subset, accounting for age, gender, BMI and diagnostic status as covariates and family as a random factor in a linear mixed model. Associations (β) below the prescreening threshold of $p < 0.05$ were recorded as '1', and those above were counted as '0'. We tallied the number of associations, and anticipated chance associations in approximately 50/1000 subsets. Analyses were conducted using the linear and nonlinear mixed effects models (nlme) package in R (Pinheiro and Bates, 2000), and degrees of freedom were estimated using the Satterthwaite option. Assumptions of linear mixed models were not rejected (see Supplementary Information).

Simultaneous Model

The transcripts selected in the univariate approach could account for shared or unique variance in superior frontal cortical thickness. To assess this, transcripts identified in the prescreening phase were entered simultaneously into a linear mixed model predicting superior frontal cortical thickness in the entire sample ($N=129$), accounting for the same covariates listed above. Gene expression variables were z -scored to promote interpretability of regression statistics. Model performance was compared with a covariate-only model, and covariation between transcripts was assessed using the `vif.mer` package (source code available at <https://github.com/aufrank/R-hacks/blob/master/mer-utils.R>). The

influence of smoking, antipsychotic use, zygosity, and estimated total intracranial volume on model fit was assessed. For all hypothesis tests, a threshold of $p < 0.05$ was used. The change in R^2 between the full and covariate-only models was approximated using the multi-model inference (MuMIn) package (Barton, 2016).

Spatial Distribution

Relationships between each transcript of interest and cortical thickness were tested vertex-wise (ie, models predicting thickness at each vertex across the cortex, accounting for the same covariates) in the full sample ($N=129$). p -Values were mapped onto the cortical surface bilaterally at each vertex. Monte Carlo simulations were used across the surface and synthesized with a cluster-forming threshold of $p < 0.05$ (two-sided) (Hagler *et al*, 2006; Hayasaka and Nichols, 2003). To visualize effects below the stringent statistical threshold, associations were mapped onto the cortical surface with and without multiple comparison corrections.

Post-mortem Human Cortex

To assess if these genes are expressed in neural tissue, we determined whether there was non-zero gene transcription of the nominated complement genes within the superior frontal cortex (bi-hemispheric) ROI using six non-psychiatric post-mortem microarray expression data sets obtained from the open-access Allen Human Brain Atlas (Hawrylycz *et al*, 2012) (see Supplementary Information). Because multiple microarray probes exist for the selected complement genes, we chose the probe that most reliably reflected 'ground truth' expression (C5: A_23_P71855; SERPING1: A_23_P139123), assessed with RNA-Seq by Miller *et al* (2014). A gene was marked as expressed above baseline within a tissue sample if a two-sided t -test comparing expression to the corresponding background was significant at $p < 0.01$ and the difference between the background subtracted signal and the background was greater than 2.6 standard deviations away from the background mean (see data documentation at <http://human.brain-map.org>). Because microarray measures are typically used to gauge relative expression (Okoniewski and Miller, 2006), we also examined available RNA-Seq data to assess whether an absolute measure of transcript expression was above zero (Wang *et al*, 2009) (see Supplementary Information).

Heritability

For those mRNA probes found to be related to superior frontal cortical thickness, we used Mx to implement structural equation modeling comparing gene expression covariance in monozygotic (MZ) ($n=34$ pairs) to dizygotic (DZ) twin pairs ($n=50$ pairs) to assess the relative contribution of additive genetics (A), dominant genetics (D), common environment (C), and unique environment (E) (Plomin *et al*, 2013) (see Supplementary Information). To maximize power, all participants with available gene expression data were used for heritability estimates ($N=190$), regardless of availability of imaging data (see Zheutlin *et al*, 2016). We tested the significance of genetic

and shared environmental contributions to each model with χ^2 difference tests (ie, directly comparing models in which each of these parameters was present *versus* absent). Heritability of superior frontal cortical thickness was also assessed in all participants with usable structural MRI data ($N = 132$), which included 22 MZ and 26 DZ twin pairs.

Case Status

The influence of case status (schizophrenia, co-twin, control) on the observed associations between complement gene expression levels and superior frontal cortical thickness was further assessed by including an interaction term between gene expression levels and case status predicting superior frontal cortical thickness.

