

Reassessing the marijuana gateway effect

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ABSTRACT

Aims Strong associations between marijuana use and initiation of hard drugs are cited in support of the claim that marijuana use *per se* increases youths' risk of initiating hard drugs (the 'marijuana gateway' effect). This report examines whether these associations could instead be explained as the result of a common factor—drug use propensity—influencing the probability of both marijuana and other drug use.

Design A model of adolescent drug use initiation in the United States is constructed using parameter estimates derived from US household surveys of drug use conducted between 1982 and 1994. Model assumptions include:

(1) individuals have a non-specific random propensity to use drugs that is normally distributed in the population; (2) this propensity is correlated with the risk of having an opportunity to use drugs and with the probability of using them given an opportunity, and (3) neither use nor opportunity to use marijuana is associated with hard drug initiation after conditioning on drug use propensity.

Findings Each of the phenomena used to support claims of a 'marijuana gateway effect' are reproduced by the model, even though marijuana use has no causal influence over hard drug initiation in the model.

Conclusions Marijuana gateway effects may exist. However, our results demonstrate that the phenomena used to motivate belief in such an effect are consistent with an alternative simple, plausible common-factor model. No gateway effect is required to explain them. The common-factor model has implications for evaluating marijuana control policies that differ significantly from those supported by the gateway model.

KEYWORDS Adolescents, drug use, marijuana gateway effect, mathematical model.

INTRODUCTION

Alcohol, tobacco and marijuana are widely regarded as 'gateway' drugs. Although the gateway concept admits a number of definitions, one in particular predominates in drug policy discussions: use of gateway drugs causes youths to have an increased risk of progressing to other, more serious drugs. For instance, in debates on marijuana decriminalization or the medicinal use of marijuana, policy makers frequently suggest that use of marijuana increases youths' risk of initiating more dangerous drugs such as cocaine and heroin (US Congressional Record 1998, 1999). Although mari-

juana is the least prevalent of the three principal gateway drugs, it is currently the focus of extensive policy reassessment in the United States, Canada, Western Europe and Australia. Using a simulation model, we demonstrate that the primary evidence supporting the marijuana gateway effect can be explained completely by the order in which youths first have the opportunity to use marijuana and other drugs, and by assuming a non-specific liability to use drugs, without any assumption that use of marijuana contributes to the risk of initiating use of hard drugs. We argue that although marijuana gateway effects may truly exist, available evidence does not favor the marijuana gateway effect over the alternative hypothesis that mari-

juana and hard drug initiation are correlated because both are influenced by individuals' heterogeneous liabilities to try drugs.

The popular concern that marijuana use increases the risk of progressing to other, more serious drugs is a long-standing one, and has influenced US drug policy since at least the 1950s (Goode 1970; Whitebread & Bonnie 1972; National Research Council 1982). Some social scientists have also suggested that marijuana gateway effects probably account for several phenomena observed in adolescent drug use initiation patterns (e.g. Goode 1970; O'Donnell & Clayton 1982; Yamaguchi & Kandel 1984b). Three such phenomena represent the primary evidence for a marijuana gateway effect. The first concerns the *relative risk* of hard drug initiation for adolescent marijuana users vs. non-users. In general, marijuana users in many countries appear to have a significantly elevated risk for drug use progression (Adler & Kandel 1981; Kandel 1975; Blaze-Temple & Lo 1992; Stenbacka, Allebeck & Romelsjö 1993; Beenstock & Rahav 2002). Indeed, one US study found their risk to be 85 times those of non-users of marijuana (Center on Addiction and Substance Abuse 1994). Another form of relative risk that is occasionally cited in support of the gateway effect is that younger marijuana initiates have a higher risk of initiating hard drug use than older marijuana initiates (O'Donnell & Clayton 1982; Yamaguchi & Kandel 1984b; Kandel & Yamaguchi 1993; Center on Addiction and Substance Abuse 1994). This relative risk differs from the first only insofar as it finds that risk of hard drug initiation is conditioned on a characteristic of the user (age), rather than on marijuana use alone. Therefore, it does not provide strong evidence supporting a gateway effect.

