Psychological Medicine

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Childhood trauma- and cannabis-associated microstructural white matter changes in patients with psychotic disorder: a longitudinal family-based diffusion imaging study

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Original Article

Cite this article: Domen P, Michielse S, Peeters S, Viechtbauer W, van Os J, Marcelis M, for Genetic Risk and Outcome of Psychosis (G.R.O.U.P.) (2019). Childhood trauma- and cannabis-associated microstructural white matter changes in patients with psychotic disorder: a longitudinal family-based diffusion imaging study. *Psychological Medicine* **49**, 628–638. https://doi.org/10.1017/S0033291718001320

Received: 11 May 2017
Revised: 19 April 2018
Accepted: 24 April 2018
First published online: 29 May 2018

Key words:
Cannabis; childhood trauma; diffusion tensor imaging; longitudinal; psychotic disorder; siblings

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Abstract

Background. Decreased white matter (WM) integrity in patients with psychotic disorder has been a consistent finding in diffusion tensor imaging (DTI) studies. However, the contribution of environmental risk factors to these WM alterations is rarely investigated. The current study examines whether individuals with (increased risk for) psychotic disorder will show increased WM integrity change over time with increasing levels of childhood trauma and cannabis exposure.

Methods. DTI scans were obtained from 85 patients with a psychotic disorder, 93 non-psychotic siblings and 80 healthy controls, of which 60% were rescanned 3 years later. In a whole-brain voxel-based analysis, associations between change in fractional anisotropy (ΔFA) and environmental exposures as well as interactions between group and environmental exposure in the model of FA and ΔFA were investigated. Analyses were adjusted for *a priori* hypothesized confounding variables: age, sex, and level of education.

Results. At baseline, no significant associations were found between FA and both environmental risk factors. At follow-up as well as over a 3-year interval, significant interactions between group and, respectively, cannabis exposure and childhood trauma exposure in the model of FA and ΔFA were found. Patients showed more FA decrease over time compared with both controls and siblings when exposed to higher levels of cannabis or childhood trauma.

Conclusions. Higher levels of cannabis or childhood trauma may compromise connectivity over the course of the illness in patients, but not in individuals at low or higher than average genetic risk for psychotic disorder, suggesting interactions between the environment and illness-related factors.

Introduction

Reduced fractional anisotropy (FA), widely reported in patients with psychotic disorder (Ellison-Wright and Bullmore, 2009), but not in individuals at higher than average genetic risk (siblings of patients) may reflect disease-related dysconnectivity or disease-related differential sensitivity to the environment (Boos *et al.*, 2013; Domen *et al.*, 2013). The risk for psychosis, a condition with adolescent onset, has been related to environmental exposures such as pre- or postnatal birth complications, cannabis use, childhood trauma (Varese *et al.*, 2012; Misiak *et al.*, 2017), and growing up in an urban environment (van Os and Kapur, 2009). These environmental stressors may be the trigger (Cornblatt *et al.*, 2003) or the 'second hit' (Maynard *et al.*, 2001), contributing to the emergence of a psychotic illness. However, the potential impact of these environmental risks on white matter (WM) connectivity (Andreasen *et al.*, 1998; Friston, 1998) has not been the subject of detailed investigation in patients with a psychotic disorder. Cross-sectional studies did explore genetic factors, showing a moderate-to-high heritability of WM FA, ranging from 0.4 to 0.7 (Voineskos, 2015). Also, several candidate genes for WM heritability have been proposed, such as neuregulin1-tyrosine kinase receptor ErbB4, involved in oligodendrocyte, myelin, and axonal development and maintenance (Wang *et al.*, 2009). Various hypotheses have been postulated, associating environmental risk factors with WM alterations. Cannabis use may induce apoptosis of oligodendrocyte progenitors, affecting WM development (Molina-Holgado *et al.*, 2002). In the

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literature to date, there is evidence to suggest a negative association between cannabis use and WM volume in patients with schizophrenia (Cahn *et al.*, 2004; Szeszko *et al.*, 2007). Results from diffusion tensor imaging (DTI) studies are less clear and have shown increased as well as decreased FA in cannabis-using *v.* non-using patients with schizophrenia (Peters *et al.*, 2010; James *et al.*, 2011). The same ambiguity is seen in samples of non-psychotic substance users compared with non-users, which, on the one hand, showed microstructural WM alterations in specific pathways (corpus callosum and superior longitudinal fascicules) (Baker *et al.*, 2013) and the hippocampus (fimbriae), corpus callosum (splenium), commissural fibers (Zalesky *et al.*, 2012), as well as, on the other hand, absence of FA differences (Arnone *et al.*, 2008).

Studies on early-life stress in otherwise healthy children have shown associations between cortisol reactivity and possible alterations in hippocampal and amygdala volumes (Pagliaccio *et al.*, 2014). Corticosteroids may suppress the final mitosis of glial cells necessary for myelination, influencing WM microstructure (Teicher *et al.*, 2002). This model is supported by studies showing reduced corpus callosum volume in paediatric inpatients with a history of abuse and neglect (Teicher *et al.*, 2004) and reduced FA in the left inferior longitudinal fasciculus (ILF) in young adults witnessing domestic violence in childhood (Choi *et al.*, 2012). To date, longitudinal diffusion weighted imaging studies of patients with schizophrenia are scarce (Canu *et al.*, 2015) and apart from studies investigating the effect of medication on WM diffusion measures (Ozcelik-Eroglu *et al.*, 2014; Reis Marques *et al.*, 2014), no study has examined whether traumatic experience has a differential effect on FA over time in individuals with or without (liability for) psychotic disorder (Bendall *et al.*, 2008).

In a cross-sectional analysis of the baseline DTI scans of the current sample, patient-specific microstructural WM alterations were found (Domen *et al.*, 2013). These alterations remained relatively stable over a 3-year time course in contrast to a decline in mean FA in the non-affected siblings compared with healthy controls (Domen *et al.*, 2017). Consequently, both patients and siblings had decreased FA with respect to controls at follow-up. The aim of the current investigation was to study whether microstructural alterations over time were conditional on the exposure on two of the most examined environmental risk factors for schizophrenia; cannabis use and childhood trauma, for which biological plausibility exists. More specifically, we hypothesized that individuals at increased genetic risk (patients and siblings) with higher levels of exposure to these environmental risk factors would show reduced WM FA over time.

Methods

Participants

Subjects were recruited in the context of a multicenter longitudinal study (Genetic Risk and Outcome of Psychosis, G.R.O.U.P.) in the Netherlands (Korver *et al.*, 2012). At baseline, 300 participants were included of which 258 underwent a DTI scan. At follow-up, approximately 3 years later (mean: 3.3 years), DTI scans were acquired from a sample of 180 participants, of which 159 provided a valid pair of DTI scans for the longitudinal analysis (see Domen *et al.* (2013, 2017) and the Supplementary Method section for further information on inclusion and exclusion criteria, family composition and diagnostic assessments (Domen *et al.*, 2013, 2017).

The standing ethics committee approved the study protocol, and all participants gave written informed consent in accordance with the committee's guidelines.

Measures

Level of psychotic symptomatology at the time of scanning was assessed with the Positive and Negative Symptom Scale (PANSS) (Kay *et al.*, 1987).

Educational level was defined as highest accomplished level of education. Handedness was assessed using the Annett Handedness Scale (Annett, 1970).

Antipsychotic medication

The determination of (lifetime) antipsychotic (AP) medication use at baseline and cumulative AP exposure during the 3-year follow-up period has been described in the online Supplementary Method section based on Domen *et al.* (2013, 2017).

