



Published in final edited form as:

Am J Psychiatry. 2013 December 1; 170(12): . doi:10.1176/appi.ajp.2013.13020234.

Microvascular Abnormality in Schizophrenia as Shown by Retinal Imaging

Madeline H. Meier, Ph.D.^{1,2,*}, Idan Shalev, Ph.D.^{1,3,*}, Terrie E. Moffitt, Ph.D.^{1,2,3,4,5}, Shitij Kapur, Ph.D.⁶, Richard S.E. Keefe, Ph.D.⁴, Tien Wong, Ph.D.^{7,8,9}, Daniel W. Belsky, Ph.D.^{3,10}, HonaLee Harrington, B.S.^{1,3,4}, Sean Hogan, MSW¹¹, Renate Houts, Ph.D.^{1,3,4}, Avshalom Caspi, Ph.D.^{1,2,3,4,5}, and Richie Poulton, Ph.D.¹¹

¹Department of Psychology and Neuroscience, Duke University, Durham, NC, USA ²Duke Transdisciplinary Prevention Research Center, Center for Child and Family Policy, Duke University, Durham, NC, USA ³Institute for Genome Sciences & Policy, Duke University, Durham, NC, USA ⁴Department of Psychiatry and Behavioral Sciences, Duke University Medical Center, Durham, NC, USA ⁵Social, Genetic, and Developmental Psychiatry Centre, Institute of Psychiatry, King's College London, UK ⁶Department of Psychosis Studies, Institute of Psychiatry, King's College London, UK ⁷Singapore Eye Research Institute, Yong Loo Lin School of Medicine, National University of Singapore, Singapore ⁸Department of Ophthalmology, Yong Loo Lin School of Medicine, National University of Singapore, Singapore ⁹Centre for Quantitative Medicine, Duke-NUS Graduate Medical School, Singapore ¹⁰Center for Aging and the Study of Human Development, Duke University Medical Center, Durham, NC USA ¹¹Dunedin Multidisciplinary Health and Development Research Unit, Department of Preventive and Social Medicine, School of Medicine, University of Otago, Dunedin, New Zealand

Abstract

Objective—Retinal and cerebral microvessels are structurally and functionally homologous, but, unlike cerebral microvessels, retinal microvessels can be noninvasively measured *in vivo* via retinal imaging. Here we test the hypothesis that individuals with schizophrenia show microvascular abnormality and evaluate the utility of retinal imaging as a tool for future schizophrenia research.

Methods—Participants were members of the Dunedin Study, a population-representative cohort followed from birth with 95% retention. Study members underwent retinal imaging at age 38 years. We assessed retinal arteriolar and venular caliber for all members of the cohort, including individuals who developed schizophrenia.

Results—Study members who developed schizophrenia were distinguished by wider retinal venules, suggesting microvascular abnormality reflective of insufficient brain oxygen supply. Analyses that controlled for confounding health conditions suggested that wider retinal venules are not simply an artifact of co-occurring health problems in schizophrenia patients. Wider venules were also associated with a dimensional measure of adult psychosis symptoms and with psychosis symptoms reported in childhood.

Conclusions—Findings provide initial support for the hypothesis that individuals with schizophrenia show microvascular abnormality. Moreover, results suggest that the same vascular

Correspondence to: T. E. Moffitt. Mail: Suite 201 Grey House, 2020 West Main Street, Duke University Box 104410, Durham, NC 27708, USA. terrie.moffitt@duke.edu. Telephone: 919-684-5831. Fax:919-684-5912.

*These authors contributed equally and are listed in alphabetical order.

The authors have no conflicts of interest to report.

mechanisms underlie subthreshold symptoms and clinical disorder and that these associations may begin early in life. These findings highlight the promise of retinal imaging as a tool for understanding the pathogenesis of schizophrenia.

Retinal imaging is a simple, non-invasive technology for assessing microvascular abnormalities in living individuals diagnosed with schizophrenia. Cerebrovascular abnormalities have been discussed as a pathological feature in schizophrenia, beginning with Meynert (1, Supplemental Figure 1). Advances in fundus photography (photographing the interior surface of the eye) and retinal image analysis now allow for the accurate quantitative assessment of the condition of small retinal blood vessels in large population-based samples (2). Retinal microvessels can be used to gauge the condition of the cerebral microvessels, because retinal and cerebral blood vessels share similar embryological origins and are homologous in structure and function (3). Of particular interest is the caliber of the retinal arterioles and venules (i.e., the size of the internal space of these microvessels), as they are the most commonly studied retinal parameters in relation to cerebrovascular disease and, unlike other retinal parameters, they are dimensionally distributed in the general population. Prior research has shown that narrower arterioles are linked with hypertension (4, 5), while wider venules predict risk of stroke, dementia, and other cerebrovascular diseases (2, 5–11). Wider venules are thought to reflect cumulative structural damage to the microvasculature and may indicate problems with the oxygen supply to the brain (2, 12). Thus, retinal venular caliber is a promising target for the first investigation of microvascular abnormality in living individuals diagnosed with schizophrenia. The purpose of the present study was to test the hypothesis that individuals with schizophrenia are distinguished by wider retinal venules and to evaluate the utility of retinal imaging as a tool for schizophrenia research.

Methods

Participants

Participants are members of the Dunedin Multidisciplinary Health and Development Study, a longitudinal investigation of the health and behavior of a complete birth cohort of consecutive births between April 1, 1972, and March 31, 1973, in Dunedin, New Zealand. The cohort of 1,037 children (91% of eligible births; 52% boys) was constituted at age 3 years. Cohort families represent the full range of socioeconomic status in the general population of New Zealand's South Island and are primarily white. Follow-up assessments were conducted at ages 5, 7, 9, 11, 13, 15, 18, 21, 26, 32, and most recently 38 years, when 95% of the 1,007 living study members underwent assessment in 2010–2012.

Schizophrenia

In the Dunedin study, schizophrenia was assessed at ages 21, 26, 32, and 38. We previously described the schizophrenia cases up to age 32 (13–15). Here we update this information with data from age 38. Full diagnostic criteria for schizophrenia were assessed with the Diagnostic Interview Schedule (DIS) (16, 17) at each age following the Diagnostic and Statistical Manual of Mental Disorders (DSM) (18, 19). To enhance the validity of our research diagnosis, we implemented special steps. First, we required hallucinations (which are not substance use-related) in addition to at least two other positive symptoms. This requirement is stricter than DSM-IV(19), which does not require hallucinations, although requiring them has been shown to reduce over-diagnosis (20). Second, because self-reports can be compromised by poor insight in schizophrenia, we required objective evidence of impairment resulting from psychosis, as reported by informants and as recorded in the study's life-history calendars, which document continuous histories of employment and relationships. Third, in our research, the DIS is administered by experienced clinicians, not lay interviewers. These clinicians record detailed case notes. Staff also rate observable