The second observation routinely cited in support of the marijuana gateway effect concerns the remarkably invariant *ordering* in adolescents' initiation of different drug classes. Adolescents rarely initiate hard drug use before marijuana (Ellickson *et al.* 1992; Kandel, Yamaguchi & Chen 1992; O'Donnell & Clayton 1982; Yamaguchi & Kandel 1984a). For instance, in a longitudinal sample of 1265 New Zealand youths between the ages of 15 and 21, Fergusson & Horwood (2000) found only three cases reporting use of hard drugs before marijuana. This figure is dramatically lower than the roughly 124 such cases that would be expected from annual incidence rates if use of marijuana and hard drugs were independent.

The third phenomenon used to support claims of a marijuana gateway effect concerns the strong relationship between the frequency of marijuana consumption and the risk of hard drug initiation: as the frequency of marijuana use increases, so too does the risk of initiating hard drug use (Ellickson *et al.* 1992; Kandel *et al.* 1992;

Fergusson & Horwood 2000). Fergusson & Horwood (2000), for instance, developed a proportional hazards model suggesting that youths reporting 50 or more uses of cannabis in the past year had hazards of progression to hard drugs that were more than 140 times greater than those for youths reporting no use of cannabis. Findings like this suggest an even stronger form of the marijuana gateway effect defined earlier: not only does marijuana use increase youths' risk of hard drug initiation, but every instance of marijuana use adds to that risk. For convenience, we refer to this phenomenon as marijuana's apparent *dose-response effect* on hard drug initiation.

The three phenomena of relative risk, ordering in drug use initiation and dose-response are not sufficient to prove that use of marijuana, rather than some associated factor, increases the risk of hard drug initiation (Joy *et al.* 1999). Indeed, a frequently cited alternative explanation is that a common factor, which we might refer to generically as a propensity for drug use, could influence use of both marijuana and hard drugs, thereby causing initiation of these drugs to be correlated (Goode 1972; Huba *et al.* 1981; Donovan & Jessor 1985; Hays *et al.* 1987; MacCoun 1998). For instance, if high drug use propensities elevate individuals' risk for use of both marijuana and hard drugs, this could explain why marijuana users have a higher relative risk of hard drug initiation in comparison with non-users.

This 'common-factor' model does not immediately account for the ordering and dose-response phenomena. To make sense of these observations, proponents of the common-factor approach suggest that ordering in drug use initiation results from the order in which opportunities to use marijuana and hard drugs are presented to young people (Goode 1972; Jessor & Jessor 1980). Those with the highest propensities to use drugs are likely to use the first one offered to them, and that happens to be marijuana in most cases. Moreover, if a high drug use propensity is associated with greater frequencies of drug use, the common-factor theory can also account for the dose-response phenomenon: marijuana use frequency is associated with risk of hard drug initiation because both are controlled by drug use propensity.

The common-factor model is appealing in part because it takes account of what is a substantial scientific literature demonstrating the existence of genetic, familial and environmental characteristics associated with a generalized risk of using both marijuana and hard drugs. For instance, several studies examining drug use among monozygotic and dizygotic twins in the USA demonstrate genetic and family environment contributions to the likelihood of any drug use (van den Bree *et al.* 1998) and any drug use initiation (Tsuang *et al.* 1998; Kendler *et al.* 1999, 2000). Similarly, community drug use or drug

availability may contribute to individuals' risk of using drugs (Lillie-Blanton, Anthony & Schuster 1993).

Although the common-factor model is plausible, previous research has not demonstrated that propensities to use drugs and environmental factors such as drug use opportunities could, in fact, account for the strong relative risk, ordering and dose-response phenomena observed among adolescents. Indeed, two lines of research provide some evidence that the common-factor model cannot account for drug use initiation without assuming a marijuana gateway effect. Firstly, several studies examine the association between marijuana use and the risk of hard drug initiation after controlling for a large number of risk factors, such as delinquency and peer drug use (Yamaguchi & Kandel 1984b; Fergusson & Horwood 2000). By the logic of this approach, any residual marijuana effect on hard drug initiation that remains after controlling for these candidate common factors lends credence to the suggestion that marijuana use *per se* increases the risk of hard drug initiation. However, if the selected covariates are less good proxies for the propensity to use drugs than is marijuana use itself, these findings are perfectly consistent with a strict common-factor model. Because this approach does not observe all or even most individual risk factors, it provides little persuasive evidence against a common-factor explanation. We will illustrate this point with data derived from the model described later on in this paper.

