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RESEARCH REPORT

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Impacts of recreational cannabis legalization on cannabis use: a longitudinal discordant twin study

Stephanie M. Zellers[1] | **J. Megan Ross**[2] | **Gretchen R. B. Saunders**[1] | **Jarrod M. Ellingson**[2,3] | **Jacob E. Anderson**[1] | **Robin P. Corley**[3] | **William Iacono**[1] | **John K. Hewitt**[3,4] | **Christian J. Hopfer**[2,3] | **Matt K. McGue**[1] | **Scott Vrieze**[1]

[1]Department of Psychology, University of Minnesota, Minneapolis, MN, USA

[2]Department of Psychiatry, University of Colorado Anschutz Medical Campus, Aurora, CO, USA

[3]Institute for Behavioral Genetics, University of Colorado Boulder, Boulder, CO, USA

[4]Department of Psychology and Neuroscience, University of Colorado Boulder, Boulder, CO, USA

Correspondence
Stephanie M. Zellers, Department of Psychology, University of Minnesota Twin Cities, N218 Elliott Hall, 75 East River Parkway, Minneapolis, MN 55455, USA.
Email: zelle063@umn.edu

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Abstract

Aims: To estimate the effect of recreational legalization on cannabis use frequency and sources of variance across legal environments.

Design: Longitudinal discordant twin and gene–environment interaction models in twins recruited from birth records and assessed prospectively.

Setting: The United States, including states with different recreational cannabis policies before and after 2014, when recreational cannabis was first legalized.

Participants: Two longitudinal, prospectively assessed samples of American twins aged 24–47 (n = 1425 in legal states, n = 1996 in illegal states), including 111 monozygotic pairs discordant for residence.

Measurements: Current cannabis use frequency (measured continuously and ordinally) was the primary outcome, and the predictor was recreational status of cannabis (legal/illegal) in the participant's state of residence at the time of assessment. Covariates include age, sex and cannabis use frequency prior to 2014.

Findings: Accounting for pre-2014 use, residents of legal states used cannabis more frequently than residents of illegal states (b = 0.21, $P = 8.08 \times 10^{-5}$). Comparing 111 pairs of monozygotic twins discordant for residence confirmed the effect (b = 0.18, P = 0.014). There was inconclusive evidence for genetic influences on cannabis use frequency that were specific to the legal environment [$\chi^2 = 2.9 \times 10^{-9}$, degrees of freedom (d.f.) = 1, $P > 0.999$]. Existing genetic influences were moderated by the legal environment, as the genetic correlation between marijuana use before and after legalization was lower in states that legalized ($r_{genetic} = 0.24$) compared with states that did not ($r_{genetic} = 0.78$, $P_{difference} = 0.016$).

Conclusions: In the United States, there appears to be a ~ 20% average increase in cannabis use frequency attributable to recreational legalization, consistent across increasingly rigorous designs. In addition, the heritability of cannabis use frequency appears to be moderated by legalization.

KEYWORDS
Behavior genetics, causal inference, co-twin control, gene–environment interaction, natural experiment, substance use

INTRODUCTION

Before 2014, cannabis could not be legally sold or purchased for recreational purposes anywhere in the United States. By early 2022, more than 141 million Americans lived in a state with recreationally legal cannabis [1]. These rapid state-by-state changes in policy resulted in vastly different cannabis environments between states. For example, Colorado began retail sales of legalized recreational cannabis in 2014 and sales topped $2.2 billion in 2020 [2, 3]. Minnesota legalized medical cannabis in the same year and it remains tightly regulated, with fewer 0 active registered users [4, 5].

Cross-sectional and repeated cross-sectional studies have played an important role in understanding the impact of recreational legalization. These studies have found greater rates of use, frequency of use and rates of cannabis use disorders in recreationally legal states compared to medically legal states and states without legal use [6–12]. Large nationally representative studies find that the odds of past 30-day use and frequent use in recreationally legal states are ~1.25 times those in recreationally illegal states [7, 12].

Cross-sectional designs cannot examine cultural or secular trends, and both cross-sectional and repeated cross-sectional designs cannot examine within-individual change, nor can they control for an individual's earlier use, other relevant variables or confounds. Indeed, cross-sectional reports on recreational cannabis policies offer conflicting explanations on whether there are pre-existing differences between states with varying cannabis laws, or if changes to laws lead to changes in use [13–15]. Furthermore, states without recreational cannabis policies have also seen increases in use over time, albeit of smaller magnitudes than recreational states [7].