symptoms manifested in affect, grooming, and speech during the full day participants spend at our research unit. Fourth, participants bring their medications, which are classified by a pharmacist. Fifth, informants report study members' positive and negative psychotic symptoms via postal questionnaires. Finally, study members' parents were interviewed about their adult child's psychotic symptoms and treatment as part of the Dunedin Family Health History Study (2003–2005). These data, accumulated in the Dunedin study at ages 21, 26, 32, and 38, were compiled into dossiers reviewed by 4 clinicians to achieve best-estimate diagnoses with 100% consensus. By age 38, 2% of the cohort ($n=20/1007$) met criteria for schizophrenia and had, according to the multi-source information collected in the dossiers, been hospitalized for schizophrenia (totaling 1,396 days of psychiatric hospitalization according to official New Zealand administrative record searches) and/or prescribed antipsychotic medications. An additional 1.7% ($n=17$) met all criteria, had hallucinations, and suffered significant life impairment but had not yet, to our knowledge, been treated specifically for psychotic illness. Together, these two groups constituted a total of 37 cases of diagnosed schizophrenia in the cohort. Of these 37 cases, 4 died before the age-38 retinal vasculature assessment and 2 refused to participate at 38. An additional 4 cases were excluded from the present report due to pregnancy, a congenital health condition, or ungradeable retinal images, leaving an effective group size of $n=27$ (55% male) for this article.

The cohort's 3.7% prevalence rate of schizophrenia is high and should be understood in the context of the following 3 methodological aspects of our study. First, our birth cohort, with a 95% participation rate, lets us count psychotic individuals overlooked by prior surveys because individuals with psychotic disorders often refuse to participate in surveys and/or die prematurely (21), and surveys often exclude homeless or institutionalized individuals with psychosis. Second, our cohort members are all from one city in the South Island of New Zealand. It is possible, given geographical variation in rates of schizophrenia (22–24), that the prevalence of schizophrenia is somewhat elevated there. No data exist to compare prevalence rates of schizophrenia in New Zealand to other countries, but the very high prevalence of suicide in NZ could be consistent with an elevated prevalence of severe mental health conditions (25). Third, our research diagnoses did not make fine-grained distinctions among psychotic disorders (e.g., schizophrenia vs. schizoaffective disorder). Thus, those diagnosed with schizophrenia here might not be considered by all clinicians to have schizophrenia. We note, however, that over half of those we diagnosed were confirmed by treatment. Moreover, etiological mechanisms appear to be similar across the continuum of psychosis (26).

Comparison groups

Study members who did not meet criteria for schizophrenia were classified into the comparison groups detailed below. We selected these medical and psychiatric comparison groups because (a) these conditions occur more commonly in individuals diagnosed with schizophrenia than in the general population, in this cohort and in other research (27, 28), and (b) hypertension, diabetes, and smoking have been associated with vessel caliber in previous retinal imaging studies (2, 5).

Hypertension at 38 ($n=110$)—Hypertension (29) was defined as systolic BP ≥ 140 mm Hg or diastolic BP ≥ 90 mm Hg (30). Prevalence=19% in the schizophrenia group and 12% in the rest of the cohort. *Pre-diabetes/diabetes at 38 ($n=154$)*. Pre-diabetes and diabetes were defined per American Diabetes Association: 5.7%–6.5% glycated hemoglobin (HbA1c) levels for pre-diabetes, and 6.5% or higher HbA1c levels for diabetes (31). Prevalence=29% in the schizophrenia group and 18% in the rest of the cohort.

Persistent tobacco dependence (n=210)—Cohort members who diagnosed with DSM (18, 19) tobacco dependence on two or more occasions between ages 18–38 were classified in the persistent tobacco-dependence group. Prevalence=56% in the schizophrenia group and 23% in the rest of the cohort.

Persistent depression (n=188)—Cohort members who diagnosed with DSM (18, 19) depression on two or more occasions between ages 18–38 were classified in the persistent-depression group. Prevalence=70% in the schizophrenia group and 21% in the rest of the cohort.

Healthy controls (n=412) lacked the aforementioned health problems.

Psychosis symptoms

Childhood psychosis symptoms were assessed at age 11 for 789 cohort members seen at the Dunedin Unit (those assessed at school unfortunately did not see the child psychiatrist), using the Diagnostic Interview Schedule for Children (DISC-C) (32). As previously described (13), children responded to 4 questions (Supplemental Table 1). Responses were summed, and children with scores of '0', '1', and '>2' were grouped as having no, weak, or strong symptoms, respectively.

Adulthood psychosis symptoms were assessed with the DIS (16, 17) at ages 21, 26, 32, and 38. Study members reported on 8 symptoms of hallucinations and delusions (Supplemental Table 1), which were summed into a single scale at each age. These 4 scales were used in a confirmatory factor analysis to estimate a continuous latent variable representing dimensional liability to adult psychosis across ages 21–38. Because the 4 scales had positive skew, they were treated as ordinal, with values ranging from 0–8. Standardized factor loadings for the age 21, 26, 32, and 38 psychosis symptom scales were 0.60, 0.87, 0.81, and 0.83, respectively. The model fit for this single latent variable was excellent ($\chi^2 = 2.13$, $p = .345$, root mean square error of approximation [RMSEA]: 0.008 (95% CI: 0.000, 0.065); Comparative Fit Index [CFI]: 1.00; Tucker-Lewis Index [TLI]: 1.00).

Assessment of retinal vessel caliber

As previously described (33), digital fundus photographs were taken at the Research Unit after 5 minutes of dark adaptation. The same camera (Canon NMR-45 with a 20D SLR backing, Japan) was used for all photographs, thereby preventing artifactual variation from different cameras. Both the left and right eyes were photographed, and the two eyes were averaged. Retinal photographs were graded at the Singapore Eye Research Institute, National University of Singapore, using semi-automated computer software (Singapore I Vessel Assessment [SIVA], software version 3.0). Trained graders, masked to participant characteristics, used the SIVA program to measure the retinal vessel diameters according to a standardized protocol with high inter-grader reliability (34). Caliber (or diameter) denotes the size of the lumen, which is the internal space of the vessel. Measurements were made for arterioles and venules where they passed through a region located 0.50–2.00 disk diameters from the optic disk margin (Figure 1) (34). Vessel calibers were based on the six largest arterioles and venules passing through this region and were summarized as central retinal artery equivalent (CRAE) and central retinal vein equivalent (CRVE) using the revised Knudtson-Parr-Hubbard formula (34, 35). Of 938 study members with retinal images, only 7 could not be graded because the images were either too dark or not centered on the optic disk. An additional 9 study members were excluded from analyses due to pregnancy. This left 922 study members with retinal vessel data. Arteriolar and venular calibers were normally distributed within our population-representative cohort. The mean arteriolar caliber among the 922 study members was 137.33 measuring units (SD=10.86, Median=137.30,

Range=105.66, 179.47), and the mean venular caliber was 196.20 measuring units (SD=14.83, Median = 195.51, Range=141.07, 245.68).