RESULTS

Prescreening

Associations within small samples are more likely to be driven by sample-specific characteristics, and thus may not always generalize to independent data sets. To reduce the likelihood of this possibility, we used a prescreening approach to nominate complement transcripts that were most consistently associated (threshold $p < 0.05$) with superior frontal cortical thickness in 1000 random subsets (85% of the sample (Figure 1). Expression levels of two genes were most consistently associated with superior frontal cortical thickness: C5 (813/1000) and SERPING1 (771/1000). The gene with the next highest number of associations, C8G, exhibited over 60% fewer associations (156/1000). A more stringent threshold of $p < 0.01$ was used to further assess the strength of these associations. Again, SERPING1 (185/1000) and C5 (138/1000) exhibited substantially more associations with superior frontal cortical thickness than C8G (2/1000). C5 and SERPING1 were selected for further examination.

Simultaneous Model

The transcripts selected in the univariate approach could account for shared or unique variance in superior frontal cortical thickness. To assess this, C5 and SERPING1 were

entered into the same linear mixed model predicting superior frontal cortical thickness in the entire sample ($N = 129$). The model that included C5 and SERPING1 gene expression predicted superior frontal cortical thickness significantly better than a model that only included covariates, *likelihood ratio* $\chi^2(2) = 13.344$, $p = 0.001$ (Table 2). Expression levels of C5 and SERPING1 accounted for an additional 7.4% of the variance in superior frontal cortical thickness when considering fixed covariates alone (conditional R^2) and an additional 0.5% of the variance when considering both fixed and random (ie, family ID) covariates (marginal R^2) (Nakagawa and Schielzeth, 2013). Both transcripts were significant in the model, suggesting that collinearity is not a major concern; this was corroborated by low VIF values of 1.02 (SERPING1) and 1.04 (C5). An increase in one standard deviation in C5 gene expression was associated with a decrease in 0.033 mm^3 of superior frontal cortical thickness (95% CI: $-0.058, -0.008$). An increase in one standard deviation in SERPING1 gene expression was associated with a decrease in 0.032 mm^3 of superior frontal cortical thickness (95% CI: $-0.057, -0.007$). Model fit was not significantly improved by the inclusion of C8G (runner-up in prescreening), smoking, antipsychotic use, zygosity, or estimated total intracranial volume (see Supplementary Information).

Table 2 Linear Mixed-Effects Model Predicting Superior Frontal Cortical Thickness ($N = 129$)

	B	SE	df	T	p
Sex (female)	0.016	0.028	80	0.57	0.574
Age	-0.009	0.001	41	-6.31	<0.001
BMI	-0.006	0.003	41	-2.27	0.029
Case status (SZ)	0.007	0.036	41	0.20	0.847
Case status (co-twin)	0.040	0.035	41	1.15	0.259
C5 (z-scored)	-0.033	0.013	41	-2.62	0.012
SERPING1 (z-scored)	-0.032	0.013	41	-2.50	0.016
Intercept	3.223	0.099	80	32.64	<0.001

AIC = -133.713; $R^2_m = 0.390$; $R^2_c = 0.576$.

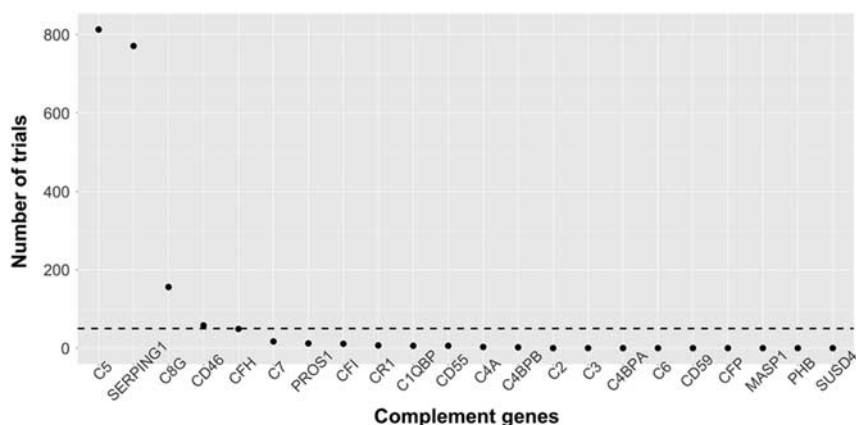


Figure 1 Number of resampled subsets (85% of sample) in which each gene was associated with superior frontal thickness below the prescreening threshold ($p < 0.05$), out of 1000 subsets. Dashed line represents number of expected associations due to chance with this threshold.