Of additional interest is the degree to which recreational legalization may moderate genetic liability to use cannabis, as it represents a major environmental change that could alter the relative importance of factors underlying individual differences in cannabis use. Tobacco policy research suggests that national attitudes and stricter state-level policies (e.g. higher taxes) exert social control and attenuate genetic risk for smoking [16, 17]. It is unknown whether similar patterns exist for cannabis.

In this study, we evaluated the effects of recreational cannabis legalization in a large sample of prospectively assessed adult twins from similar cohorts of individuals born in Colorado and Minnesota, demographically similar states with different cannabis policies. While many participants still reside in their birth states, some participants have migrated to other states resulting in pairs discordant for exposure to recreational legalization. The prospective longitudinal data and natural experiment allow for temporal sequencing of exposure and outcome, as well as controlling for earlier use. This is particularly important, because use may be higher in states that go on to recreationally legalize compared to states that do not, even prior to the enactment of recreational policies [7, 12].

Furthermore, observing differences within twin pairs provides a natural way to control potential confounding factors, such as genes, socio-economic status, community norms and parental attitudes, reducing the number of alternative explanations for the pattern of results. In other words, twins provide extremely well-matched controls for each other and permit more precise estimation of the causal impact of recreational legalization than studies of unrelated individuals. Additionally, the twin design allows estimation of heritability and environmental variation underlying cannabis use in disparate environments.

We answer these key questions using a longitudinal discordant twin design and biometric variance decompositions: (1) how much more frequently is cannabis used by residents of a recreationally legal state, controlling for a wide variety of unmeasured genetic and environmental confounders; (2) what are the sources and magnitudes of variance underlying cannabis use (i.e. genetic, shared environmental, unique environmental); and (3) how do those sources vary over time and between environments? This project was pre-registered on 11 March 2021, at https://osf.io/a3sk7/.

METHOD

Participants

We analyzed data from 3452 individuals (data freeze-dated 16 March 2021) drawn from two over-arching samples: the Minnesota Center for Twin Family Research [18] and the University of Colorado Boulder Center for Antisocial Drug Dependence [19]. Individuals were assessed before and after 2014 when recreational cannabis was legalized in Colorado and medical cannabis was legalized in Minnesota. The joint post-2014 assessment was identical for participants from both sites; pre-2014 assessments were conducted independently and subsequently harmonized. Table 1 lists descriptive statistics for ages and assessment years, which are presented in more detail in Supporting information, Table S1. Each participant contributed two data points: one pre-2014 and one post-2014. The pre-2014 assessment was selected as each participant's most recent pre-2014 measure of cannabis use. The post-2014 assessment was the intake survey from the joint assessment.

The full sample comprised 1407 males and 2045 females. Consistent with the demographics of their birth cohorts, 3168 (92%) participants were white and 181 (5%) reported Hispanic ethnicity (see Supporting information, Methods).

Measures

Residency

Thirty-one individuals were excluded on the basis of residence (one participant missing all residence items, 26 international participants, four domestic participants with missing/invalid ZIP code) resulting in an analytical sample of 3421. Using established definitions of recreational legalization and enactment dates (Supporting information, Table S2), participants' residence was classified based on ZIP code and assessment date [20, 21].

TABLE 1 Descriptives for ages and years of assessment by cohort

Pre-2014							
Study	**Mean age**	**SD age**	**Min. age**	**Max. age**	**Median test year**	**Min. test year**	**Max. test year**
Colorado	25.3	2.8	16.5	34.4	2010	2002	2013
Minnesota	24.2	4.7	16.9	32.7	2009	1996	2013
Post-2014							
Study	**Mean age**	**SD age**	**Min. age**	**Max. age**	**Median test year**	**Min. test year**	**Max. test year**
Colorado	34.0	2.6	27.9	41.1	2019	2018	2021
Minnesota	34.8	5.6	24.8	47.8	2019	2018	2021

Age changes from pre- to post-2014				
Study	**Mean age change**	**SD age change**	**Min. age change**	**Max. age change**
Colorado	8.8	1.7	4.6	17.7
Minnesota	10.6	3.6	4.3	23.8

Sample sizes by zygosity							
		Monozygotic		**Same-sex dizygotic**		**Opposite-sex dizygotic**	
Study	**Total sample size**	**Individ., *n***	**Pairs, *n***	**Individ., *n***	**Pairs, *n***	**Individ., *n***	**Pairs, *n***
Colorado	1752	848	363	556	208	348	139
Minnesota	1700	1073	437	627	234	0	0

Individ., *n* = total number of individuals; Pairs, *n* = number of complete pairs; SD = standard deviation.