Statistical analysis

Prior to all analyses, arteriolar and venular caliber were each adjusted for the effect of the other vessel, as recommended (2, 36), in order to isolate the unique effects for each vessel and adjust for any potential effects of refractive errors (37). Vessel calibers were then standardized on the population-representative cohort (M=0.00, SD=1.00). Sex was included as a covariate in all analyses.

Our analyses proceeded as follows. First, to replicate previous studies documenting associations between vessel caliber, hypertension, diabetes, and smoking, we used ANOVA to compare mean vessel caliber for each group to a group of healthy individuals (i.e., a group with none of the aforementioned conditions). Next, to test our hypothesis that individuals with schizophrenia are distinguished specifically by wider venules, we compared venular and arteriolar caliber among individuals with schizophrenia to individuals with hypertension, pre-diabetes/diabetes, persistent tobacco dependence, and persistent depression. As an additional check to ensure that an association between schizophrenia and wider venules could not be explained by the collective effects of these conditions, we conducted a multivariate regression, predicting venular caliber from schizophrenia while controlling for all of these conditions simultaneously. In this multivariate regression, we treated blood pressure (systolic and diastolic) and pre-diabetes/diabetes (i.e., glycated hemoglobin) as continuous variables.

Second, to test our hypothesis that wider venular caliber is associated with adult psychosis symptoms, we obtained the parametric correlation between latent dimensional liability to adult psychosis and venular caliber.

Third, to test our hypothesis that wider venular caliber is associated with child psychosis symptoms, we obtained the polychoric correlation between childhood psychosis symptoms, a three-level ordinal variable, and venular caliber.

Results

Do study members who developed schizophrenia have wider retinal venular caliber?

Table 1 shows mean venular and arteriolar calibers at age 38 for cohort members who developed schizophrenia (n=27), as well as all comparison groups. Means reflect effect sizes for how different each group is from the cohort norm. Differences between pairs of groups can also be interpreted as effect sizes. Effect sizes of 0.20, 0.50, and 0.80 reflect small, medium, and large effects, respectively (38).

The means show four noteworthy findings. First, replicating previous retinal imaging studies (2, 5), study members with hypertension, pre-diabetes/diabetes, and tobacco dependence all had wider venules than healthy study members. Second, study members diagnosed with schizophrenia had much wider venules at age 38 than all other groups, except individuals with hypertension. Third, individuals with schizophrenia had wider venules than a psychiatric control group with persistent depression. Fourth, unlike the schizophrenia group, the hypertension group also had much narrower arterioles than all other groups. This is consistent with prior research linking narrower arterioles specifically to hypertension (2, 5) and suggests that hypertension cannot explain the wider venules among the schizophrenia group.

Schizophrenia was also associated with wider venular caliber in a multiple regression model, adjusted for arteriolar caliber and sex ($\beta=0.61$, $SE = 0.19$, $t(920)=3.14$, $p=.002$), and this association remained statistically significant after also controlling for systolic blood pressure, diastolic blood pressure, glycated hemoglobin, persistent tobacco dependence, and persistent depression ($\beta=0.49$, $SE=0.19$, $t(915) = 2.57$, $p=.011$). Wider venules among individuals diagnosed with schizophrenia could also not be explained by current antipsychotic medication use; venular caliber for the subset of individuals diagnosed with schizophrenia who did not take antipsychotic medication in the year prior to retinal imaging ($n=22$) was even wider ($M=0.69$, $SD=1.15$). Results were similar for those who had never ($n=12$, $M=0.63$, $SD=1.19$) versus ever ($n=15$, $M=0.56$, $SD=1.17$) received treatment specifically for psychotic illness.

Figure 2 shows the distribution of venular caliber (adjusted for arteriolar caliber and sex and standardized on the population-representative cohort) for each group. This figure shows that the distribution for venular caliber in the schizophrenia group was shifted to the right, reflecting wider venules. For example, 70% of the schizophrenia group members had venular calibers wider than the cohort mean of $Z=0.00$, compared to only 40% of the healthy group ($\chi^2 = 9.91$, $p=.002$). This nonparametric test does not depend on extreme outlier observations. Thus, a statistically significantly larger proportion of individuals with schizophrenia had wider than average venules (regardless of outliers).

Is retinal venular caliber associated with liability to adult psychosis?

Approximately one third of the entire population endorsed one or more psychotic symptoms in adulthood, which were aggregated into a latent liability score. The association between this latent liability to adult psychosis and venular caliber, adjusted for arteriolar caliber and sex, was 0.15, $p<.001$.

Is retinal venular caliber associated with childhood psychosis symptoms?

Of the 13 children who had significant psychotic symptoms at age 11, only 3 were diagnosed with adult schizophrenia. The association between these childhood psychosis symptoms (age 11) and venular caliber (age 38), adjusted for arteriolar caliber and sex, was 0.13, $p=.015$ (Figure 3).

Discussion

In our population-based birth cohort, study members who developed schizophrenia showed retinal microvascular abnormality, specifically wider venular caliber. Our analyses that controlled for confounding health conditions suggest the possibility that wider venules may be a distinguishing feature of schizophrenia and not simply an artifact of co-occurring health problems in schizophrenia patients, as the widest venules were observed for the schizophrenia group. Moreover, wider venules were associated with a greater dimensional liability to experience psychosis symptoms in adulthood. This is consistent with theory and research suggesting that the same mechanisms underlie subthreshold symptoms and clinical disorder (26). Finally, wider venules were associated with childhood psychosis symptoms at age 11 years, which may suggest that pathological vascular mechanisms leading to the association between schizophrenia and wider venules operate from early life.

The specific pathophysiological mechanisms underlying wider retinal venular caliber are not yet entirely understood (2). Wider venules have been shown to be associated with inflammation (39–42), endothelial dysfunction (42, 43), and hypoxia/ischemia (12), for example. Notably, inflammation (44–46), endothelial dysfunction/dysregulation of the nitric oxide signaling pathway (47, 48), and hypoxia/ischemia (49) are all seen in schizophrenia.

Genetic factors also influence retinal venular caliber (50–52). Interestingly, genetic linkage regions for venular caliber are implicated in endothelial function and vasculogenesis (50, 51). Thus, some individuals may have a genetic propensity to develop wider venules. It is currently unclear whether venular caliber plays a causal role in the development of schizophrenia or whether it might represent an associated epiphenomenon. Nevertheless, it has been hypothesized that wider venules reflect, in part, cumulative structural damage to the microvasculature (for example, from inflammation and/or endothelial dysfunction) and indicate problems with the oxygen supply to the brain (2, 12).