A second approach to contrasting the gateway and common-factor models of drug use initiation uses instrumental variables in an effort to account for both observed and unobserved person-level risk of initiation. Two of these studies (DeSimone 1998; Pacula 1998) suggest that common factors alone cannot explain observed gateway phenomena. The third (Beenstock & Rahav 2002) provides qualified evidence that observed marijuana gateway phenomena are not attributable to a gateway effect, but instead derive from individuals' predispositions to use both marijuana and hard drugs. However, none of these studies take into account the observation that opportunities to use marijuana precede those for hard drugs, and may themselves be associated with propensity to use drugs through, for instance, drug-seeking behavior. This is a critical omission, since proponents of the common-factor model have consistently cited the ordering in drug use opportunities as an essential part of the explanation of ordering in drug use initiation. Indeed, in a series of analyses on US and Panamanian data, Anthony, Van Etten and colleagues have shown that gender, race and neighborhood differences observed in rates of drug use initiation are attributable, to a large extent, to differences in the rates at which groups are exposed to drug use opportunities (Crum, Lillie-Blanton & Anthony 1996; Van Etten, Neumark & Anthony 1997, 1999;

Delva *et al.* 1999; Van Etten & Anthony 1999). Thus, econometric models have not tested the common-factor model adequately.

In this report we describe a Monte Carlo model of drug use initiation with parameters selected to match the drug use experiences of the population of US residents under the age of 22. The model describes the joint distribution of four events: the ages of first opportunity to use marijuana and hard drugs, and the ages of first use of marijuana and hard drugs. Each of these events depends on a common factor—drug use propensity—but conditional on this factor, the ages of first opportunity to use and first use of marijuana are independent of opportunity to use and use of hard drugs. Thus, the model is designed to exclude any causal gateway effect. Random draws from the modeled joint distribution are used to examine the relative risk, ordering and dose-response phenomena that might be expected by chance in the US if model assumptions are accurate.

METHODS

Procedure

We build a common-factor model of adolescent drug use initiation using parameter estimates derived from a representative sample of youths in the US population. With this model, we observe the rates at which phenomena of relative risk, ordering and dose-response can occur when no causal gateway effects are present. We compare these rates to those observed in the sample of US youths to demonstrate that a common-factor model designed to match US rates of drug use initiation and drug use opportunities without a gateway effect can still reproduce all of the gateway phenomena observed in the population. In the remainder of this section we describe the model specification and the statistical methods used to estimate the values for the model parameters and the gateway effects observed among youths in the US.

Model specification

Drug use propensity

Each case is assigned an arbitrary propensity to use drugs, θ , which we conceptualize as the resultant shared risk of reporting use of both marijuana and hard drugs after accounting for all person-level risk factors that remain more or less constant during adolescence. Examples of such invariant predispositions to report drug use could include genetic and family environmental history factors (Kendler *et al.* 1999; Tsuang *et al.* 1998; van den Bree *et al.* 1998; Kendler *et al.* 2000) and community

drug use or drug availability (Lillie-Blanton, Anthony & Schuster 1993). We assume that propensity is correlated not just with the probability of drug use, but also with the probability of having the opportunity to use drugs at any particular age. This assumption is supported by several considerations. Firstly, we define propensity as resulting, in part, from environmental risk factors. Local drug use norms and the availability of drugs are examples of environmental influences likely to affect both individuals' risk of drug use and their risk of having an opportunity to use drugs (Lillie-Blanton *et al.* 1993). Drug use propensity is also likely to be correlated with age of first opportunity to use drugs because individuals with greater propensities are more likely to seek out drug use opportunities, or recognize them when they present themselves. Finally, empirical studies document a strong association between the risk of drug offers (and, by extension, opportunities) and a range of characteristics likely to correlate with drug use propensity, such as smoking, alcohol use and parental substance use (Stenbacka *et al.* 1993). Each of these considerations suggests propensity will be correlated with drug use opportunities as well as drug use.