Table 2 presents descriptives of states and residence status: 1425 participants lived in recreationally legal states, 1612 lived in a state with comprehensive medical cannabis [tetrahydrocannabinol (THC) and cannabidiol (CBD) products], 292 lived in states with limited medical cannabis (CBD products), and 92 participants lived in states without any medical cannabis, for a total of 1996 participants residing in recreationally illegal states. There were 212 discordant twin pairs in total, 111 of which were monozygotic twin pairs. We defined recreational legalization as a binary variable in our analyses and did not differentiate between comprehensive, limited and no medical policy states.

Cannabis use frequency

We utilized frequency of cannabis use, as opposed to quantity or heavy use, due to ease of measurement, availability of the measure at both sites prior to 2014 and ease of harmonization. Pre-2014 assessments from Colorado operationalized cannabis use frequency continuously as 'number of days used in the last 180 days', and those assessments from Minnesota operationalized cannabis use frequency ordinally as 'typical frequency of use across the last year'. We harmonized pre-2014 data to create a continuous measure of days of use during a period of 6 months, which was log-transformed to curtail excessive leverage of extreme responses. At the post-2014 joint assessment, both items were assessed. Ordinal response options, harmonization mappings and results from an analogous ordinal measure are available in the Supporting information. Unless otherwise noted, results from both frameworks agreed in the direction of effect and significance.

Covariates

One component of the Minnesota-born sample was selected for higher childhood externalizing psychopathology [22]. We created a binary covariate to indicate if participants were part of this selected sample (286 participants; 8%) or all other non-selected community samples. This cohort indicator, age and sex were included as fixed effects in all analyses.

Analyses

Research question 1

To evaluate differences in mean cannabis use frequency, we combined the longitudinal design with a discordant twin analysis. Both groups were 'unexposed' to recreationally legal cannabis at baseline and some participants were non-randomly exposed during the study; differences in current cannabis frequency were evaluated, controlling for cannabis frequency at baseline.

First, we evaluated the individual-level effect of residing in a recreationally legal state using a mixed-effects model: $Y = XB + Zu + \epsilon$.

TABLE 2 Residence descriptives

		Individuals, *n*	Percentage
Individual residence	Legal	1425	41.7
	Illegal	1996	58.3
Twin-pair residence	Concordant legal	918	26.8
	Concordant illegal	1382	40.4
	Discordant	414	12.1
	Singletons	707	20.7
State of residence	Colorado	1196	35.0
	Minnesota	1313	38.3
	Other	912	26.7

Here Y is post-2014 cannabis use frequency, X is the design matrix that includes residence, Z is the design matrix for the random effect of individual nested within family u and ϵ is the error term. Therefore, B is the matrix of individual-level fixed effects of legalization on post-2014 cannabis use frequency. Important to this design, we have shown in previous work using these same data that little to no differences existed in the trajectories of cannabis frequency prior to recreational legalization [23]. That is to say, prior to 2014, early use and the rate at which cannabis use escalated in adolescent and young adulthood were the same in these cohorts. This permits an investigation of how the cohorts have diverged after the passage of recreational policies.

Next, we modified this regression into a co-twin control to account for within and between twin-pair effects to further control unmeasured shared confounders [24]. All pairs were included for analysis in this model: $Y_{ij} = B_0 + B_B\overline{X}_{.j} + B_w\left(X_{ij} - \overline{X}_{.j}\right) + Zu + \epsilon_{ij.}$ Here $\overline{X}_{.j}$ corresponds to the average exposure within twin-pair j and $X_{ij} - \overline{X}_{.j}$ corresponds to the discordance of twin i from their co-twin within pair j. Therefore, B_B represents the between-pair effect (i.e. the average effect of legalization across twin pairs). B_W represents the within-pair effect (i.e. average difference in frequency of use between twins within a pair when residence is discordant).