While our study is the first to investigate the microvasculature in living schizophrenia patients, our findings converge with a growing body of literature that implicates the vasculature in schizophrenia. First, individuals with schizophrenia are at increased risk of developing cardiovascular disease (27), and recent evidence suggests that the same genes influence both schizophrenia and risk for cardiovascular disease (53). Second, a large proportion of replicated candidate genes for schizophrenia are regulated by hypoxia and/or are expressed in the vasculature (49, 54). Third, altered cerebral blood flow and blood volume as well as mitochondrial dysfunction in schizophrenia have all been hypothesized to arise from vascular abnormalities (55–57). Fourth, individuals with schizophrenia show impaired vasodilation (58–60) and abnormalities of the nailfold capillary bed (61). Fifth, post-mortem analysis of the brains of schizophrenia patients have revealed evidence of atypically simplified angioarchitecture and lack of normal arborization of vessels (62), ultrastructural capillary damage (63), and molecular alterations of the cerebral microvasculature (64). Taken together, evidence of vascular involvement in schizophrenia is accumulating, and the long-standing hypothesis of vascular pathology in schizophrenia (Supplemental Figure 1) highlights the need for an innovative method to assess the microvasculature in living schizophrenia patients.

Results of our study should be interpreted in the context of limitations. First, the prevalence of schizophrenia in our cohort is high. Given the lack of clear boundaries between mental health and illness, it is possible that our cohort members diagnosed with schizophrenia might not be considered by all clinicians to have schizophrenia. However, over half of the members of our schizophrenia group had received treatment specifically for psychotic illness, and there were no differences in venular caliber between those who did and did not receive treatment. Second, our finding is based on a relatively small group of individuals (n=27) who developed schizophrenia. Larger samples are needed to determine the replicability and robustness of the finding. We note, however, two aspects of our study that bolster our findings and are important for psychiatric research aimed towards identifying biological abnormalities (65): 1) we reported effect sizes for diagnosed schizophrenia in relation to both healthy and medically or psychiatrically unhealthy comparison groups, a practice which can substantially reduce or eliminate biased and invalid conclusions (66), and 2) we showed an association between wider venules and latent dimensional liability to adult psychosis in the population-representative cohort. Doing this circumvented some of the problems associated with studying categorical diagnoses (65).

Another limitation is that we assessed retinal vessel caliber at a single time point (age 38), and thus, we cannot know whether wider venules might be detectable before the onset of schizophrenia. Retinal imaging of microvessels is a relatively new technology that was not available in the early years of our longitudinal study. However, our finding of an association between psychosis symptoms at age 11 years, before the onset of schizophrenia, and venular caliber at age 38 years suggests the hypothesis that abnormal vascular processes may begin in childhood. In support of this possibility, research indicates that variation in the retinal vessel calibers of children is informative, at least with regard to blood pressure (67, 68).

Retinal imaging makes possible the prospective tracking of vascular changes as they relate to the onset, waxing, and waning of symptoms, and future research using longitudinal, high-risk, and experimental designs could use this method to address a variety of important questions. For example, longitudinal and high-risk studies can determine whether retinal vessel caliber in juveniles predicts risk of developing psychosis or accompanies the progression of schizophrenia, as might be expected given the neurodevelopmental nature of schizophrenia (69). Research questions could also be extended to examine associations between retinal vessel caliber and neuropsychological impairment in schizophrenia, as we previously showed that wider venular caliber in adulthood was associated with poorer neuropsychological test performance in childhood and midlife (33). Experimental studies are ideally suited to addressing whether changes in retinal vessel caliber are associated with improvement or deterioration in symptoms. Along these lines, a recent study found that oxygen supplementation improved symptoms of schizophrenia, including neuropsychological functioning (70), and the addition of retinal imaging to this design could help elucidate the mechanisms by which treatment works.

In conclusion, we provide initial evidence of retinal vessel caliber abnormality (specifically wider venular caliber) in schizophrenia and psychosis, a finding that is consistent with the hypothesis of microvascular pathology in schizophrenia (71). The non-invasive nature of retinal imaging, its relative cost-effectiveness, and the availability of the technology in primary care, optometry, and ophthalmology centers all suggest the value of retinal imaging analysis as an exciting tool for schizophrenia research.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

We thank the Dunedin Study members, their families, Unit research staff, and Study founder Phil Silva. The Dunedin Multidisciplinary Health and Development Research Unit is supported by the New Zealand Health Research Council. This research received support from US-National Institute on Aging (AG032282) and UK Medical Research Council (MR/K00381X). MHM was supported by US-NIDA (P30 DA023026). Idan Shalev was supported by US-NICHD (HD061298) and the Jacobs Foundation. The study protocol was approved by the institutional ethical review boards of the participating universities. Study members gave informed consent before participating.

References

1. Meynert, T. *Psychiatrie: Klinik der erkrankungen des vorderhirns*. Vienna, Braumüller: 1884.
2. Sun C, Wang JJ, Mackey DA, Wong TY. Retinal vascular caliber: Systemic, environmental, and genetic associations. *Surv Ophthalmol*. 2009; 54(1):74–95. [PubMed: 19171211]
3. Patton N, Aslam T, MacGillivray T, Pattie A, Deary IJ, Dhillon B. Retinal vascular image analysis as a potential screening tool for cerebrovascular disease: A rationale based on homology between cerebral and retinal microvasculatures. *J Anat*. 2005; 206(4):319–48. [PubMed: 15817102]
4. Cheung CYL, Ikram MK, Sabanayagam C, Wong TY. Retinal microvasculature as a model to study the manifestations of hypertension. *Hypertension*. 2012; 60(5):1094. [PubMed: 23045470]
5. Ikram MK, Ong YT, Cheung CY, Wong TY. Retinal vascular caliber measurements: Clinical significance, current knowledge and future perspectives. *Ophthalmologica*. 2012 Epub 2012/09/26.
6. McGeechan K, Liew G, Macaskill P, Irwig L, Klein R, Klein BEK, Wang JJ, Mitchell P, Vingerling JR, de Jong PTVM, Witteman JCM, Breteler MMB, Shaw J, Zimmet P, Wong TY. Prediction of incident stroke events based on retinal vessel caliber: A systematic review and individual-participant meta-analysis. *Am J Epidemiol*. 2009; 170(11):1323–32. [PubMed: 19884126]