Although epidemiological studies provide evidence supporting the existence of a drug use propensity (Tsuang *et al.* 1998; van den Bree *et al.* 1998; Kendler *et al.* 1999, 2000), no information exists about its distribution in the population of adolescents. Thus, in the model we draw drug use propensities, θ , at random from a standard normal distribution.

Drug use opportunities

We assume that for any individual, the age of first opportunity to use marijuana, Y_M , and the age of first opportunity to use hard drugs, Y_H , are drawn at random from distributions describing the risk of first marijuana or hard drug use opportunity at each age. These risk distributions are functions of the individual's drug use propensity: higher propensities shift the risk curves so that exposure to a drug use opportunity is more likely at earlier ages. Thus, between the ages 0 and 22, we define the cumulative distribution of age of first opportunity to use marijuana as $1 - S_{YM}(t, \theta)$, where $S_{YM}(t, \theta)$ is the survival function describing the probability that age of first opportunity to use marijuana exceeds t , conditional upon θ . Similarly, the distribution of age of first opportunity to use hard drugs is given by $1 - S_{YH}(t, \theta)$. We use a frailty model to construct these conditional survival functions. Frailty models are a standard approach to describing joint survival functions when risks for each modeled event are presumed to correlate due to heterogeneity across individuals in the population (Hosmer & Lemeshow 1999; Therneau & Grambsch 2000):

$$S_{YM}(t, \theta) = S_{YM}^*(t)^{f(\theta)} \text{ for marijuana, and} \quad (1)$$

$$S_{YH}(t, \theta) = S_{YH}^*(t)^{f(\theta)} \text{ for hard drugs.} \quad (2)$$

The function f transforms θ to the corresponding value from the Gamma distribution with mean of 1 and variance β_1 . Under this parameterization the frailty model produces a correlation between age of first use opportunities Y_M and Y_H that increases as β_1 grows. We estimate β_1 and the functions $S_{YM}^*(t)$ and $S_{YH}^*(t)$ from US data on adolescent drug use opportunities, as described below. The estimated functions are defined so that marginal survival functions for the model (expected values over θ of $S_{YM}(t, \theta)$ and $S_{YH}(t, \theta)$) equal marginal survival functions fit to our sample of US data.

Drug use initiation

For any individual, first use of marijuana, Z_M , is a random variable drawn from a distribution describing the individual's risk of initiating marijuana at each age. Each individual's risk distribution depends on his or her drug use propensity and age when first presented the opportunity to use marijuana, Y_M . Youths with greater propensities have a greater risk of use at every age, beginning with their age at first opportunity to use a drug.

Specifically, given an individual's drug use propensity and age of first opportunity to use marijuana, the cumulative probability distribution for age of marijuana initiation is given by $1 - S_{ZM}(t, \theta, Y_M)$, where $S_{ZM}(t, \theta, Y_M)$ is the conditional survival function for marijuana initiation. For $t = 8, 9 \dots 22$,

$$S_{ZM}(t, \theta, Y_M) = \begin{cases} 0, & \text{if } Y_M > t \\ 1 - \pi_M, & \text{if } Y_M \leq 8, t = 8 \\ F_{\beta_2}(\psi_{Mt}^* - \theta) S_{ZM}(t-1, \theta, Y_M), & \text{if } Y_M \leq t, t > 8, \end{cases} \quad (3)$$

where F_{β_2} is the cumulative probability function for a normal distribution with mean 0 and variance β_2 . Thus, the parameters π_M and ψ_{Mt}^* , $t = 9 \dots 22$ define for the model the marginal probabilities $\Pr\{Z_M < 9 \mid Y_M < 9\}$ and the marginal probabilities $\Pr\{Z_M = t \mid Y_M \leq t, Z_M \geq t\} = E[F_{\beta_2}(\psi_{Mt}^* - \theta_i)]$, respectively. Age of initiation of hard drugs, Z_H , is drawn independent of Y_M and Z_M from an analogous distribution defined by the parameters β_2 , π_H and ψ_{Ht}^* , $t = 9 \dots 22$.