Discordant twin analyses were conducted in a pooled analysis of all twins as well as stratified by zygosity [25, 26]. This approach balanced the power afforded by the larger sample size for the pooled twins with the precise control for shared confounding variables in zygosity-stratified analyses. The degree of potential genetic and shared environmental confounding was evaluated by comparing the magnitude of the individual-level effect to the magnitudes of the within-pair effects in monozygotic and dizygotic groups [24]. If B_{W-MZ} is of comparable magnitude to B, the effect is considered to be consistent with a causal explanation. Alternatively, if B_{W-MZ} is negligible, while the B_{W-DZ} is less than B, this is consistent with an effect entirely due to genetic and shared environmental confounding. Lastly, if the B_{W-MZ} is less than B_{W-DZ}, which is in turn less than the B, this is consistent with an effect partially due to confounding. To formally compare B_{W-MZ} to B, we computed the mean difference between standardized B_{W-MZ} and B and the 95% confidence interval (CI) around the difference throughout 1000 bootstrap replicates.

Research questions 2 and 3

To evaluate the magnitude and sources of variation underlying cannabis use, we utilized a gene–environment interaction model where twins within a pair may be discordant for some measured environment [27]. The gene–environment interaction model tests two key questions: (1) do the magnitudes of genetic and environmental effects differ as a function of environmental exposure (i.e. scalar effects model) and (2) whether the same genes influence cannabis use frequency to the same extent in each environment (i.e. common effects model).

We biometrically decomposed the variation and covariation underlying cannabis use frequency over time into additive genetic, shared environmental and unique environmental sources. Additive genetic effects are the result of genetic influences on a trait that combine allelic effects additively. Shared environmental effects are those influences in the environment that make twins within the same family more similar to each other (e.g. the rearing environment). Unique environmental effects are those influences that make twins within a pair less similar to each other; for example, events that one twin may experience but their co-twin does not, or measurement error.

A full description of the gene–environment interaction model, which estimates variance components separately for each residence and a gene–environment interaction term, is presented in the Supporting information, Methods. Overall model fit was assessed by comparing the gene–environment interaction model to a saturated model in which twin variance–covariance matrices were freely estimated for each group with no structure imposed. We also fitted two types of reduced models to compare to the overall gene–environment model via likelihood ratio test: (1) a common effect model, where genetic effects are restricted to only those genetic influences common to each environment, but the relative magnitudes of effect in any given environment are free to vary; and (2) scalar effects models, where the relative magnitude of genetic and environmental effects are constrained to be equal between the two environments. CIs were computed using maximum likelihood [28].

Statistical software and missing data

Data cleaning, analyses and plotting were conducted in RStudio (version 1.4.1106) using the packages lme4 version 1.1–23 [29], lmerTest version 3.1–3 [30] and OpenMx version 2.17.3 [31]. Six individuals were missing on post-2014 cannabis use, and 87 individuals were missing on pre-2014 cannabis frequency; these individuals were listwise-deleted in individual and discordant twin models. Singletons (n = 707) are missing on residence when decomposed into between- and within-pair effects and were listwise-deleted in discordant twin models. Biometric analyses conducted in OpenMx use full-information maximum likelihood, so all same-sex complete pairs were included regardless of missingness on covariates or cannabis frequency.

Ethics approval

The University of Minnesota Institutional Review Board (IRB) determined that this work was not research involving human subjects as defined by Worksheet HRP-310 and therefore did not require ongoing IRB approval. Participants provided informed consent prior to assessment.

RESULTS

Research question 1

Figure 1, Supporting information, Table S3 and Supporting information, Fig. S1 present the mean of cannabis use frequency in each residence over time. After controlling for covariates, pre-2014 mean cannabis frequency was not significantly different between states that did not legalize and states that later legalized [χ^2 = 1.24, degrees of freedom (d.f.) = 1, P = 0.266], but post-2014 mean cannabis frequency was higher in recreationally legal states compared to illegal states (χ^2 = 7.30, d.f. = 1, P = 0.007).