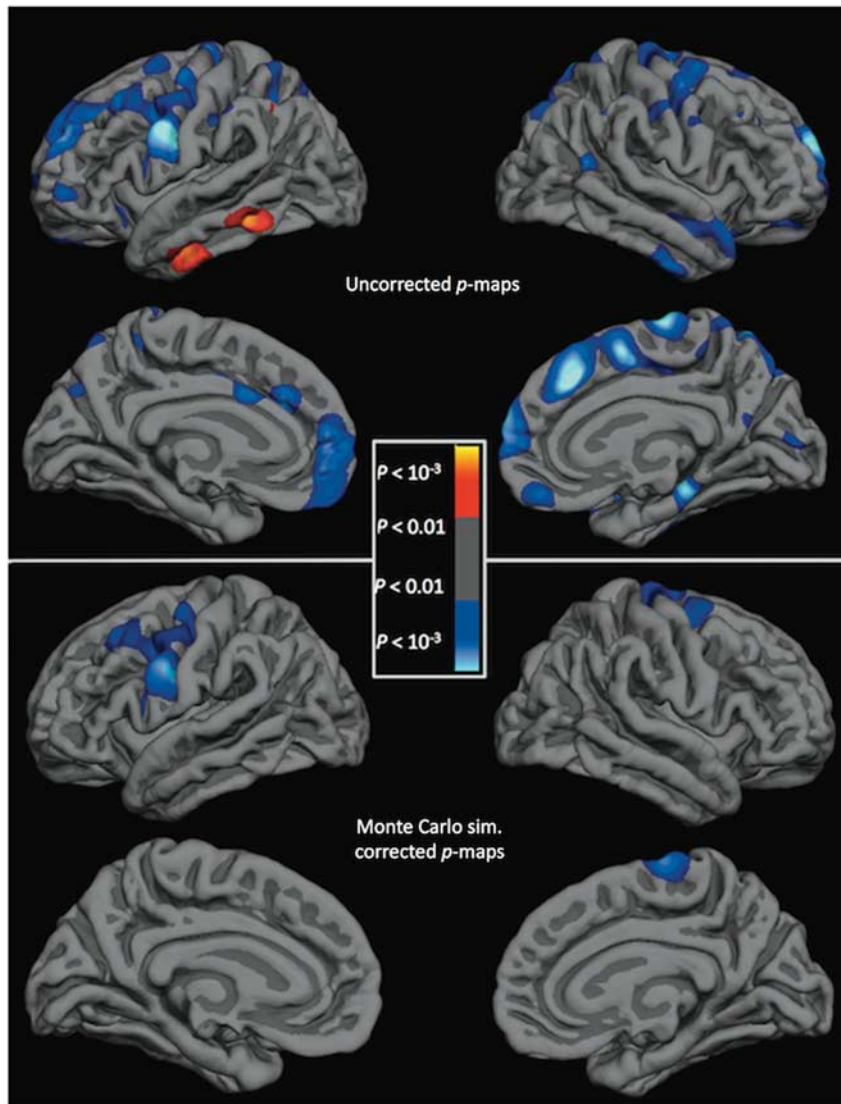


Figure 2 Statistical brain atlases plotting the association between SERPING1 gene expression levels and cortical thickness across the cortex. Cooler colors represent a negative association between gene expression levels and cortical thickness. Sim., simulation.

Spatial Distribution

C5 and SERPING1 could be associated with cortical thickness throughout the brain or predominantly with the superior frontal cortex. To assess this, relationships between expression levels and cortical thickness were tested vertex-wise in the full sample. Significant negative correlations with SERPING1 gene expression levels and cortical thickness (Figure 2) survived the whole-brain analysis with cluster-based multiple correction in clusters covering the superior frontal cortex (cluster size = 11.7 mm², clusterwise $p = 0.017$) and precuneus (7.1 mm², $p = 0.040$) in the left hemisphere and the superior frontal cortex (8.6 mm², $p < 0.001$), rostral middle frontal cortex (46.3 mm², $p = 0.004$), and insula (38.9 mm², $p = 0.001$) in the right hemisphere. Significant negative correlations with C5 gene expression levels and cortical thickness (Figure 3) survived correction in clusters covering the precentral gyrus in both the left (54.4 mm², $p < 0.001$) and right (22.9 mm², $p = 0.014$) hemispheres. We

also display the uncorrected statistical significance maps of the relationship between cortical thickness and SERPING1 and C5 expression, with a nominal $p < 0.05$ threshold. In addition to the regions previously identified, SERPING1 levels exhibited a negative correlation with thickness in the precentral and postcentral gyrii, and across the temporal gyrii in the right hemisphere (Figure 2). C5 levels were additionally negatively correlated with thickness in the middle frontal cortex in the left hemisphere and the superior frontal cortex in both hemispheres, and were positively correlated with the middle and inferior temporal gyrii in the left hemisphere (Figure 3).