The value of β_2 is the same for both marijuana and hard drugs. This parameter affects the correlation between Z_M and Z_H by controlling the influence of propensity on the probability of initiation. It is chosen so that the model produces a correlation between $L_M = Z_M - Y_M$ and $L_H = Z_H - Y_H$ for youths who used both marijuana and hard drugs by age 22 that matches the same correlation observed in data on adolescents in the US. We set the remaining parameter values so that the marginal

probabilities in the model (i.e. $Pr\{Z_M < 9 \mid Y_M < 9\}$, $Pr\{Z_H < 9 \mid Y_H < 9\}$, $Pr\{Z_M = t \mid Y_M \leq t, Z_M \geq t\}$ and $Pr\{Z_H = t \mid Y_H \leq t, Z_H \geq t\}$, $t = 9 \dots 22$) match the corresponding estimates from our sample of data from the US population.

The joint distribution for Y_M , Z_M , Y_H and Z_H is:

$$\Pr\{Y_M = y_M, Z_M = z_M, Y_H = y_H, Z_H = z_H\} = \int \{S_{ZM}(z_M - 1, y_M, \theta) - [S_{ZM}(z_M, y_M, \theta)] \times [S_{YM}(y_M - 1, \theta) - S_{YM}(y_M, \theta)] \times [S_{ZH}(z_H - 1, y_H, \theta) - S_{ZH}(z_H, y_H, \theta)] \times [S_{YH}(y_H - 1, \theta) - S_{YH}(y_H, \theta)]\} \phi(\theta) d\theta, \quad (4)$$

where ϕ denotes the density function for a standard normal random variable.

Figure 1 depicts our procedure for drawing random observations from this distribution.

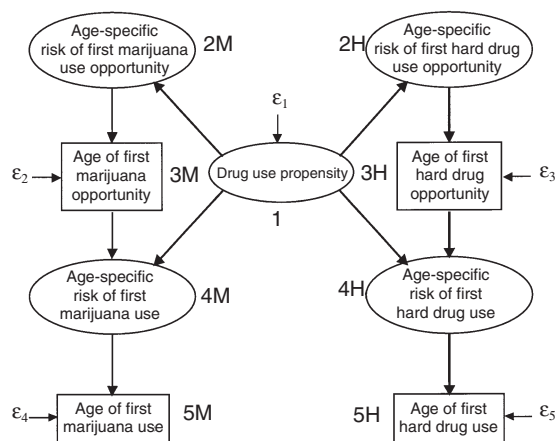


Figure 1 Procedure for generating simulated observations from the model of adolescent drug use initiation. Firstly, a random drug use propensity, θ , is drawn (1), which uniquely determines the risks (or probabilities) of having an opportunity to use marijuana, $S_{YM}(t, \theta)$, and hard drugs, $S_{YH}(t, \theta)$, at every age $t = 0-22$ (2M & 2H: note that epsilons in the figure are used to denote draws of separate, independent random variables from the indicated distributions). A random variable is then drawn from the distribution defined by S_{YM} to determine the age of first opportunity to use marijuana, Y_M , and an independent random variable is drawn to determine the age of the first opportunity to use hard drugs, Y_H (3M & 3H). The values of θ and Y_M then uniquely determine the risk of marijuana initiation at every age greater than Y_M , $S_{ZM}(t, \theta, Y_M)$, and similarly the values of θ and Y_H uniquely determine the risk of hard drug initiation for every age greater than Y_H , $S_{ZH}(t, \theta, Y_H)$ (4M & 4H). Another set of random variables that are independent of each other and all previous random variables are then drawn from the distributions determined by $S_{ZM}(t, \theta, Y_M)$ and $S_{ZH}(t, \theta, Y_H)$ to set age of initiation of marijuana, Z_M , and hard drugs, Z_H (5M & 5H). The additional parameters of the model were all determined to match the marginal distribution of a sample of US youths from the NHSDA.

Marijuana use frequency

To examine the dose-response relationship between marijuana use frequency and the risk of hard drug initiation, we categorize each case that initiated use of marijuana into one of five past year use frequencies (no past year use, 1-2 times, 3-11 times, 12-51 times and 52 or more times) at each age, beginning with the age of marijuana initiation. Cases are assigned a marijuana use intensity random effect, ξ_i , which is used to draw a marijuana use frequency from the distribution of use frequencies observed in the US sample with corresponding ages and number of years since marijuana initiation.