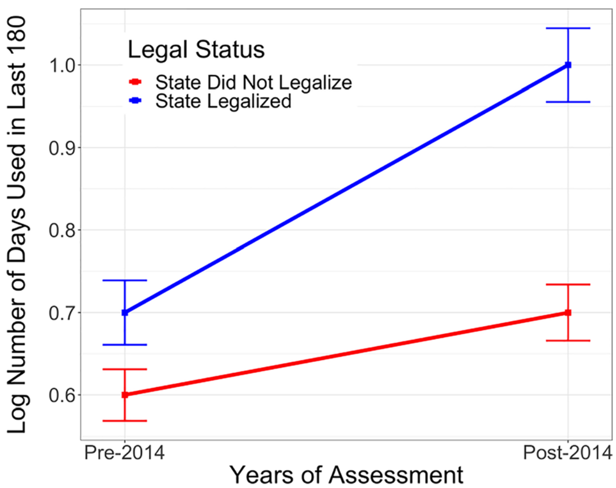

FIGURE 1 Line graph depicting mean differences in the continuous measure of cannabis use prior to and after the first recreational legalization event, split by participant residence at the post-2014 assessment. Bars represent ± one standard error

Table 3 and Supporting information, Table S4 present the fixed effects for the individual and co-twin control analyses. At the individual level residents of recreationally legal states used cannabis more frequently than their recreationally illegal counterparts (B = 0.21, $P = 8.08 \times 10^{-5}$), and this effect was robust after controlling for pre-2014 cannabis frequency. The effect of legalization was also robust to all shared genetic and shared environmental confounds, as the results throughout the co-twin models are consistent in direction and comparable in magnitude to the individual level effect (B_{W-MZ} = 0.18, P = 0.014). We confirmed this via bootstrap; the effects were not significantly different from each other [mean difference = 0.073, 95% CI = (−0.070, 0.216)].

To explore this result further, we evaluated alternative definitions of cannabis use: life-time use and use in the last 12 months. We also evaluated cannabis frequency only in last-year users, as 69% of individuals reported no last-year use. Recreational legalization was significantly associated with greater odds of both life-time (B = 0.45, P = 0.001) and recent (B = 0.61, $P = 1.12 \times 10^{-5}$) cannabis use at the individual level, but only the effect on recent use was maintained in the within-pair analysis (B = 0.33, P = 0.017). When examining the effect of legalization on frequency only in recent users, the individual (B = 0.12, P = 0.258) and within-pair effect of legalization (B = 0.21, P = 0.290) were greatly attenuated. This suggests that the effect of recreational legalization on mean cannabis frequency is driven by more individuals using, rather than by increasing frequency within users.

Research questions 2 and 3

On average, monozygotic twins ($r \sim 0.50$) were more strongly correlated in their frequencies of cannabis use than their same-sex dizygotic ($r \sim 0.35$) or opposite-sex dizygotic ($r \sim 0.25$) counterparts (see Supporting information, Tables S5, S6 and S7), which indicates the influence of additive genetic influences on cannabis frequency.

Both the saturated and reduced scalar effects models fitted worse than the full gene–environment interaction model (see Supporting information, Table S8 for fit statistics), indicating appropriateness of the twin structure and differences in the magnitude of genetic and environmental influences over time and between environments. Figure 2 and Supporting information, Fig. 2 present bar graphs of the biometric decompositions over time and between residences. The significant findings are described here; see Supporting information, Tables S9 and S10 for all G × E model parameter estimates.

Further investigation of specific parameters revealed that heritability could be equated between three of the four estimates (post-2014 legal, post-2014 illegal and pre-2014 legal; χ^2 = 3.3, d.f. = 2, P = 0.191). Heritability pre-2014 in states that did not subsequently legalize could not be equated to the other three estimates (χ^2 = 7.7, d.f. = 1, P = 0.006). In other words, heritability was larger prior to 2014 in states that remain illegal compared to pre-2014 in states that would

TABLE 3 Results of individual-level mixed model and zygosity-stratified co-twin control mixed models