Substance use

Substance use was measured at both time points with the Composite International Diagnostic Interview (CIDI) sections B-J-L (WHO, 1990). As data of drug use over the last 3 years were not available, cannabis and other drug exposure was assessed as reported frequency of use during the last 12 months and lifetime use (mean number of times until baseline measurement). CIDI frequency data on alcohol (weekly consumptions), lifetime cannabis, and other drug use was available at follow-up for, respectively, 158 participants (1% missing data), 155 participants (3% missing data), and 157 participants (1% missing data). Despite the fact that the association between alcohol or other drugs and psychosis risk has been studied less than cannabis and provided a less clear picture, these substances may well contribute to some of the WM variation (Nesvåg *et al.*, 2007; Willi *et al.*, 2017), and were therefore considered potential confounders (see Statistical analyses).

Childhood trauma: Childhood trauma was assessed at baseline with the Dutch version of the Childhood Trauma Questionnaire Short Form (CTQ) (Thombs *et al.*, 2009). The short CTQ consists of 25 items rated on a five-point Likert scale (1 = never true to 5 = very often true) inquiring about traumatic experiences in childhood. Five types of childhood maltreatment were assessed: emotional, physical and sexual abuse, and emotional and physical neglect, with five questions covering each type of trauma (Bernstein *et al.*, 1997). The mean of these 25 items (range 5.0–25.0) created a general measure of childhood trauma. The CTQ data were missing for one patient.

Image acquisition

Magnetic resonance imaging scans were obtained at Maastricht University, the Netherlands, using an Allegra Magnetom MR (Siemens, Erlangen, Germany) operating at 3.0 Tesla. At both measurement points, microstructural anatomy was examined using DTI with an echo-planar-imaging sequence (field of view 230 mm × 230 mm, TR 10800 ms, TE 84 ms, voxel size 1.8 mm × 1.8 mm × 1.8 mm, *b*-value 1000 s/mm^2, 85 slices, no overlap). As a result of an update of the scanner software during baseline acquisition, two DTI sequences were used: one with 76 directions [of which four T2-weighted (B0) and 72 diffusion-

https://doi.org/10.1017/S0033291718001320 Published online by Cambridge University Press

weighted (B1000)] and one with 81 directions (8 × B0 and 73 × B1000). Gradient directions were identical in both sequences. A potential association between the proportion of baseline scans and group was investigated using a *Pearson* χ^2 test.

At follow-up, the DTI sequence comprised 81 directions (8 × B0 and 73 × B1000). Total acquisition time of the DTI sequence was 15 min.

DTI analysis

Processing of DTI data was performed using tract-based spatial statistics (TBSS) v1.2 in FSL 4.1.6 (FMRIB Analysis Group, Oxford, UK, http://www.fmrib.ox.ac.uk/analysis/research/tbss). The consecutive processing steps are described in the online Supplementary Method section (based on Domen *et al.*, 2013, 2017). For the current study, three mean FA skeletons were created; for the cross-sectional analysis at baseline ($n = 258$: controls, siblings, patients) and at follow-up ($n = 180$), and for the longitudinal analysis ($n = 159$), one based on six groups (3 groups × 2 time points).

Statistical analyses

In order to use a multilevel (mixed-effects) model and to be able to calculate a mean FA 'change' (mean FA at baseline minus mean FA at follow-up) for the longitudinal model, which was not compatible with the standard protocol in TBSS, data were analyzed in R (version 3.2.0), a free software environment for statistical computing and graphics (Team, 2015). From the 38 labeled WM tracts, skeleton mean FA values per participant per time point were extracted and exported to R. Since the mean FA values per subject were based on varying number of voxels, depending on the region, we used a model in which the error variance for a particular observation was inversely weighted by the number of voxels within the corresponding region.

Cross-sectional analysis at baseline and follow-up

As of the three-level grouping structure of the data, compromising statistical independence of the observations, a multilevel (mixed-effects) model was fitted. FA was the dependent variable, group (dummy variables with the controls as the reference category, controls = 0, siblings = 1, patients = 2), and the environmental exposures (lifetime and last year cannabis exposure, childhood trauma exposure) were the independent variables and random effects (intercepts) were added for both subject and family.

The statistical basic model was: $FA = \beta_0 + \beta_1$ (group) $+ \beta_2$ (environmental exposure) $+ \beta_3$ (group × environmental exposure). This model included the *a priori* hypothesized confounding variables age, sex, and level of education as fixed effects. In case of significant findings, additional covariates [i.e. alcohol consumption, lifetime other drug use, and body mass index (BMI)] were separately added to the model.

Main effects of the environmental exposures (controlled for group), as well as group × environmental exposures interactions in the model of FA were examined. The environmental exposures were entered both as linear and as factored variables (i.e. representing the distribution of scores divided by its tertiles: lifetime cannabis use: no, moderate, or heavy cannabis use; childhood trauma exposure: low, moderate, or high trauma exposure), allowing visualization of dose–response. In case of significant interaction effects, stratified analyses were conducted in order to quantify whether the association between environmental exposure and FA differed between the three groups.

To examine whether childhood trauma and lifetime cannabis use contributed independent effects, planned sensitivity analyses were performed with both environmental exposures in the model.

To examine whether the scanner software update at baseline affected the results, the interaction analyses at baseline were repeated in subgroups stratified by the number of scan directions: 76 ($n = 191$) *v.* 81 ($n = 67$) directions.

Longitudinal analysis

A mean FA 'change' (delta, Δ) per participant per region ($n = 159$) was calculated by subtracting mean FA at baseline from mean FA at follow-up. The same analyses were carried out as described in the cross-sectional part, now using ΔFA as the dependent variable and group and the environmental exposures (lifetime and last year cannabis exposure, childhood trauma exposure) as the independent variables.

In addition, to control for a potential effect of depression on ΔFA, the main longitudinal analysis was repeated with exclusion of the subgroup of participants in the control ($n = 11$) and sibling group ($n = 15$) with a history of a depressive disorder.

Since our previous study showed a small effect of last 3-year and lifetime AP use on ΔFA (Domen *et al.*, 2017), planned sensitivity analyses were performed to rule out potential AP effects, using patient subgroups [with low, moderate, and high AP exposure (for the number of participants per subgroup see online Supplementary Table)]. Thus, the group × environmental exposure interactions in the model of ΔFA were examined in three AP subgroups to ascertain whether a potential effect remained significant in the respective subgroups.

Results

Demographics

The patients represented a relatively stable population (not in need of inpatient care or intensive treatment), as reflected by the low PANSS scores and the number of patients that fulfilled the remission criteria (Table 1). The gender distribution in the samples was skewed, showing more male patients and male siblings as heavy cannabis users and more male patients and female controls exposed to high levels of childhood trauma at follow-up (Table 2). The mean current dosage of AP medication in terms of standard haloperidol equivalents was 5.5 milligrams (mg) (S.D. = 4.6) at baseline and 4.7 mg (S.D. = 5.1) at follow-up (over the last 3 years). The proportion of baseline scans with 76 directions did not differ between the groups (84% in controls, 82% in siblings, and 71% in patients: $\chi^2 = 3.02$, df = 2, $p = 0.22$).