Post-mortem Human Cortex

Not all genes expressed in peripheral blood leukocytes are expressed in the human brain, nor is gene expression consistent across the human brain (Sullivan *et al*, 2006). We examined whether SERPING1 and C5 were expressed in

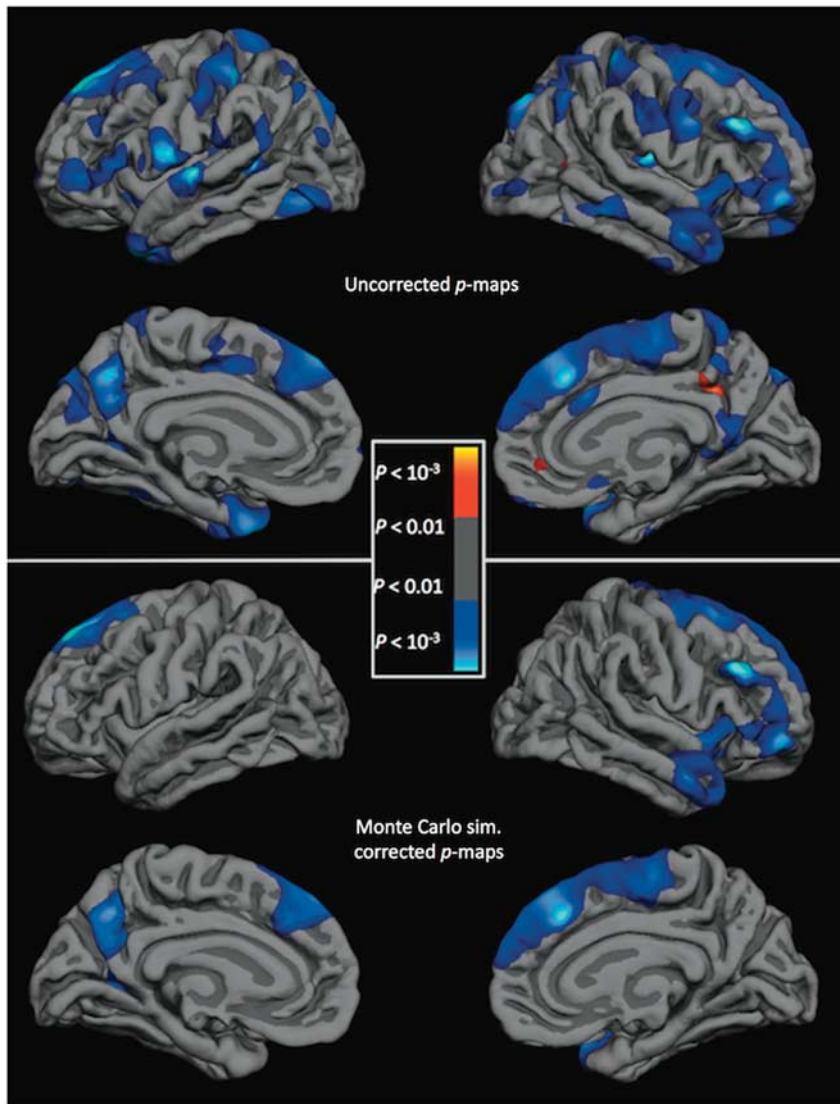


Figure 3 Statistical brain atlases plotting the association between C5 gene expression levels and cortical thickness across the cortex. Cooler colors represent a negative association between gene expression levels and cortical thickness. Sim., simulation.

Table 3 Number of Superior Frontal Cortical Samples from Each Donor with Microarray Complement Gene Expression Levels Above Baseline and Average Gene Expression across the Sample

	Superior frontal samples (#)	SERPING1 (# samples expressed)	SERPING1 expression ratio	C5 (# samples expressed)	C5 expression ratio
Donor 10021	26	26	1	25	0.96
Donor 9861	38	30	0.79	29	0.76
Donor 12876	12	12	1	10	0.83
Donor 14380	15	15	1	15	1
Donor 15496	19	19	1	19	1
Donor 15697	19	19	1	19	1
Average			0.97		0.93

post-mortem superior frontal cortical samples contained in the Allen Human Brain Atlas (Hawrylycz *et al*, 2012). Using microarray data, the mean percentage of samples with non-zero expression of complement genes in superior frontal cortex

compared with background expression levels was 97% and 93% for SERPING1 and C5, respectively (Table 3). RNA-Seq data confirmed non-zero expression levels of SERPING1 and C5 in all available samples (see Supplementary Information).