7. Ikram MK, de Jong FJ, Bos MJ, Vingerling JR, Hofman A, Koudstaal PJ, de Jong PTVM, Breteler MMB. Retinal vessel diameters and risk of stroke - the Rotterdam Study. *Neurology*. 2006; 66(9): 1339–43. [PubMed: 16682664]
8. Ikram MK, De Jong FJ, Van Dijk EJ, Prins ND, Hofman A, Breteler MMB, De Jong PTVM. Retinal vessel diameters and cerebral small vessel disease: The Rotterdam Scan Study. *Brain*. 2006; 129:182–8. [PubMed: 16317022]
9. de Jong FJ, Schrijvers EMC, Ikram MK, Koudstaal PJ, de Jong PTVM, Hofman A, Vingerling JR, Breteler MMB. Retinal vascular caliber and risk of dementia - the Rotterdam Study. *Neurology*. 2011; 76(9):816–21. [PubMed: 21288987]
10. Wong TY, Kamineni A, Klein R, Sharrett AR, Klein BE, Siscovick DS, Cushman M, Duncan BB. Quantitative retinal venular caliber and risk of cardiovascular disease in older persons - the Cardiovascular Health Study. *Arch Intern Med*. 2006; 166(21):2388–94. [PubMed: 17130394]
11. Yatsuya H, Folsom AR, Wong TY, Klein R, Klein BEK, Sharrett AR, Investigators AS. Retinal microvascular abnormalities and risk of lacunar stroke - Atherosclerosis Risk in Communities Study. *Stroke*. 2010; 41(7):1349–55. [PubMed: 20522816]
12. de Jong FJ, Vernooij MW, Ikram MK, Ikram MA, Hofman A, Krestin GP, Van der Lugt A, de Jong PTVM, Breteler MMB. Arteriolar oxygen saturation, cerebral blood flow, and retinal vessel diameters - the Rotterdam Study. *Ophthalmology*. 2008; 115(5):887–92. [PubMed: 18067967]
13. Poulton R, Caspi A, Moffitt TE, Cannon M, Murray R, Harrington H. Children's self-reported psychotic symptoms and adult schizophreniform disorder: A 15-year longitudinal study. *Arch Gen Psychiatry*. 2000; 57(11):1053–8. [PubMed: 11074871]
14. Cannon M, Caspi A, Moffitt TE, Harrington H, Taylor A, Murray RM, Poulton R. Evidence for early-childhood, pan-developmental impairment specific to schizophreniform disorder - results from a longitudinal birth cohort. *Arch Gen Psychiatry*. 2002; 59(5):449–56. [PubMed: 11982449]
15. Reichenberg A, Caspi A, Harrington H, Houts R, Keefe RS, Murray RM, Poulton R, Moffitt TE. Static and dynamic cognitive deficits in childhood preceding adult schizophrenia: A 30-year study. *Am J Psychiatry*. 2010; 167(2):160–9. [PubMed: 20048021]
16. Robins LN, Helzer JE, Croughan J, Ratcliff KS. National Institute of Mental Health Diagnostic Interview Schedule: Its history, characteristics, and validity. *Arch Gen Psychiatry*. 1981; 38(4): 381–9. [PubMed: 6260053]
17. Robins, LN.; Cottler, L.; Bucholz, KK.; Compton, W. Diagnostic Interview Schedule for DSM-IV. St Louis, MO: Washington University School of Medicine; 1995.
18. American Psychiatric Association. Diagnostic and Statistical Manual of Mental Disorders. 3. Washington, DC: American Psychiatric Association; 1987. revised
19. American Psychiatric Association. Diagnostic and Statistical Manual of Mental Disorders, fourth edition. Washington, DC: American Psychiatric Association; 1994.
20. Kendler KS, Gallagher TJ, Abelson JM, Kessler RC. Lifetime prevalence, demographic risk factors, and diagnostic validity of nonaffective psychosis as assessed in a us community sample - the National Comorbidity Survey. *Arch Gen Psychiatry*. 1996; 53(11):1022–31. [PubMed: 8911225]
21. Dutta R, Murray RM, Allardyce J, Jones PB, Boydell JE. Mortality in first-contact psychosis patients in the UK: A cohort study. *Psychol Med*. 2012; 42(8):1649–61. [PubMed: 22153300]
22. Youssef HA, Kinsella A, Waddington JL. Evidence for geographical variations in the prevalence of schizophrenia in rural Ireland. *Arch Gen Psychiatry*. 1991; 48(3):254–8. [PubMed: 1996920]
23. Arajarvi R, Suvisaari J, Suokas J, Schreck M, Haukka J, Hintikka J, Partonen T, Lonnqvist J. Prevalence and diagnosis of schizophrenia based on register, case record and interview data in an isolated Finnish birth cohort born 1940–1969. *Soc Psych Psych Epid*. 2005; 40(10):808–16.
24. Torrey EF, Mcguire M, Ohare A, Walsh D, Spellman MP. Endemic psychosis in western Ireland. *Am J Psychiat*. 1984; 141(8):966–70. [PubMed: 6465372]
25. Ferguson, S.; Blakely, T.; Allan, B.; Colling, S. Suicide rates in new zealand: Exploring associations with social and economic factors. Wellington, New Zealand: Ministry of Health; 2005.