Individual-level model				Twin models									
	Individual				All twins			Same-sex dizygotic twins			Monozygotic twins		
Param.	B	95% CI	P	Param.	B	95% CI	P	B	95% CI	P	B	95% CI	P
Int.	2.46	1.91, 3.00	$1.38e^{-18}$	Int.	2.54	1.92, 3.15	$1.24e^{-15}$	2.20	1.08, 3.32	$1.30e^{-4}$	2.47	1.67, 3.26	$1.65e^{-9}$
Legal status	0.21	0.11, 0.32	$8.08e^{-5}$	Between-pair	0.16	0.02, 0.29	0.024	0.31	0.06, 0.55	0.013	0.05	−0.14, 0.23	0.624
				Within-pair	0.17	0.06, 0.29	0.002	0.19	−0.03, 0.40	0.096	0.18	0.04, 0.32	0.014
Age	−0.04	−0.05, −0.02	$7.61e^{-7}$	Age	−0.04	−0.05, −0.02	$3.38e^{-6}$	−0.04	−0.07, −0.01	0.006	−0.03	−0.05, −0.01	0.001
Sex	−0.32	−0.43, −0.22	$2.02e^{-09}$	Sex	−0.32	−0.44, −0.20	$1.30e^{-7}$	−0.11	−0.33, 0.10	0.300	−0.33	−0.50, −0.17	$7.78e^{-5}$
Intake cohort	0.22	−0.01, 0.44	0.059	Intake cohort	0.31	0.06, 0.57	0.017	0.46	0.05, 0.87	0.027	0.25	−0.10, 0.59	0.159
Pre-2014 use	0.02	0.016, 0.018	$5.04e^{-151}$	Pre-2014 Use	0.02	0.016, 0.019	$2.80e^{-121}$	0.02	0.015, 0.020	$1.01e^{-44}$	0.02	0.015, 0.019	$1.06e^{-60}$

The minimal attenuation between the individual-level effect for legal status and co-twin within-pair effects indicates minimal genetic and shared environmental confounding. Param. = parameter; Int. = intercept; *B* = unstandardized regression parameter estimate; 95% CI = confidence interval; *P* = exact *P*-value.

legalize or post-2014 in both residence types. Additionally, the total amount of environmental influences in pre-2014 cannabis use was larger (shared environment χ^2 = 8.7, d.f. = 1, P = 0.003; unique environment χ^2 = 4.9, d.f. = 1, P = 0.027) in states that would go on to legalize compared to states that would not.

Mirroring the heritability results, the genetic correlation between pre- and post-2014 use was larger (χ^2 = 5.8, d.f. = 1, P = 0.016) in states that did not legalize (r_{GI} = 0.78) compared to states that did (r_{GL} = 0.24), indicating that legalization moderates the genetic effects on cannabis use frequency over time. This result was not significant under the ordinal measure (χ^2 = 2.3, d.f. = 1, P = 0.129). There were no detectable specific genes relevant only under exposure to recreationally legal environments (χ^2 = 2.9 × 10^{-9}, d.f. = 1, P > 0.999). In other words, a common effects model fit best, where the same genes influenced cannabis use frequency in each environment, but to different extents.

DISCUSSION

We evaluated the effect of recreational cannabis legalization on cannabis use frequency and the sources of variation underlying it. Our study has numerous strengths, including longitudinal cannabis use data prior to and after recreational legalization in states with different current recreational policies, monozygotic twins discordant for residence and harmonizable measures between study sites prior to 2014. These strengths permit us to replicate the effect of recreational cannabis policies, previously demonstrated by large repeated cross-sectional population studies, and further improve causal inference by controlling for many potential confounders.

Using a longitudinal design accounting for age, sex and earlier cannabis use, we found a ~ 24% increase in mean cannabis use frequency attributable to legalization. Furthermore, co-twin control results indicate that within monozygotic pairs, the twin living in a legal state uses cannabis ~20% more frequently than their illegally residing co-twin. This pattern of results is consistent with a causal, environmentally mediated effect of legalization on frequency of use, over and above prior use and secular trends in use in the United States. Our results are consistent with other studies indicating increases in use attributable to legalization [6–8, 11, 32].

Follow-up analyses suggest the increase in mean frequency may be more clearly understood as increased prevalence of recent use in life-time users. Consistent with developmental gradation of substance use, most life-time users initiated prior to 2014. Our analyses suggest that among individuals who have used in their life-time, cannabis legalization may cause increased likelihood of recent use, but cannabis legalization is unlikely to cause initiation in individuals who were life-time abstainers prior to legalization. An analysis of the subset of recent users indicates that use occurs at similar average frequencies in legal and illegal environments.