Cross-sectional analysis of FA and environmental risk factors at baseline

There were no significant associations between cannabis exposure and FA (lifetime: $B = 0.002$, $p = 0.24$, last year: $B = 1.0 \times 10^{-5}$, $p = 0.43$) or between childhood trauma exposure and FA ($B = -0.001$, $p = 0.60$). In addition, no significant interactions were found between cannabis exposure and group in the model of FA (lifetime: $\chi^2 = 1.3$, df = 2, $p = 0.52$, last year: $\chi^2 = 0.1$, df = 2, $p = 0.93$) and between childhood trauma and group in the model of FA

https://doi.org/10.1017/S0033291718001320 Published online by Cambridge University Press

Table 1. Demographic characteristics of the participants [baseline ($n = 258$) and longitudinal analysis ($n = 159$)]

	Controls		Siblings		Patients	
Time point	Baseline	Follow-up	Baseline	Follow-up	Baseline	Follow-up
Number	80	49	93	55	85	55
Scan interval (days)	1222 ± 198		1177 ± 101		1196 ± 121	
Age at scan (years)	30.8 ± 10.8	34.4 ± 10.9	29.4 ± 8.8	34.1 ± 8.5	28.3 ± 7.0	32.0 ± 6.2
Sex male (%)	29 (36%)	19 (39%)	49 (53%)	29 (53%)	58 (68%)	40 (73%)
Handedness[a]	76.3	83.2	73.9	78.0	72.8	72.2
Level of education[b]	5.4 ± 1.8	5.4 ± 2.0	5.1 ± 2.1	5.4 ± 2.1	4.1 ± 2.0	4.5 ± 1.9
Body mass index	23.3 ± 3.2	24.3 ± 3.7	23.3 ± 3.3	24.2 ± 3.9	24.5 ± 4.2	25.9 ± 4.8
Age of onset (years)	–		–		22.8 ± 6.4	21.8 ± 6.3
Illness duration (years)	–		–		5.4 ± 3.6	10.3 ± 4.0
Antipsychotics	–		–		6693 ± 6254[c]	5335 ± 5715[d]
Diagnosis						
Schizophrenia	–		–		59	33
Schizoaffective dis.	–		–		9	16
Schizophreniform dis.	–		–		4	–
Psychotic dis. NOS	–		–		11	6
Brief psychotic episode	–		–		2	–
Major depressive disorder[e]	12	11	18	15	–	
Substance use						
Cannabis	7.8 ± 21.9[f]	4.8 ± 32.0[g]	19.3 ± 37.2[f]	7.1 ± 49.1[g]	44.0 ± 47.0[f]	36.5 ± 105[g]
Other drugs	0.90 ± 4.7[f]	0.0	6.2 ± 31.4[f]	0.0	42.4 ± 90.8[f]	15.2 ± 57.0[g]
Alcohol	5.0 ± 7.0[h]	6.3 ± 10.8[i]	9.8 ± 17.3[h]	6.0 ± 5.4[i]	5.0 ± 9.1[h]	4.9 ± 7.6[i]
Trauma score	6.7 ± 1.8	6.6 ± 1.5	6.8 ± 1.5	6.6 ± 1.2	8.0 ± 2.5	7.5 ± 2.0
PANSS						
Positive symptoms	7.3 ± 1.1	7.4 ± 0.8	7.3 ± 0.9	7.4 ± 0.7	10.4 ± 5.0	11.6 ± 5.7
Negative symptoms	8.2 ± 1.0	8.0 ± 0.2	8.4 ± 2.0	8.0 ± 0.3	12.0 ± 5.9	11.1 ± 4.2
Disorganization	10.2 ± 1.2	10.1 ± 0.3	10.3 ± 0.7	10.1 ± 0.4	12.5 ± 4.1	11.8 ± 2.5
Excitement	8.3 ± 1.1	8.3 ± 0.5	8.6 ± 1.4	8.3 ± 0.6	9.7 ± 2.7	9.7 ± 2.5
Emotional distress	9.2 ± 2.1	9.4 ± 1.7	9.9 ± 2.6	9.7 ± 2.2	13.2 ± 5.2	14.1 ± 5.0
Remission (%)	–	–	–	–	57%	62%

PANSS, Positive and Negative Syndrome Scale; dis, disorder; NOS, not otherwise specified.
Means ± s.d., range are reported.
[a]Range: from −100 (entirely left-handed) to +100 (entirely right-handed).
[b]Range: 0 = no education to 8 = university degree.
[c]Cumulative exposure, lifetime until baseline in haloperidol equivalents.
[d]Cumulative exposure, last 3 years in haloperidol equivalents.
[e]History of major depressive disorder, no current episodes at baseline or in last 3 years.
[f]Mean number of times; lifetime.
[g]Mean number of times; last 12 months.
[h]Weekly consumptions; lifetime.
[i]Weekly consumptions; last 12 month.

($\chi^2 = 2.9$, df = 2, $p = 0.24$) (all analyses with linear environmental variables). The results did not change after stratification by number of scan directions (76 directions: cannabis exposure; lifetime: $\chi^2 = 1.4$, df = 2, $p = 0.49$, last year: $\chi^2 = 0.2$, df = 2, $p = 0.89$, childhood trauma exposure: $\chi^2 = 2.3$, df = 2, $p = 0.31$; and 81 directions: cannabis exposure; lifetime: $\chi^2 = 1.2$, df = 2, $p = 0.56$, last year: $\chi^2 = 1.5$, df = 2, $p = 0.48$, childhood trauma exposure: $\chi^2 = 0.2$, df = 2, $p = 0.93$).

Cross-sectional analysis of FA and environmental risk factors at follow-up

No significant associations between cannabis exposure (linear variable) and FA (lifetime: $B = 1.0 \times 10^{-4}$, $p = 0.95$, last year: $B = -3.0 \times 10^{-6}$, $p = 0.88$) or between childhood trauma exposure (linear variable) and FA ($B = -0.001$, $p = 0.67$) were found at follow-up.

https://doi.org/10.1017/S0033291718001320 Published online by Cambridge University Press

Table 2. Within-group distribution of the environmental exposures

	Controls	m/f ratio	Siblings	m/f ratio	Patients	m/f ratio	χ^2	*p*
Cannabis use (baseline)								
No	58 (73%)	34/66	59 (64%)	47/53	31 (39%)	48/52	29.8	0.00
Moderate	8 (10%)	38/62	11 (12%)	36/64	6 (8%)	33/67		
Heavy	13 (17%)	46/54	22 (24%)	73/27	43 (53%)	84/16		
Cannabis use (follow-up)								
No	37 (76%)	38/62	35 (64%)	49/51	20 (39%)	60/40	17.6	0.001
Moderate	5 (10%)	40/60	6 (11%)	33/67	5 (10%)	20/80		
Heavy	7 (14%)	43/57	14 (25%)	71/29	26 (51%)	88/12		
Childhood trauma (baseline)								
Low	38 (48%)	47/53	36 (39%)	50/50	21 (25%)	48/52	20.1	0.00
Moderate	26 (32%)	27/73	34 (36%)	50/50	22 (26%)	82/18		
Heavy	16 (20%)	25/75	23 (25%)	61/39	41 (49%)	71/29		
Childhood trauma (follow-up)								
Low	21 (43%)	52/48	23 (42%)	52/48	17 (31%)	53/47	6.5	0.17
Moderate	18 (37%)	28/72	18 (33%)	59/41	15 (27%)	80/20		
Heavy	10 (20%)	30/70	14 (25%)	43/57	23 (42%)	83/17		

The number of subjects per group (and proportion of total group) for the baseline ($n = 258$) and longitudinal analysis (follow-up, $n = 159$) per environmental stress factor. The difference between groups in proportion of high, medium, and low cannabis use was analyzed with the Pearson's (χ^2).
m/f ratio, male/female ratio.

Cannabis

No significant interaction was found between last year cannabis use and group in the model of FA ($\chi^2 = 0.8$, df = 2, $p = 0.66$). A significant interaction was found between, respectively, (lifetime) cannabis exposure ($\chi^2 = 9.3$, df = 2, $p = 0.01$) and group in the model of FA. This interaction remained significant after controlling for childhood trauma ($\chi^2 = 9.6$, df = 2, $p = 0.008$), BMI ($\chi^2 = 9.7$, df = 2, $p = 0.008$), alcohol use ($\chi^2 = 9.8$, df = 2, $p = 0.008$), and other drug use ($\chi^2 = 7.6$, df = 2, $p = 0.02$) (all linear variables).

Stratified analyses showed a mean FA decrease in the heavy cannabis using patients, which was significantly different from the controls and the siblings. An association in opposite direction was found in cannabis-using siblings, but only for the moderate cannabis exposure level and not for the highest exposure level (see Table 3).