26. van Os J, Linscott RJ, Myin-Germeys I, Delespaul P, Krabbendam L. A systematic review and meta-analysis of the psychosis continuum: Evidence for a psychosis proneness-persistence-impairment model of psychotic disorder. *Psychol Med.* 2009; 39(2):179–95. [PubMed: 18606047]
27. Hennekens CH, Hennekens AR, Hollar D, Casey DE. Schizophrenia and increased risks of cardiovascular disease. *Am Heart J.* 2005; 150(6):1115–21. [PubMed: 16338246]
28. Buckley PF, Miller BJ, Lehrer DS, Castle DJ. Psychiatric comorbidities and schizophrenia. *Schizophrenia Bull.* 2009; 35(2):383–402.
29. Perloff D, Grim C, Flack J, Frohlich ED, Hill M, McDonald M, Morgenstern BZ. Human blood pressure determination by sphygmomanometry. *Circulation.* 1993; 88(5 Pt 1):2460–70. [PubMed: 8222141]
30. Cleeman JI, Grundy SM, Becker D, Clark LT, Cooper RS, Denke MA, Howard WJ, Hunninghake DB, Illingworth DR, Luepker RV, McBride P, McKenney JM, Pasternak RC, Stone NJ, Van Horn L, Brewer HB, Ernst ND, Gordon D, Levy D, Rifkind B, Rossouw JE, Savage P, Haffner SM, Orloff DG, Proschan MA, Schwartz JS, Sempos CT, Shero ST, Murray EZ. Executive summary of the third report of the national cholesterol education program (NCEP) expert panel on detection, evaluation, and treatment of high blood cholesterol in adults (adult treatment panel iii). *Jama-J Am Med Assoc.* 2001; 285(19):2486–97.
31. Expert Committee on the Diagnosis and Classification of Diabetes Mellitus: Report of the expert committee on the diagnosis and classification of diabetes mellitus. *Diabetes Care.* 1997; 20(7): 1183–97. [PubMed: 9203460]
32. Costello, A.; Edelbrock, C.; Kalas, R.; Kessler, M.; Klaric, SA. Diagnostic Interview Schedule for Children (DISC). Rockville, MD: National Institute of Mental Health; 1982.
33. Shalev I, Moffitt TE, Wong T, Meier MH, Houts R, Ding J, Cheung C, Ikram MK, Caspi A, Poulton R. Retinal vessel caliber and lifelong neuropsychological functioning: An investigative tool for cognitive epidemiology. *Psychol Sci.* (in press).
34. Cheung CYL, Hsu W, Lee ML, Wang JJ, Mitchell P, Lau QP, Hamzah H, Ho M, Wong TY. A new method to measure peripheral retinal vascular caliber over an extended area. *Microcirculation.* 2010; 17(7):495–503. [PubMed: 21040115]
35. Knudtson MD, Lee KE, Hubbard LD, Wong TY, Klein R, Klein BEK. Revised formulas for summarizing retinal vessel diameters. *Curr Eye Res.* 2003; 27(3):143–9. [PubMed: 14562179]
36. Liew G, Sharrett AR, Kronmal R, Klein R, Wong TY, Mitchell P, Kifley A, Wang JJ. Measurement of retinal vascular caliber: Issues and alternatives to using the arteriole to venule ratio. *Invest Ophth Vis Sci.* 2007; 48(1):52–7.
37. Wong TY, Wang JJ, Rochtchina E, Klein R, Mitchell P. Does refractive error influence the association of blood pressure and retinal vessel diameters? The blue mountains eye study. *Am J Ophthalmol.* 2004; 137(6):1050–5. [PubMed: 15183789]
38. Cohen J. A power primer. *Psychol Bull.* 1992; 112(1):155–9. [PubMed: 19565683]
39. Klein R, Klein BEK, Knudtson MD, Wong TY, Tsai MY. Are inflammatory factors related to retinal vessel caliber? The Beaver Dam Eye Study. *Arch Ophthalmol-Chic.* 2006; 124(1):87–94.
40. Ikram MK, de Jong FJ, Vingerling JR, Wittman JCM, Hofman A, Breteler MMB, de Jong PTVM. Are retinal arteriolar or venular diameters associated with markers for cardiovascular disorders? The Rotterdam Study. *Invest Ophth Vis Sci.* 2004; 45(7):2129–34.
41. Liew G, Sharrett AR, Wang JJ, Klein R, Klein BEK, Mitchell P, Wong TY. Relative importance of systemic determinants of retinal arteriolar and venular caliber. *Arch Ophthalmol-Chic.* 2008; 126(10):1404–10.
42. Wong TY, Islam FMA, Klein R, Klein BEK, Cotch MF, Castro C, Sharrett AR, Shahar E. Retinal vascular caliber, cardiovascular risk factors, and inflammation: The Multi-Ethnic Study of Atherosclerosis (MESA). *Invest Ophth Vis Sci.* 2006; 47(6):2341–50.
43. Nguyen TT, Islam FMA, Farouque HMO, Klein R, Klein BEK, Cotch MF, Herrington DM, Wong TY. Retinal vascular caliber and brachial flow-mediated dilation the Multi-Ethnic Study of Atherosclerosis. *Stroke.* 2010; 41(7):1343–8. [PubMed: 20508189]
44. Fan XD, Pristach C, Liu EY, Freudenreich O, Henderson DC, Goff DC. Elevated serum levels of c-reactive protein are associated with more severe psychopathology in a subgroup of patients with schizophrenia. *Psychiatry Res.* 2007; 149(1–3):267–71. [PubMed: 17112596]

45. Fan XD, Liu EY, Freudenreich O, Park JH, Liu DT, Wang JJ, Yi ZH, Goff D, Henderson DC. Higher white blood cell counts are associated with an increased risk for metabolic syndrome and more severe psychopathology in non-diabetic patients with schizophrenia. *Schizophr Res.* 2010; 118(1–3):211–7. [PubMed: 20189773]
46. Potvin S, Stip E, Sepehry AA, Gendron A, Bah R, Kouassi E. Inflammatory cytokine alterations in schizophrenia: A systematic quantitative review. *Biol Psychiatry.* 2008; 63(8):801–8. [PubMed: 18005941]
47. Israel AK, Seeck A, Boettger MK, Rachow T, Berger S, Voss A, Bar KJ. Peripheral endothelial dysfunction in patients suffering from acute schizophrenia: A potential marker for cardiovascular morbidity? *Schizophr Res.* 2011; 128(1–3):44–50. [PubMed: 21371864]
48. Bernstein HG, Bogerts B, Keilhoff G. The many faces of nitric oxide in schizophrenia. A review. *Schizophr Res.* 2005; 78(1):69–86. [PubMed: 16005189]
49. Schmidt-Kastner R, van Os J, Steinbusch HWM, Schmitz C. Gene regulation by hypoxia and the neurodevelopmental origin of schizophrenia. *Schizophr Res.* 2006; 84(2–3):253–71. [PubMed: 16632332]
50. Xing C, Klein BEK, Klein R, Jun G, Lee KE, Iyengar SK. Genome-wide linkage study of retinal vessel diameters in the Beaver Dam Eye Study. *Hypertension.* 2006; 47(4):797–802. [PubMed: 16505201]
51. Ikram MK, Xueling S, Jensen RA, Cotch MF, Hewitt AW, Ikram MA, Wang JJ, Klein R, Klein BEK, Breteler MMB, Cheung N, Liew G, Mitchell P, Uitterlinden AG, Rivadeneira F, Hofman A, de Jong PTVM, van Duijn CM, Kao L, Cheng CY, Smith AV, Glazer NL, Lumley T, McKnight B, Psaty BM, Jonasson F, Eiriksdottir G, Aspelund T, Harris TB, Launer LJ, Taylor KD, Li XH, Iyengar SK, Xi QS, Sivakumaran TA, Mackey DA, MacGregor S, Martin NG, Young TL, Bis JC, Wiggins KL, Heckbert SR, Hammond CJ, Andrew T, Fahy S, Attia J, Holliday EG, Scott RJ, Islam FMA, Rotter JI, McAuley AK, Boerwinkle E, Tai ES, Gudnason V, Siscovick DS, Vingerling JR, Wong TY, Consortium GB. Four novel loci (19q13, 6q24, 12q24, and 5q14) influence the microcirculation in vivo. *Plos Genet.* 2010; 6:10.
52. Fahy SJ, Sun C, Zhu G, Healey PR, Spector TD, Martin NG, Mitchell P, Wong TY, Mackey DA, Hammond CJ, Andrew T. The relationship between retinal arteriolar and venular calibers is genetically mediated, and each is associated with risk of cardiovascular disease. *Invest Opth Vis Sci.* 2011; 52(2):975–81.
53. Andreassen OA, Djurovic S, Thompson WK, Schork AJ, Kendler KS, O'Donovan MC, Rujescu D, Werge T, van de Bunt M, Morris AP, McCarthy MI, Roddey JC, McEvoy LK, Desikan RS, Dale AM. Improved detection of common variants associated with schizophrenia by leveraging pleiotropy with cardiovascular-disease risk factors. *American journal of human genetics.* 2013; 92(2):197–209. [PubMed: 23375658]
54. Schmidt-Kastner R, van Os J, Esquivel G, Steinbusch HW, Rutten BP. An environmental analysis of genes associated with schizophrenia: Hypoxia and vascular factors as interacting elements in the neurodevelopmental model. *Mol Psychiatry.* 2012; 17(12):1194–205. [PubMed: 22290124]
55. Bachneff SA. Regional cerebral blood flow in schizophrenia and the local circuit neurons hypothesis. *Schizophrenia Bull.* 1996; 22(1):163–82.
56. Cohen BM, Yurgeluntodd D, English CD, Renshaw PF. Abnormalities of regional distribution of cerebral vasculature in schizophrenia detected by dynamic susceptibility contrast MRI. *Am J Psychiatr.* 1995; 152(12):1801–3. [PubMed: 8526249]
57. Prabakaran S, Swatton JE, Ryan MM, Huffaker SJ, Huang JTT, Griffin JL, Wayland M, Freeman T, Dudbridge F, Lilley KS, Karp NA, Hester S, Tkachev D, Mimmack ML, Yolken RH, Webster MJ, Torrey EF, Bahn S. Mitochondrial dysfunction in schizophrenia: Evidence for compromised brain metabolism and oxidative stress. *Mol Psychiatr.* 2004; 9(7):684–97.
58. Ward PE, Sutherland J, Glen EMT, Glen AIM. Niacin skin flush in schizophrenia: A preliminary report. *Schizophr Res.* 1998; 29(3):269–74. [PubMed: 9516668]
59. Lien YJ, Huang SS, Liu CM, Hwu HG, Faraone SV, Tsuang MT, Chen WJ. A genome-wide quantitative linkage scan of niacin skin flush response in families with schizophrenia. *Schizophrenia Bull.* 2013; 39(1):68–76.