Most of our non-recreationally residing sample lived in states with comprehensive medical cannabis policies, and most of our recreationally residing participants lived in Colorado. Our results therefore can be most accurately described as the incremental effect

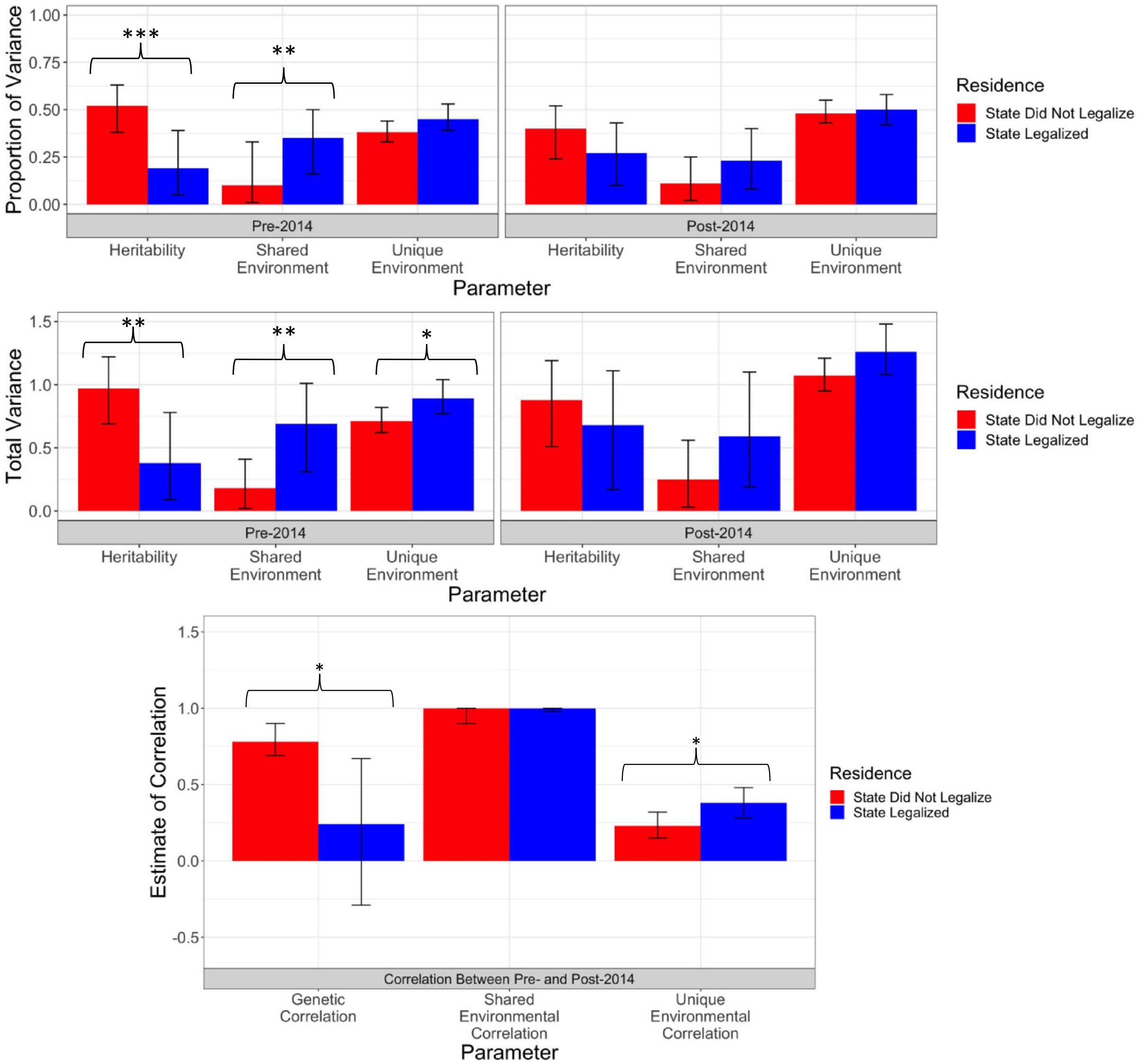

FIGURE 2 Bar graphs depicting the continuous biometric decompositions between environments and over time; error bars represent the likelihood-based 95% confidence interval around the point estimate. The top panel depicts proportions of variance, the middle panel depicts total amounts of variance and the bottom panel depicts the genetic correlation between times. Initially, heritability and the genetic correlation are larger in states that do not legalize compared to states that do legalize and shared/unique environmental effects are larger in states that do legalize compared to states that do not legalize. These differences do not persist to post-2014. *P < 0.05, **P < 0.01, ***P < 0.001; confidence intervals for shared environmental correlations have upper boundaries at 1 due to boundary conditions inplicit in the model structure. Note that some parameter comparisons are significantly different despite overlapping confidence intervals; parameters within a residence group are correlated and thus the difference in two point estimates is not a simple function of the difference in intervals