Childhood trauma

A significant interaction between childhood trauma exposure and group in the model of FA ($\chi^2 = 6.1$, df = 2, $p = 0.05$) was found. The interaction remained significant after controlling for alcohol use ($\chi^2 = 8.8$, df = 2, $p = 0.01$), inconclusive for lifetime cannabis use ($\chi^2 = 4.9$, df = 2, $p = 0.09$) and BMI ($\chi^2 = 5.5$, df = 2, $p = 0.06$), however not significant anymore with addition of other drug use ($\chi^2 = 4.4$, df = 2, $p = 0.11$) (all linear variables).

Stratified analyses showed a mean FA decrease in patients exposed to a high childhood trauma level, which was significantly different from the siblings and inconclusive from the controls (see Table 3).

Longitudinal analysis of ΔFA and environmental risk factors

In the whole group, there was no significant association between, respectively, lifetime cannabis exposure ($B = -3.0 \times 10^{-5}$, $p = 0.16$), last year cannabis exposure ($B = -1.0 \times 10^{-5}$, $p = 0.45$), or childhood trauma exposure (all linear variables) and ΔFA ($B = -7.0 \times 10^{-4}$, $p = 0.13$).

Cannabis

There was a significant interaction between (lifetime) cannabis exposure and group in the model of ΔFA ($\chi^2 = 6.2$, df = 2, $p = 0.04$). This interaction remained significant after controlling for childhood trauma ($\chi^2 = 5.9$, df = 2, $p = 0.05$), BMI ($\chi^2 = 5.8$, df = 2, $p = 0.05$), alcohol use ($\chi^2 = 5.9$, df = 2, $p = 0.05$), other drug use ($\chi^2 = 7.4$, df = 2, $p = 0.02$), and scan type ($\chi^2 = 6.5$, df = 2, $p = 0.04$). After exclusion of the 26 participants with a history of depression (16% reduction in sample size), the interaction became inconclusive ($\chi^2 = 5.4$, df = 2, $p = 0.07$) (all linear variables).

Stratified analyses showed a significant effect in patients, indicating a decrease in FA over time with increasing cannabis exposure in patients, resulting in a significant group difference between patients and controls and between patients and siblings. Compared with patients with no cannabis use, patients with heavy cannabis consumption had significantly more FA decrease over time. This was not the case for the moderate *v.* no cannabis use comparison (Table 4, Fig. 1).

Childhood trauma

A significant interaction between trauma exposure and group in the model of ΔFA ($\chi^2 = 11.3$, df = 2, $p = 0.003$) was found. The interaction remained significant after controlling for lifetime cannabis

https://doi.org/10.1017/S0033291718001320 Published online by Cambridge University Press

Table 3. Mean FA as a function of group status and environmental exposure at follow-up

Environmental exposure	Patients			Siblings			Controls			Group differences		
	N	*B*	*p*	*N*	*B*	*p*	*N*	*B*	*p*		χ^2	*p*
Lifetime cannabis												
Cannabis (linear)		−0.005	0.02*		0.004	0.07		0.003	0.31	P *v.* C	4.6	0.03*
										P *v.* S	8.2	0.004*
										S *v.* C	0.09	0.76
No cannabis use[a]	21			39			45					
Moderate cannabis use	5	−0.01	0.29	7	0.01	0.04*	4	0.002	0.84	P *v.* C	0.77	0.38
										P *v.* S	4.4	0.04*
										S *v.* C	1.2	0.27
Heavy cannabis use	31	−0.01	0.02*	14	0.007	0.14	8	0.007	0.30	P *v.* C	4.8	0.03*
										P *v.* S	7.2	0.007*
										S *v.* C	0.007	0.94
Childhood trauma												
Trauma (linear)		−0.006	0.03*		0.002	0.52		0.003	0.33	P *v.* C	4.8	0.03*
										P *v.* S	4.1	0.04*
										S *v.* C	0.09	0.77
Low trauma[a]	18			28			30					
Medium trauma	24	−0.009	0.09	23	−0.005	0.31	19	0.005	0.26	P *v.* C	4.0	0.05*
										P *v.* S	0.4	0.53
										S *v.* C	2.3	0.13
High trauma	18	−0.01	0.03*	10	0.007	0.24	9	0.004	0.53	P *v.* C	3.5	0.06
										P *v.* S	5.7	0.02*
										S *v.* C	0.1	0.77

N, number of participants; P *v.* C, patients *v.* controls; P *v.* S, patients *v.* siblings; S *v.* C, siblings *v.* controls.
Results from the interaction: environmental exposure × group in the model of FA. The *B*'s represent the stratified group effect sizes. Group differences are displayed with χ^2, and the *p* value (<0.05*).
[a]Reference level.

use ($\chi^2 = 12.3$, df = 2, $p = 0.002$), BMI ($\chi^2 = 10.5$, df = 2, $p = 0.005$), alcohol use ($\chi^2 = 12.0$, df = 2, $p = 0.003$), other drug use ($\chi^2 = 14.6$, df = 2, $p = 0.0007$), and scan type ($\chi^2 = 11.5$, df = 2, $p = 0.003$). The interaction was inconclusive after exclusion of the 26 participants with a history of depression ($\chi^2 = 5.6$, df = 2, $p = 0.06$) (all linear variables).

Stratified analysis revealed a significant negative association between childhood trauma and ΔFA in patients, resulting in a significant patient–control and patient–sibling difference. Compared with low trauma exposure, patients exposed to high trauma levels had significantly more FA decrease over time. This was not the case for moderate compared with low trauma exposure (Table 4, Fig. 1).

Sensitivity analyses in AP medication subgroups

In the AP medication subgroup analyses (with smaller *N*), interactions between both environmental risk factors and group in the model of ΔFA remained largely significant, most prominent in patients with the lowest AP exposure levels (lifetime and 3-year interval). Wald tests showed that the significant negative associations between the environmental factor and ΔFA in the low AP subgroups were significantly different for the patient–control and the patient–sibling comparison (see online Supplementary Table S1).

Discussion

Despite the absence of cross-sectional associations between environmental risk factors and WM FA at baseline, there were significant interactions between group and cannabis and childhood trauma exposure in models of FA at follow-up and FA change over a 3-year time period. Patients exposed to the highest levels of cannabis or childhood trauma had a greater FA decrease over time compared with controls and siblings.

Cannabis exposure and WM alterations

Higher levels of (lifetime) cannabis exposure in patients with psychotic disorder were not associated with FA alterations at baseline, but with significant FA reduction over a 3-year period compared with siblings and healthy controls. This is the first

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https://doi.org/10.1017/S0033291718001320 Published online by Cambridge University Press