60. Hudson CJ, Lin A, Cogan S, Cashman F, Warsh JJ. The niacin challenge test: Clinical manifestation of altered transmembrane signal transduction in schizophrenia? *Biol Psychiatry*. 1997; 41(5):507–13. [PubMed: 9046982]
61. Curtis CE, Iacono WG, Beiser M. Relationship between nailfold plexus visibility and clinical, neuropsychological, and brain structural measures in schizophrenia. *Biol Psychiatry*. 1999; 46(1): 102–9. [PubMed: 10394479]
62. Senitz D, Winkelmann E. Neuronal structure abnormality in the orbito-frontal cortex of schizophrenics. *Journal fur Hirnforschung*. 1991; 32(2):149–58. [PubMed: 1791296]
63. Uranova NA, Zimina IS, Vikhrevva OV, Krukov NO, Rachmanova VI, Orlovskaya DD. Ultrastructural damage of capillaries in the neocortex in schizophrenia. *World J Biol Psychia*. 2010; 11(3):567–78.
64. Harris LW, Wayland M, Lan M, Ryan M, Giger T, Lockstone H, Wuethrich I, Mimmack M, Wang L, Kotter M, Craddock R, Bahn S. The cerebral microvasculature in schizophrenia: A laser capture microdissection study. *Plos One*. 2008; 3(12)
65. Kapur S, Phillips AG, Insel TR. Why has it taken so long for biological psychiatry to develop clinical tests and what to do about it? *Mol Psychiatry*. 2012 Epub 2012/08/08.
66. Schwartz S, Susser E. The use of well controls: An unhealthy practice in psychiatric research. *Psychol Med*. 2011; 41(6):1127–31. [PubMed: 20810003]
67. Li LJ, Cheung CYL, Liu Y, Chia A, Selvaraj P, Lin XY, Chan YM, Varma R, Mitchell P, Wong TY, Saw SM. Influence of blood pressure on retinal vascular caliber in young children. *Ophthalmology*. 2011; 118(7):1459–65. [PubMed: 21444115]
68. Gopinath B, Baur LA, Wang JJ, Teber E, Liew G, Cheung N, Wong TY, Mitchell P. Blood pressure is associated with retinal vessel signs in preadolescent children. *J Hypertens*. 2010; 28(7): 1406–12. [PubMed: 20410837]
69. Insel TR. Rethinking schizophrenia. *Nature*. 2010; 468(7321):187–93. [PubMed: 21068826]
70. Bloch Y, Applebaum J, Osher Y, Amar S, Azab AN, Agam G, Belmaker RH, Bersudsky Y. Normobaric hyperoxia treatment of schizophrenia. *J Clin Psychopharmacol*. 2012; 32(4):525–30. [PubMed: 22722511]
71. Hanson DR, Gottesman II. Theories of schizophrenia: A genetic-inflammatory-vascular synthesis. *Bmc Med Genet*. 2005; 6:7. [PubMed: 15707482]

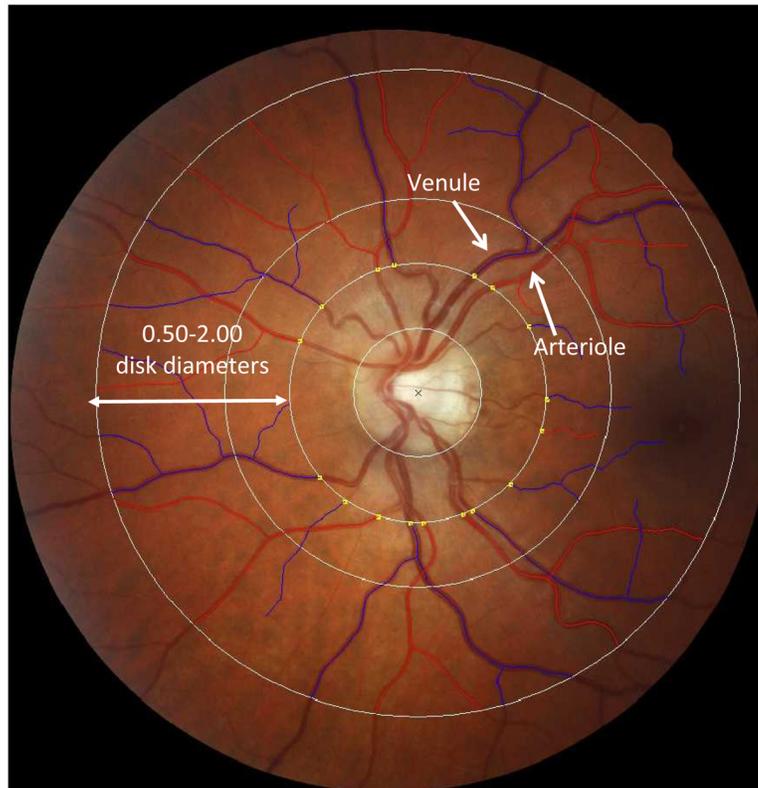


Figure 1. Retinal digital photograph. Measurements were made for the 6 largest arterioles (red) and venules (blue) passing through the region located 0.50–2.00 disk diameters from the optic disk margin.