Heritability

Variance in gene expression and cortical thickness can be predominantly influenced by inherited genetic factors, common environmental factors, or both factors. Heritability models were used to assess the relative influence of these factors on variance in SERPING1 and C5 expression. The best fitting model for SERPING1 included a genetic component of 46%, indicating moderate heritability of variance in expression levels (Table 4). For C5, the best fitting model included a shared environment component of 64%, indicating moderate influence of the shared environment. The best fitting model for superior frontal thickness included an additive genetic (A) component of 65%, indicating high heritability. Heritability models for C5 and SERPING1 did not exhibit good fit to the data, but were best described by the selected models (see Supplementary Information).

Case Status

There was not a significant main effect of case status (Table 2) or an interaction of case status with C5 or SERPING1 (data not shown) predicting superior frontal cortical thickness in the simultaneous model.

DISCUSSION

We have provided preliminary evidence that complement gene expression may be associated with superior frontal cortical thickness in humans. Expression level of two nominated complement genes (C5, SERPING1) contributed uniquely to prediction of superior frontal cortical thickness across diagnostic groups. Vertex-wise analyses suggested that SERPING1 expression was most strongly associated with this region of the cortex. Evidence for moderate heritability of variance in SERPING1 expression levels and confirmation that these genes are expressed in the human superior frontal cortex further support the plausibility of a mechanistic link between genetic variants influencing the complement system and cortical thickness in humans.

The transcripts associated with superior frontal cortical thickness in our sample included both an inhibitor (SERPING1) and an activator (C5) of the complement system. SERPING1 encodes the plasma protease C1 inhibitor (C1-INH), a potent anti-inflammatory protein that inhibits activation of the complement system by binding to pro-inflammatory complement proteins (eg C1q, C3b) (Davis *et al*, 2010). Intriguingly, C1q and C3b have been implicated in synaptic pruning (Orsini *et al*, 2014). The observed negative association between SERPING1 mRNA levels and cortical thickness is counterintuitive, and could reflect an unmeasured compensatory process. In contrast, C5 encodes the C5 protein, which is cleaved into two active components: C5a, a potent inflammatory protein that recruits immune cells (Woodruff *et al*, 2010) and C5b, which initiates the formation of the membrane attack complex leading to cell rupture and death (Orsini *et al*, 2014).

The observed associations between C5 and SERPING1 expression and superior frontal cortical thickness cannot address causality, but represent a first step towards assessing whether complement-mediating synaptic pruning may occur

Table 4 Heritability Estimates for Complement Gene Expression

Phenotype	Illumina probe	Model	Heritability
C5	ILMN_I1746819	CE	0.6355 (C)
SERPING1	ILMN_I1670305	AE	0.4669 (A)
Superior frontal cortical thickness	–	AE	0.6547 (A)

Note: C = shared environment; A = additive genetics (primary influence on gene expression levels identified by heritability analyses).

in the human prefrontal cortex. To further test this theory, the assumptions underlying these preliminary analyses need to be assessed and expanded upon. First, the correlation between expression levels of SERPING1 and C5 and superior frontal thickness could reflect a chance fluctuation in expression levels, a third variable effect, or the trace of earlier development. Gene expression levels in PBMCs tend to be relatively consistent within individuals across a period of months (Radich *et al*, 2004). However, longitudinal assessments of complement gene expression are needed. Complement expression and cortical thickness could both be influenced by an unmeasured third variable, which future studies could assess (see Supplementary Information). Alternatively, complement expression in middle age may reflect individual differences in complement activity earlier in development. If complement proteins interact differently with specific cell types during neurodevelopment, they could differentially influence thickness in distinct cortical regions. In adulthood, associations between expression levels and thickness in those regions could still be observed cross-sectionally. From this perspective, it is intriguing that our SERPING1 association maps correspond closely with cortical maps of increased rates of thinning in adolescents who contract schizophrenia (Cannon *et al*, 2015). This association could be further elucidated with longitudinal studies of complement expression and cortical thickness in adolescents and additional investigation of these complement proteins in neurodevelopment.