Table 4. Mean ΔFA as a function of group status and environmental exposure

	Patients				Siblings				Controls				Group differences		
Environmental exposure	*N*	ΔFA mean ± S.D.	*B*	*p*	*N*	ΔFA mean ± S.D.	*B*	*p*	*N*	ΔFA mean ± S.D.	*B*	*p*		χ^2	*p*
Lifetime cannabis															
Cannabis (linear)			−0.003	0.02*			0.001	0.41			0.001	0.39	P *v.* C	4.1	0.04*
													P *v.* S	4.7	0.03*
													S *v.* C	0.03	0.87
No cannabis use[a]	20	0.0014 ± 0.03			35	−0.0040 ± 0.03			37	−0.0005 ± 0.03					
Moderate cannabis use	5	0.0038 ± 0.03	0.002	0.60	6	0.0003 ± 0.03	0.004	0.25	5	0.0040 ± 0.03	0.003	0.47	P *v.* C	0.02	0.90
													P *v.* S	0.1	0.71
													S *v.* C	0.1	0.80
Heavy cannabis use	26	−0.0041 ± 0.03	−0.006	0.02*	14	−0.0022 ± 0.03	0.002	0.51	7	0.0040 ± 0.03	0.002	0.47	P *v.* C	3.7	0.05*
													P *v.* S	4.3	0.04*
													S *v.* C	0.03	0.86
Childhood trauma															
Trauma (linear)			−0.004	0.0005*			0.0002	0.90			0.002	0.26	P *v.* C	9.7	0.002*
													P *v.* S	6.4	0.01*
													S *v.* C	0.6	0.45
Low trauma[a]	17	0.0034 ± 0.03			23	−0.0018 ± 0.03			21	−0.00003 ± 0.03					
Medium trauma	15	0.0016 ± 0.03	−0.002	0.42	18	−0.0068 ± 0.03	−0.003	0.17	18	−0.00002 ± 0.03	0.0008	0.75	P *v.* C	0.7	0.42
													P *v.* S	0.1	0.76
													S *v.* C	1.4	0.24
High trauma	23	−0.0060 ± 0.03	−0.009	0.0005*	14	−0.0004 ± 0.03	0.001	0.71	10	0.0031 ± 0.03	0.004	0.23	P *v.* C	10.0	0.002*
													P *v.* S	7.2	0.007*
													S *v.* C	0.4	0.50

N, number of participants; P *v.* C, patients *v.* controls; P *v.* S, patients *v.* siblings; S *v.* C, siblings *v.* controls.
Results from the interaction: environmental exposure × group in the model of ΔFA. The *B*'s represent the stratified group effect sizes. Group differences are displayed with χ^2, and the *p* value (<0.05*).
[a]Reference level.

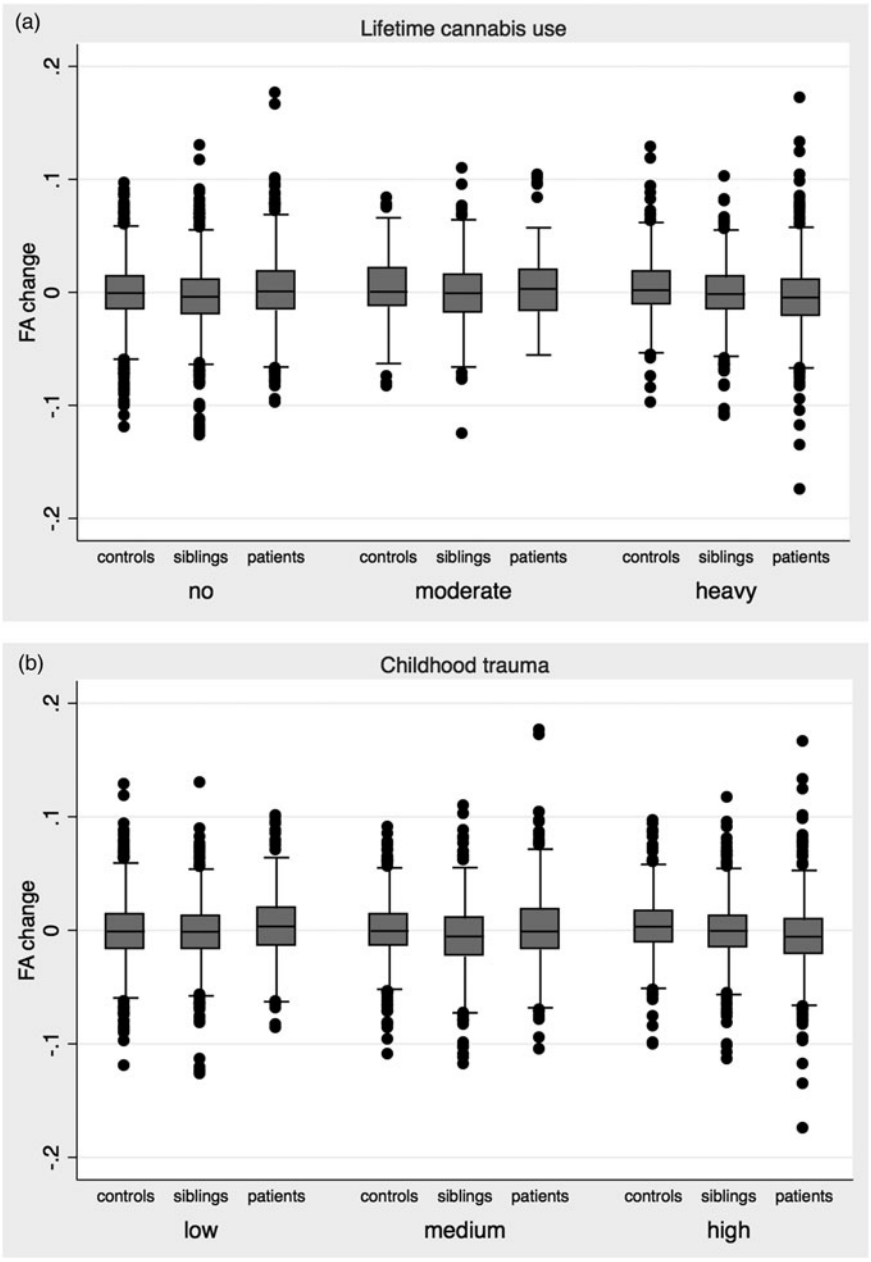


Fig. 1. The association between, respectively, cannabis (*a*) and childhood trauma (*b*) (dummy variables) and ΔFA, stratified per group. The effect of high cannabis exposure *v.* no cannabis exposure and high trauma exposure *v.* low trauma exposure on mean whole-brain ΔFA was significantly different for patients compared with controls (cannabis; $\chi^2 = 3.7$, $p = 0.05$, trauma; $\chi^2 = 10.0$, $p = 0.002$) and for patients compared with siblings (cannabis; $\chi^2 = 4.3$, $p = 0.04$, trauma; $\chi^2 = 7.2$, $p = 0.007$) (*$p < 0.05$).

longitudinal study examining the effect of cannabis on WM FA in relation to (familial risk for) psychotic disorder, suggesting that the extent of WM alterations is conditional on the level of cannabis exposure in patients with the disorder. Especially, cannabis use before or at disease onset may cause an additional reduction in WM FA, given the absence of an interaction between group and last year cannabis use in the model of ΔFA. This finding complies with other structural imaging findings of more severe WM deficits in young adults exposed to cannabis prior to the age of 16 (Cookey *et al.*, 2014). It strengthens the evidence, from both preclinical human and animal models, for a neurotoxic effect of cannabis in adolescence (Rubino and Parolaro, 2014); a sensitive age period for the neuronal maturation of the endocannabinoid system, possibly resulting in disrupted network connectivity of various brain areas.

To date, three longitudinal DTI studies examined substance abuse in non-psychotic populations. A lower rate of change in FA was found in adolescent cannabis users ($n = 23$) in five clusters of fronto-parietal association fibers over a 2-year interval (Becker *et al.*, 2015). Moreover, a significant FA decrease over time in the left ILF in adolescents with cannabis use disorder ($n = 19$), associated with more cannabis exposure, compared with healthy controls (Epstein and Kumra, 2015). A third study showed poorer WM integrity after an 18-month follow-up, although mainly predicted by alcohol, not marijuana, in seven fronto-parietal tracts in adolescent substance users ($n = 41$) (Bava *et al.*, 2013).