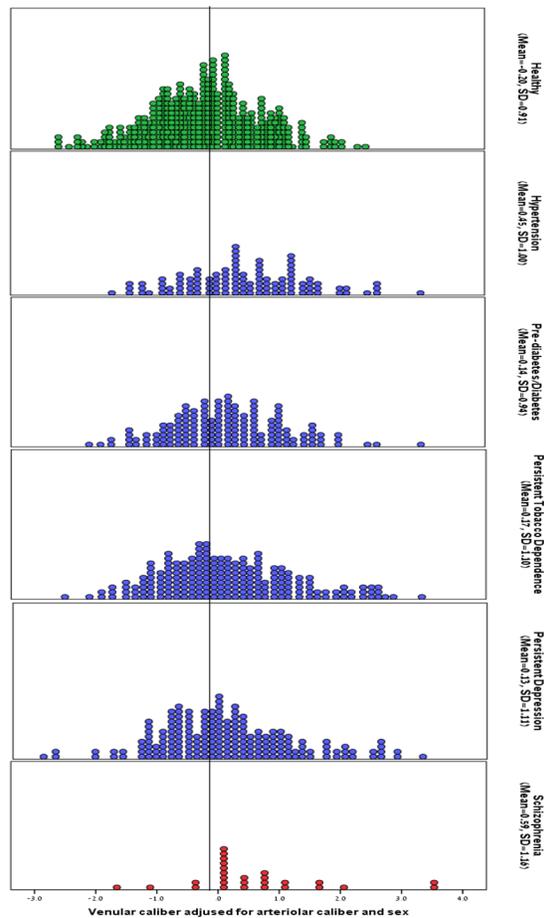


Figure 2. Distribution of retinal venular caliber for the healthy, hypertension, pre-diabetes/diabetes, persistent tobacco dependence, persistent depression, and schizophrenia groups. Scores were adjusted for arteriolar caliber and sex and standardized ($M=0.00$, $SD=1.00$) on the population-representative cohort. The vertical line represents the mean for the healthy group. Both parametric and nonparametric statistical analyses showed that individuals diagnosed with schizophrenia had significantly wider venules – a finding that does not depend on extreme values.

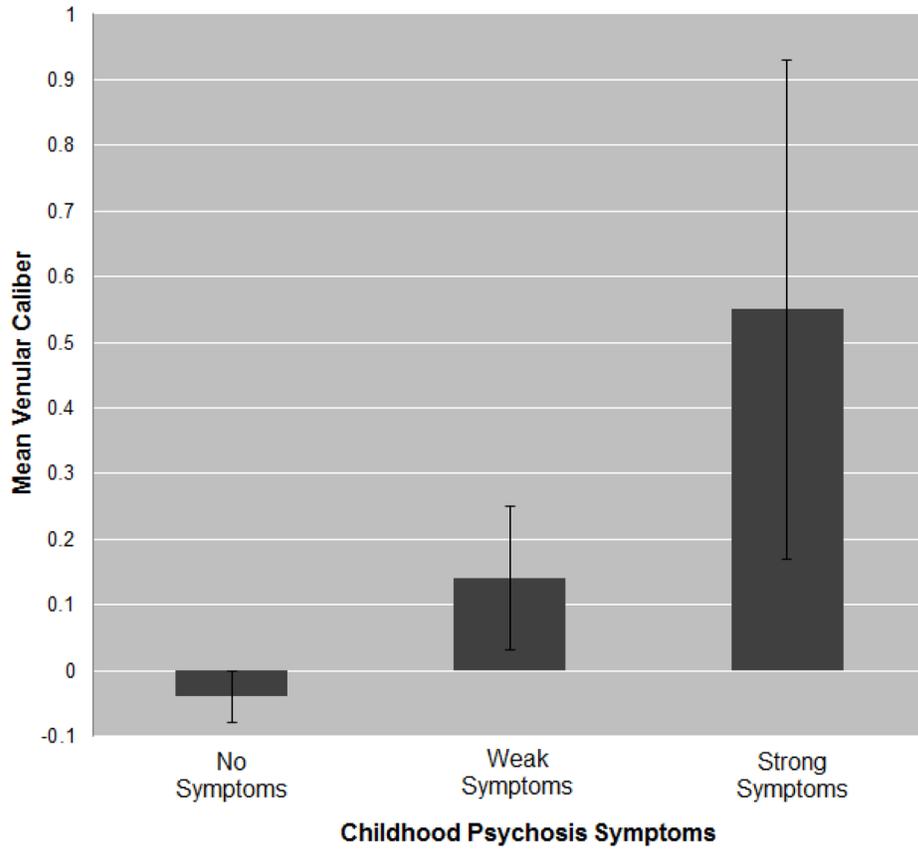


Figure 3. Mean retinal venular caliber at age 38 as a function of childhood psychosis symptoms. Venular caliber values were adjusted for arteriolar caliber and sex and standardized on the population-representative cohort. As previously described,¹³ no symptoms reflects a summed score of ‘0’ [n=673; 50.2% were male]; weak symptoms reflect a score of ‘1’ [n=103; 66.0% male]; strong symptoms reflect a score of ‘2’ [n=13; 61.5% male]. At minimum, study members could enter the strong symptom group by obtaining a score of 1 (yes, likely) for 2 symptoms, or by obtaining a score of 2 (yes, definitely) for 1 symptom. Children who exhibited strong psychosis symptoms had the widest venular calibers as adults. Error bars = standard errors.

Table 1

Mean retinal vessel caliber for the schizophrenia and comparison groups.

Group	n	Venule			Arteriole		
		M	SD	95% CI	M	SD	95% CI
Schizophrenia	27	0.59 ^H	1.16	0.14, 1.05	-0.13	1.04	-0.54, 0.28
Healthy	412	-0.20 ^S	0.91	-0.29, -0.12	0.15	0.93	0.06, 0.24
Hypertension	110	0.45 ^H	1.00	0.26, 0.64	-0.75 ^{S,H}	1.06	-0.95, -0.55
Pre-diabetes/Diabetes	154	0.14 ^{S,H}	0.94	-0.01, 0.29	-0.08 ^H	1.00	-0.24, 0.08
Persistent Tobacco Dependence	210	0.17 ^H	1.10	0.02, 0.32	0.02	1.04	-0.12, 0.16
Persistent Depression	188	0.13 ^{S,H}	1.11	-0.03, 0.29	-0.08 ^H	0.99	-0.22, 0.06

Note. Statistical tests compare each group to the schizophrenia and healthy groups. Superscript 'H' reflects a statistically significant difference as compared to the healthy group. Superscript 'S' reflects a statistically significant difference as compared to the schizophrenia group. Means for each vessel were adjusted for the other vessel and sex and standardized on the population-representative cohort (M=0.00, SD=1.00). Thus, means reflect effect sizes for how different each group is from the cohort norm. Differences between pairs of groups can also be interpreted as effect sizes. Effect sizes of 0.20, 0.50, and 0.80 reflect small, medium, and large effects, respectively.