of recreational legalization after comprehensive medical legalization, as is the typical pattern of recent legalization efforts, and our results are most generalizable to recreational environments similar to Colorado's. Similarly, our findings are most generalizable to those in established adulthood, a time when individuals tend to reduce their drug use [33, 34]. Interestingly, we saw escalation, not reduction, of average use in both recreationally legal and illegal states, although to different degrees (Fig. 1). It may be that marijuana legalization and other secular trends have perturbed normative adult reductions in marijuana use.

Additionally, we found differences in the sources of variation underlying cannabis use over time using a gene–environment interaction model. The larger environmental variation prior to legalization in states that would go on to legalize may reflect a larger range of environmental factors relevant to cannabis use, such as social attitudes around cannabis use or ease of obtaining cannabis, compared to non-legal states. There was no new genetic variation specific to recreationally legal environments but the genetic correlation between earlier and later use was larger in states that do not legalize (r_g = 0.78) as opposed to states that do (r_g = 0.24). This suggests the genetic variation underlying cannabis use in different environments are reflections of the same genes, although the effects of those genes over time are stronger in non-legal environments as opposed to legal environments [16, 17].

One potential alternative explanation for increases in use associated with legalization could be that it instead reflects an increased openness to report activities that are no longer illegal. We cannot determine whether this is the case, but we note that we also saw increases in reported cannabis use by residents of illegal states. An additional limitation to causal inference in the present research is non-shared environmental confounds, such as pre-existing twin differences that may lead to migration to more or less liberal states or state-level confounds. States that legalize are probably different in other ways, and these other differences may be what causes increases in cannabis use. We did not control for state-level variables other than legal status, but existing studies analyzing state trends have included additional state-level variables to address these concerns and have identified comparable effect sizes as the present study [7, 35]. These complementary state-level and individual-level results provide evidence that is consistent with, but not dispositive of, a causal effect.

Our sample was representative of birth cohorts in Minnesota and Colorado, but consequently was largely white. An important extension of our work would be to investigate individual differences in the context of cannabis policy with respect to sex or racial background. Prior to recreational legalization, black Americans disproportionately bore the consequences of cannabis law enforcement [36, 37]. Racial disparities in pre-legalization enforcement could mean that the legalization-related environmental changes experienced by black Americans were more dramatic than those experienced by their white counterparts, but we are not able to address this issue effectively in these samples.

CONCLUSIONS

Cannabis is the most commonly used federally illegal drug in the United States and it is an addictive substance associated with many negative health and psychosocial outcomes [38]. Through the use of zygosity-stratified co-twin control analyses, we found a $\sim 20\%$ increase in cannabis use frequency, consistent with a causal effect of recreational legalization. These results do not, by themselves, demonstrate how more frequent use in legal states translates to changes in health or behavioral consequences, therefore future work is necessary to further address complex questions around the public health impacts of legalization and vulnerability to widely available marijuana.

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DECLARATION OF INTERESTS

None declared.

AUTHOR CONTRIBUTIONS

Stephanie M. Zellers: Conceptualization; formal analysis; visualization. **J. Megan Ross:** Conceptualization. **Gretchen R. B. Saunders:** Formal analysis. **Jarrod M. Ellingson:** Conceptualization. **Jacob E. Anderson:** Data curation. **Robin P. Corley:** Data curation. **William Iacono:** Conceptualization; funding acquisition; supervision. **John K. Hewitt:** Conceptualization; funding acquisition; supervision. **Christian J. Hopfer:** Conceptualization; funding acquisition; supervision. **Matt K. McGue:** Conceptualization; formal analysis; funding acquisition; supervision. **Scott Vrieze:** Conceptualization; formal analysis; funding acquisition; project administration; supervision.

ORCID

Stephanie M. Zellers https://orcid.org/0000-0001-8927-3483
J. Megan Ross https://orcid.org/0000-0003-4424-5301
Gretchen R. B. Saunders https://orcid.org/0000-0001-5972-9785
Jarrod M. Ellingson https://orcid.org/0000-0001-9932-2656

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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