In previous cross-sectional studies, positive as well as negative associations between FA and cannabis use in patients with schizophrenia have been reported. James *et al.* (2011) revealed associations between early cannabis use and decreased FA in, e.g. the internal capsule, corona radiata, superior and ILF, in patients with adolescent-onset schizophrenia (James *et al.*, 2011). In contrast, Peters *et al.* (2009) found FA increases in the bilateral uncinate fasciculus, anterior internal capsule, and frontal WM in

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patients with recent-onset schizophrenia who had started using cannabis before the age of 17 years, compared with a similar group with no history of cannabis use (Peters *et al.*, 2009). Reduced FA has also been found in the splenium of the corpus callosum in non-cannabis using patients with schizophrenia compared with patients with schizophrenia and early-onset cannabis use (before age 15 years) (Dekker *et al.*, 2010). It has been shown that cannabis use may have different effects at various neurodevelopmental stages of life (Jakabek *et al.*, 2016). In the present study, absence of a significant cross-sectional association between FA and lifetime cannabis exposure at baseline in contrast to significant associations at follow-up between, respectively, high and moderate cannabis exposure and FA in patients and siblings compared with controls may imply an age-related effect. The effect of cannabis on brain WM may only be visible after many years, depending on the WM developmental curvature of the specific subject and the timing of the measurement.

The opposite direction of effect, i.e. the FA increases in relatives with increasing lifetime cannabis exposure may suggest a delayed maturation, an imaging artifact or even a protective effect of a small amount of cannabis. A cannabinoid neuroprotective effect on brain matter with improvement in WM efficiency (Westlye *et al.*, 2010) has been proposed by recent *in vitro* studies (Sarne and Mechoulam, 2005).

The negative association between especially the heavy cannabis using patients with psychotic disorder and FA may fit with the hypothesis that heavy cannabis use at a young age may have altered the normal trajectory of WM brain maturation. Interference on the extensive pruning and myelination processes in an already vulnerable adolescent brain (Lubman *et al.*, 2015) may have caused additional reduction in WM FA later on in life. Whether this has clinical implications or influences on long-term prognosis needs further investigation.

Childhood trauma exposure and WM alterations

The present study examined the association between childhood trauma and FA in individuals with (risk for) psychotic disorder. At baseline, neither a significant interaction between childhood trauma exposure and group in the model of FA was found, nor a main effect of childhood trauma in any of the groups. However, at follow-up, a significant (dose–response) negative association between childhood trauma exposure and group in the model of FA was found in patients with psychotic disorder. In other words, higher exposure to childhood trauma is associated with lower whole-brain mean FA later in life. As with cannabis, differences in baseline and follow-up results may be explained by the timing of genetic and environmental influences (and their interactions) impacting cerebral plasticity during the life span.

The follow-up findings are in line with several studies that show reduced FA in non-psychotic traumatized subjects (Choi *et al.*, 2012; Daniels *et al.*, 2013) in stress-processing-related areas, such as the corpus callosum (Jackowski *et al.*, 2008; Paul *et al.*, 2008) and the cingulum bundle (Wang *et al.*, 2010; Zhang *et al.*, 2011). Thus, cross-sectional studies indicate that the FA reductions in traumatized populations may show overlap with the WM abnormalities in schizophrenia (Kubicki *et al.*, 2007; Ellison-Wright and Bullmore, 2009), suggesting that (part of) the WM tract alterations may be non-specific, contributing to different phenotypes.

The current study did also find a greater FA decline over a 3-year period in the patients with the highest level of childhood trauma exposure with respect to siblings and healthy controls. This significant FA decline over time associated with higher levels of childhood trauma may fit with the literature describing the neurotoxic impact of childhood trauma on WM development at a sensitive age period (Heim and Binder, 2012).

The patient-specific finding with regard to childhood trauma may refer to a complicated interplay between trauma-related factors and psychosis-related factors to account for the more pronounced WM alterations, predominantly in the group with the highest trauma exposure. Although a causal relationship between childhood trauma and WM decreases cannot be determined from these data, experiencing severe childhood trauma may cause an additive effect on already disrupted WM development. Alternatively, illness-related factors such as disadvantageous life style and health issues (e.g. reduced physical activity, social deprivation, smoking) (von Hausswolff-Juhlin *et al.*, 2009) may have contributed to increased cerebral vulnerability in patients, either or not in interaction with the environmental exposures under investigation.

Methodological considerations

Apart from the strength of this study – a relatively large longitudinal imaging design with a gene–environment approach – some limitations need to be addressed.

The sample size of some longitudinal subgroup analyses was only modest or small, resulting in loss of power (and thus weak statistical effects) and increased likelihood of false-negative results. Taken together with a rather skewed gender distribution in our sample, gender-specific sub-analyses were not considered feasible although it is known that several WM tracts show gender-specific FA differences (Menzler *et al.*, 2011; Kanaan *et al.*, 2014).

A full understanding of the biological and clinical relevance of the reported small changes in FA is hampered. Nevertheless, one can imagine that disproportionally higher changes may arise due to stronger regional effects, either or not in combination with higher mean trauma levels. Future studies with larger sample sizes may provide more precise estimates of regional FA effect sizes associated with these environmental exposures.

Conform the various results across studies on the association between AP use and WM alterations (Szeszko *et al.*, 2008; Ozcelik-Eroglu *et al.*, 2014; Reis Marques *et al.*, 2014), and the small effect of last 3-year and lifetime AP use on ΔFA found in our previous analyses (Domen *et al.*, 2017), the current results suggest a minor confounding effect of AP use as not all the G × E interactions remained significant in different AP subgroups. However, the results of these sensitivity analyses must be viewed with caution given the sizable lack of power (patient–AP subgroups comprised one-third of the sample).

It is unlikely that the two DTI sequences used at baseline would have contributed to a systematic bias, as the proportions of the two sequences were almost equal between the groups. In addition, stratified analyses (by number of scan directions) and adjustment for scanning sequence did not change the results, fitting the suggestion that the variation in tensor estimation is negligible with more than 30 diffusion directions (Jones, 2004). Extracting mean FA values from the TBSS skeleton has the disadvantage of only examining the central portion of the WM tract, but will procure that WM was indeed examined. This is in line

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with more recent cannabis – diffusion studies that took a distance from a voxel-based comparison approach (Jakabek *et al.*, 2016).

Lastly, FA is a rather non-specific diffusion measure, containing information on myelination, fiber organization, and number of axons, and therefore not completely synonymous to 'WM integrity', so that the current findings must be interpreted with caution (O'Donnell and Pasternak, 2015). Nonetheless, a whole-brain, hypothesis-generating approach was chosen, as studies investigating the influence of environmental risk factors on WM alterations in patients with psychotic disorder are scarce and ambiguous.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0033291718001320

Acknowledgements. The authors thank Truda Driesen and Inge Crolla for their coordinating roles in the data collection, as well as the G.R.O.U.P. investigators: Richard Bruggeman, Wiepke Cahn, Lieuwe de Haan, René S. Kahn, Carin Meijer, Inez Myin-Germeys, Jim van Os, and Durk Wiersma.

Financial support. This work was supported by the Dutch organization for scientific research NWO [Genetic Risk and Outcome of Psychosis (G.R.O.U.P)] and the European Community's Seventh Framework Programme under Grant Agreement No. HEALTH-F2-2009-241909 (European Network of National Schizophrenia Networks Studying Gene-Environment Interactions Consortium).

Both funding sources had no further role in study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the paper for publication.

Conflict of interest. Jim van Os is or has been, in the last 3 years, an unrestricted research grant holder with, or has received financial compensation as an independent symposium speaker from Lundbeck and Janssen. Machteld Marcelis has received, in the last 3 years, financial compensation as an independent symposium speaker from Lundbeck and Janssen. All other authors report no biomedical financial interests or potential conflicts of interest.

Ethical standards. The authors assert that all procedures contributing to this work comply with the ethical standards of the relevant national and institutional committees on human experimentation and with the Helsinki Declaration of 1975, as revised in 2008.

References

Andreasen NC, Paradiso S and O'Leary DS (1998) "Cognitive dysmetria" as an integrative theory of schizophrenia; a dysfunction in cortical – subcortical – cerebellar circuitry. *Schizophrenia Bulletin* **24**, 203–218.