A second assumption is that complement expression levels in PBMCs reflect complement expression levels in microglia. Microglia are particularly similar in function to peripheral monocytes, and gene expression patterns between the two may be relatively consistent (Saijo and Glass, 2011) (see Supplementary Information). However, peripheral immune activation can affect brain function via other pathways, including stimulation of the vagus nerve by peripheral immune proteins, transport of immune proteins across the blood brain barrier, and peripheral lymphocytes entering the brain (O'Connor *et al*, 2014). Additional work is needed to investigate these pathways.

Third, this theory suggests that the complement-mediated synaptic pruning contributes to reductions in cortical gray matter thickness in adolescence. However, the extent to which adolescence is a period of synaptic pruning, and if this contributes to observed cortical thinning (Gogtay *et al*, 2004), is debated (see Supplementary Information). Other neurodevelopmental changes that could contribute to cortical gray matter loss include myelination and gains in white matter volume (Catts *et al*, 2013). Additionally, the majority of research on the role of complement in synaptic

pruning has been focused on the developing visual cortex (Chu *et al*, 2010; Schafer *et al*, 2012; Sekar *et al*, 2016). Further work is needed to confirm that the complement system is involved in synaptic pruning in the human prefrontal cortex during adolescence.

Fourth, this theory suggests that dysregulation of the complement system could result in an accelerated rate of cortical synaptic pruning, causing vulnerable individuals to cross below a critical threshold of synaptic density needed to support cognitive functioning and leading to psychosis (Cannon, 2015). The lack of influence of case status suggests that the association between complement gene expression and cortical thickness could reflect normative brain development, rather than a disease or medication effect. However, case status differences may be more apparent during adolescence, in which pruning is likely actively taking place. Longitudinal studies in adolescents at different levels of risk for schizophrenia may clarify whether complement system activity is associated with greater changes in superior frontal thickness in at-risk individuals.

To increase the likelihood of identifying reproducible signal in our relatively small sample, we used a resampling procedure to identify individual complement genes associated with superior frontal cortical thickness in many random sample replicates. As a second check for Type I error, we conducted a parallel approach in which we prescreened genes using 1000 bootstrapped samples. These analyses yielded the same conclusion (see Supplementary Information). The spatial analyses may also be considered a reliability check (see Supplementary Information). Though not a focus of our hypotheses, C5 expression levels correlated with thickness of the precentral gyrus and survived correction in the spatial analysis, suggesting that this is likely a robust association. Replication in independent samples is needed to confirm and further assess these associations.

These analyses are vulnerable to the inherent limitations of data acquisition techniques and data availability. For example, we were not able to account for some factors that may influence gene expression and microarray analyses (eg, time of blood draw, inflammatory and fasting status, sample cell type composition) (Whitney *et al*, 2003). We could not follow-up on identified complement targets in PBMCs or confirm expression with quantitative PCR in the Swedish sample. We did not have information on time of blood draw, isolation and storage of samples, sample quality, or cortical thickness for the Allan Brain Atlas post-mortem samples. The slightly older imaging equipment (ie 1.5T scanner, 1 mm³ resolution) used may have very slightly influenced measures of cortical thickness (Gronenschild *et al*, 2012; Han *et al*, 2006).

This study identified initial evidence suggesting that expression levels of SERPING1, a complement system gene, are associated with superior frontal cortical thickness in humans. These findings are a first step towards establishing the plausibility of a pathway linking the complement system with cortical thickness in humans. Further research is needed to confirm and expand upon the observed associations and assess whether these pathways may play a role in the etiology of schizophrenia. If so, this could provide novel targets for the prevention of schizophrenia.

FUNDING AND DISCLOSURE

TDC is a consultant to the Los Angeles County Department of Mental Health and Boehringer Ingelheim Pharmaceuticals. DMA and KA's work was funded by NSF Graduate Research Fellowships (DGE-1122492). The remaining authors declare no potential conflict of interest.

ACKNOWLEDGMENTS

We thank the study participants, research staff members, and the Swedish Board of Health and Welfare. We also thank Avram Holmes, David Glahn, and Sebastian Therman for their comments on drafts of the manuscript. We thank the National Institute of Mental Health (RO1 MH052857, Principal Investigator: TDC) and the Stockholm County Council (ALF 20100305) for financial support.

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Supplementary Information accompanies the paper on the Neuropsychopharmacology website (<http://www.nature.com/npp>)