Annett M (1970) A classification of hand preference by association analysis. *British Journal of Psychology* **61**, 303–321.

Arnone D, Barrick TR, Chengappa S, Mackay CE, Clark CA and Abou-Saleh MT (2008) Corpus callosum damage in heavy marijuana use: preliminary evidence from diffusion tensor tractography and tract-based spatial statistics. *NeuroImage* **41**, 1067–1074.

Baker ST, Yucel M, Fornito A, Allen NB and Lubman DI (2013) A systematic review of diffusion weighted MRI studies of white matter microstructure in adolescent substance users. *Neuroscience & Biobehavioral Reviews* **37**, 1713–1723.

Bava S, Jacobus J, Thayer RE and Tapert SF (2013) Longitudinal changes in white matter integrity among adolescent substance users. *Alcoholism, Clinical & Experimental Research* **37**(suppl. 1), E181–E189.

Becker MP, Collins PF, Lim KO, Muetzel RL and Luciana M (2015) Longitudinal changes in white matter microstructure after heavy cannabis use. *Developmental Cognitive Neuroscience* **16**, 23–35.

Bendall S, Jackson HJ, Hulbert CA and McGorry PD (2008) Childhood trauma and psychotic disorders: a systematic, critical review of the evidence. *Schizophrenia Bulletin* **34**, 568–579.

Bernstein DP, Ahluvalia T, Pogge D and Handelsman L (1997) Validity of the childhood trauma questionnaire in an adolescent psychiatric population. *Journal of the American Academy of Child and Adolescent Psychiatry* **36**, 340–348.

Boos HB, Mandl RC, van Haren NE, Cahn W, van Baal GC, Kahn RS and Hulshoff Pol HE (2013) Tract-based diffusion tensor imaging in patients with schizophrenia and their non-psychotic siblings. *European Neuropsychopharmacology* **23**, 295–304.

Cahn W, Hulshoff Pol HE, Caspers E, van Haren NE, Schnack HG and Kahn RS (2004) Cannabis and brain morphology in recent-onset schizophrenia. *Schizophrenia Research* **67**, 305–307.

Canu E, Agosta F and Filippi M (2015) A selective review of structural connectivity abnormalities of schizophrenic patients at different stages of the disease. *Schizophrenia Research* **161**, 19–28.

Choi J, Jeong B, Polcari A, Rohan ML and Teicher MH (2012) Reduced fractional anisotropy in the visual limbic pathway of young adults witnessing domestic violence in childhood. *NeuroImage* **59**, 1071–1079.

Cookey J, Bernier D and Tibbo PG (2014) White matter changes in early phase schizophrenia and cannabis use: an update and systematic review of diffusion tensor imaging studies. *Schizophrenia Research* **156**, 137–142.

Cornblatt BA, Lencz T, Smith CW, Correll CU, Auther AM and Nakayama E (2003) The schizophrenia prodrome revisited: a neurodevelopmental perspective. *Schizophrenia Bulletin* **29**, 633–651.

Daniels JK, Lamke JP, Gaebler M, Walter H and Scheel M (2013) White matter integrity and its relationship to PTSD and childhood trauma – a systematic review and meta-analysis. *Depression and Anxiety* **30**, 207–216.

Dekker N, Schmitz N, Peters BD, van Amelsvoort TA, Linszen DH and de Haan L (2010) Cannabis use and callosal white matter structure and integrity in recent-onset schizophrenia. *Psychiatry Research* **181**, 51–56.

Domen P, Peeters S, Michielse S, Gronenschild E, Viechtbauer W, Roebroeck A, van Os J and Marcelis M (2017) Differential time course of microstructural white matter in patients with psychotic disorder and individuals at risk: a 3-year follow-up study. *Schizophrenia Bulletin* **43**, 160–170.

Domen PA, Michielse S, Gronenschild E, Habets P, Roebroeck A, Schruers K, van Os J and Marcelis M (2013) Microstructural white matter alterations in psychotic disorder: a family-based diffusion tensor imaging study. *Schizophrenia Research* **146**, 291–300.

Ellison-Wright I and Bullmore E (2009) Meta-analysis of diffusion tensor imaging studies in schizophrenia. *Schizophrenia Research* **108**, 3–10.

Epstein KA and Kumra S (2015) White matter fractional anisotropy over two time points in early onset schizophrenia and adolescent cannabis use disorder: a naturalistic diffusion tensor imaging study. *Psychiatry Research* **232**, 34–41.

Friston KJ (1998) The disconnection hypothesis. *Schizophrenia Research* **30**, 115–125.

Heim C and Binder EB (2012) Current research trends in early life stress and depression: review of human studies on sensitive periods, gene-environment interactions, and epigenetics. *Experimental Neurology* **233**, 102–111.

Jackowski AP, Douglas-Palumberi H, Jackowski M, Win L, Schultz RT, Staib LW, Krystal JH and Kaufman J (2008) Corpus callosum in maltreated children with posttraumatic stress disorder: a diffusion tensor imaging study. *Psychiatry Research* **162**, 256–261.

Jakabek D, Yucel M, Lorenzetti V and Solowij N (2016) An MRI study of white matter tract integrity in regular cannabis users: effects of cannabis use and age. *Psychopharmacology* (*Berlin*) **233**, 3627–3637.

James A, Hough M, James S, Winmill L, Burge L, Nijhawan S, Matthews PM and Zarei M (2011) Greater white and grey matter changes associated with early cannabis use in adolescent-onset schizophrenia (AOS). *Schizophrenia Research* **128**, 91–97.

Jones DK (2004) The effect of gradient sampling schemes on measures derived from diffusion tensor MRI: a Monte Carlo study. *Magnetic Resonance in Medicine* **51**, 807–815.

Kanaan RA, Chaddock C, Allin M, Picchioni MM, Daly E, Shergill SS and McGuire PK (2014) Gender influence on white matter microstructure: a tract-based spatial statistics analysis. *PLoS ONE* **9**, e91109.

Kay SR, Fiszbein A and Opler LA (1987) The positive and negative syndrome scale (PANSS) for schizophrenia. *Schizophrenia Bulletin* **13**, 261–276.

https://doi.org/10.1017/S0033291718001320 Published online by Cambridge University Press

Korver N, Quee PJ, Boos HB, Simons CJ and de Haan L (2012) Genetic risk and outcome of psychosis (GROUP), a multi-site longitudinal cohort study focused on gene-environment interaction: objectives, sample characteristics, recruitment and assessment methods. *International Journal of Methods in Psychiatric Research* **21**, 205–221.

Kubicki M, McCarley R, Westin CF, Park HJ, Maier S, Kikinis R, Jolesz FA and Shenton ME (2007) A review of diffusion tensor imaging studies in schizophrenia. *Journal of Psychiatric Research* **41**, 15–30.

Lubman DI, Cheetham A and Yucel M (2015) Cannabis and adolescent brain development. *Pharmacology and Therapeutics* **148**, 1–16.

Maynard TM, Sikich L, Lieberman JA and LaMantia AS (2001) Neural development, cell-cell signaling, and the "two-hit" hypothesis of schizophrenia. *Schizophrenia Bulletin* **27**, 457–476.

Menzler K, Belke M, Wehrmann E, Krakow K, Lengler U, Jansen A, Hamer HM, Oertel WH, Rosenow F and Knake S (2011) Men and women are different: diffusion tensor imaging reveals sexual dimorphism in the microstructure of the thalamus, corpus callosum and cingulum. *NeuroImage* **54**, 2557–2562.

Misiak B, Krefft M, Bielawski T, Moustafa AA, Sąsiadek MM and Frydecka D (2017) Toward a unified theory of childhood trauma and psychosis: a comprehensive review of epidemiological, clinical, neuropsychological and biological findings. *Neuroscience & Biobehavioral Reviews* **75**, 393–406.

Molina-Holgado E, Vela JM, Arevalo-Martin A, Almazan G, Molina-Holgado F, Borrell J and Guaza C (2002) Cannabinoids promote oligodendrocyte progenitor survival: involvement of cannabinoid receptors and phosphatidylinositol-3 kinase/Akt signaling. *The Journal of Neuroscience* **22**, 9742–9753.

Nesvåg R, Frigessi A, Jönsson EG and Agartz I (2007) Effects of alcohol consumption and antipsychotic medication on brain morphology in schizophrenia. *Schizophrenia Research* **90**, 52–61.

O'Donnell LJ and Pasternak O (2015) Does diffusion MRI tell us anything about the white matter? An overview of methods and pitfalls. *Schizophrenia Research* **161**, 133–141.

Ozcelik-Eroglu E, Ertugrul A, Oguz KK, Has AC, Karahan S and Yazici MK (2014) Effect of clozapine on white matter integrity in patients with schizophrenia: a diffusion tensor imaging study. *Psychiatry Research* **223**, 226–235.

Pagliaccio D, Luby JL, Bogdan R, Agrawal A, Gaffrey MS, Belden AC, Botteron KN, Harms MP and Barch DM (2014) Stress-system genes and life stress predict cortisol levels and amygdala and hippocampal volumes in children. *Neuropsychopharmacology* **39**, 1245–1253.

Paul R, Henry L, Grieve SM, Guilmette TJ, Niaura R, Bryant R, Bruce S, Williams LM, Richard CC, Cohen RA and Gordon E (2008) The relationship between early life stress and microstructural integrity of the corpus callosum in a non-clinical population. *Neuropsychiatric Disease and Treatment* **4**, 193–201.

Peters BD, Blaas J and de Haan L (2010) Diffusion tensor imaging in the early phase of schizophrenia: what have we learned? *Journal of Psychiatric Research* **44**, 993–1004.

Peters BD, de Haan L, Vlieger EJ, Majoie CB, den Heeten GJ and Linszen DH (2009) Recent-onset schizophrenia and adolescent cannabis use: MRI evidence for structural hyperconnectivity? *Psychopharmacology bulletin* **42**, 75–88.

Reis Marques T, Taylor H, Chaddock C, Dell'acqua F, Handley R, Reinders AA, Mondelli V, Bonaccorso S, Diforti M, Simmons A, David AS, Murray RM, Pariante CM, Kapur S and Dazzan P (2014) White matter integrity as a predictor of response to treatment in first episode psychosis. *Brain* **137**, 172–182.

Rubino T and Parolaro D (2014) Cannabis abuse in adolescence and the risk of psychosis: a brief review of the preclinical evidence. *Progress in Neuropsychopharmacology & Biological Psychiatry* **52**, 41–44.

Sarne Y and Mechoulam R (2005) Cannabinoids: between neuroprotection and neurotoxicity. *Current Drug Targets. CNS and Neurological Disorders* **4**, 677–684.

Szeszko PR, Robinson DG, Ashtari M, Vogel J, Betensky J, Sevy S, Ardekani BA, Lencz T, Malhotra AK, McCormack J, Miller R, Lim KO, Gunduz-Bruce H, Kane JM and Bilder RM (2007) Anterior cingulate grey-matter deficits and cannabis use in first-episode schizophrenia. *British Journal of Psychiatry* **190**, 230–236.

Szeszko PR, Robinson DG, Sevy S, Kumra S, Rupp CI, Betensky JD, Lencz T, Ashtari M, Kane JM, Malhotra AK, Gunduz-Bruce H, Napolitano B and Bilder RM (2008) Clinical and neuropsychological correlates of white matter abnormalities in recent onset schizophrenia. *Neuropsychopharmacology* **33**, 976–984.

Team RC (2015) *R: A Language and Environment for Statistical Computing*. In R Foundation for Statistical Computing: Vienna, Austria.

Teicher MH, Andersen SL, Polcari A, Anderson CM and Navalta CP (2002) Developmental neurobiology of childhood stress and trauma. *Psychiatric Clinics of North America* **25**, 397–426, vii-viii.

Teicher MH, Dumont NL, Ito Y, Vaituzis C, Giedd JN and Andersen SL (2004) Childhood neglect is associated with reduced corpus callosum area. *Biological Psychiatry* **56**, 80–85.

Thombs BD, Bernstein DP, Lobbestael J and Arntz A (2009) A validation study of the Dutch childhood trauma questionnaire-short form: factor structure, reliability, and known-groups validity. *Child Abuse & Neglect* **33**, 518–523.

van Os Jand Kapur S (2009). Schizophrenia. *The Lancet* **374**, 635–645.

Varese F, Smeets F, Drukker M, Lieverse R, Lataster T, Viechtbauer W, Read J, van Os J and Bentall RP (2012) Childhood adversities increase the risk of psychosis: a meta-analysis of patient-control, prospective- and cross-sectional cohort studies. *Schizophrenia Bulletin* **38**, 661–671.

Voineskos AN (2015) Genetic underpinnings of white matter 'connectivity': heritability, risk, and heterogeneity in schizophrenia. *Schizophrenia Research* **161**, 50–60.

von Hausswolff-Juhlin Y, Bjartveit M, Lindstrom E and Jones P (2009) Schizophrenia and physical health problems. *Acta Psychiatrica Scandinavica* **119**(suppl. 438), 15–21.

Wang F, Jiang T, Sun Z, Teng SL, Luo X, Zhu Z, Zang Y, Zhang H, Yue W, Qu M, Lu T, Hong N, Huang H, Blumberg HP and Zhang D (2009) Neuregulin 1 genetic variation and anterior cingulum integrity in patients with schizophrenia and healthy controls. *Journal of Psychiatry & Neuroscience* **34**, 181–186.

Wang HH, Zhang ZJ, Tan QR, Yin H, Chen YC, Wang HN, Zhang RG, Wang ZZ, Guo L, Tang LH and Li LJ (2010) Psychopathological, biological, and neuroimaging characterization of posttraumatic stress disorder in survivors of a severe coalmining disaster in China. *Journal of Psychiatric Research* **44**, 385–392.

Westlye LT, Walhovd KB, Dale AM, Bjornerud A, Due-Tonnessen P, Engvig A, Grydeland H, Tamnes CK, Ostby Y and Fjell AM (2010) Life-span changes of the human brain white matter: diffusion tensor imaging (DTI) and volumetry. *Cerebral Cortex* **20**, 2055–2068.

World Health Organization (WHO) (1990) *Composite International Diagnostic Interview (CIDI): a) CIDI-interview (version 1.0), b) CIDI-user manual, c) CIDI-training manual, d) CIDI-computer programs*. Geneva: WHO.

Willi TS, Barr AM, Gicas K, Lang DJ, Vila-Rodriguez F, Su W, Thornton AE, Leonova O, Giesbrecht CJ, Procyshyn RM, Rauscher A, MacEwan WG, Honer WG and Panenka WJ (2017) Characterization of white matter integrity deficits in cocaine-dependent individuals with substance-induced psychosis compared with non-psychotic cocaine users. *Addiction Biology* **22**, 873–881.

Zalesky A, Solowij N, Yucel M, Lubman DI, Takagi M, Harding IH, Lorenzetti V, Wang R, Searle K, Pantelis C and Seal M (2012) Effect of long-term cannabis use on axonal fibre connectivity. *Brain* **135**, 2245–2255.

Zhang L, Zhang Y, Li L, Li Z, Li W, Ma N, Hou C, Zhang Z, Zhang Z, Wang L, Duan L and Lu G (2011) Different white matter abnormalities between the first-episode, treatment-naive patients with posttraumatic stress disorder and generalized anxiety disorder without comorbid conditions. *Journal of Affective Disorders* **133**, 294–299.

https://doi.org/10.1017/S0033291718001320 Published online by Cambridge University Press