We hypothesize that marijuana use frequency is positively correlated with propensity to use drugs. However, because propensity is unobservable, we know of no good data for estimating this correlation. Therefore, we conduct a sensitivity analysis in which the risk of hard drug initiation at each marijuana use frequency is examined as the correlation between ξ_i and θ_i ranges from 0 to 1.

Parameter estimation

This section summarizes the statistical methods used to estimate values for each of the model's parameters, β_1 , S_{YM}^* , S_{YH}^* , β_2 , π_M , π_H and ψ_{Mt}^* and ψ_{Ht}^* , $t = 9 \dots 22$. It also describes the methods used to estimate the observed values of the relative risk, ordering and dose-response effects from a sample of data from the US population.

Data source

Estimates for the model parameters and observed values of the relative risk, ordering and dose-response effects were derived from the National Household Survey of Drug Abuse (NHSDA). The NHSDA is an ongoing probability sample survey of the US civilian, non-institutionalized population aged 12 years and older (US Department of Health and Human Services 1999). Data on all 58 846 respondents, 12-25 years of age, from birth cohorts 1964 through 1982, were pooled from the 1982 through 1994-A NHSDA in order to create stable estimates of quite rare events. This pooling was justified by preliminary analyses suggesting that drug use opportunity and initiation survival probabilities were similar across birth cohorts. NHSDA sample weights were applied to make the pooled sample representative of the included birth cohorts. The selected survey years included questions on the ages of initiation and first opportunities to use marijuana, heroin, cocaine and hallucinogens. More recent data on drug use opportunities are not available because these questions were dropped from subsequent administrations of the NHSDA. First opportunity to use and initiation into use of hard drugs were defined as the earliest

reported age of opportunity and use of heroin, cocaine or hallucinogens. Because these data are self-reports of illicit behavior and improper events, they are subject to a variety of well-known biases. Nevertheless, longitudinal investigations indicate that ordering of drug use initiation, a central concern of the present analysis, is reported reliably (Golub *et al.* 2000). Therefore, for our purposes, recall bias is unlikely to significantly affect our principal findings.

Statistical methods

Estimation of β_1 To best match the correlation in ages of first opportunities to use marijuana and hard drugs observed in the NHSDA, we selected $\beta_1 = 3.22$, the maximum likelihood estimate of β_1 for model (1 & 2) fit to a 5% random sample of the NHSDA data, stratified by year of survey administration and birth cohort. The estimate was obtained using the S-Plus Software (MathSoft, Seattle, WA, USA) using the methods described in Therneau & Grambsch (2000).

Estimation of S_{YM}^* and S_{YH}^* The estimates of S_{YM}^* and S_{YH}^* derived directly from the marginal survival functions $S_{YM}(t)$ and $S_{YH}(t)$, which we estimate using data from the NHSDA. We used the actuarial life table method (Miller 1981) to estimate the survival function for first opportunity to use marijuana, $S_{YM}(t)$, defined as the probability that a randomly chosen individual's first opportunity to

use marijuana occurs after age t . The actuarial life table method estimates the probability of a first opportunity to use at age t as the ratio of the number of individuals who report the first opportunity at age t to the number of individuals eligible to have a first opportunity at age t . Individuals are ineligible if they had a previous opportunity to use or if they are censored. Respondents are censored if they are interviewed before age t and report no opportunities to use prior to the interview. We used weighted sums in the ratio to account for unequal probability of selection in the NHSDA. The survival function at age t is obtained by multiplying the age-specific probabilities of an opportunity to use. We used analogous procedures to estimate a survival function for the first opportunity to use hard drugs, $S_{YH}(t)$, and survival functions for initiation of marijuana use, $S_{ZM}(t)$, and hard drug use, $S_{ZH}(t)$ (Fig. 2).

Because $f(\theta)$ is distributed as a Gamma random variable with mean one and variance β_1 , $E[S_{YM}^*(t)^{f(\theta)}] = 1 - \beta_1 \log S_{YM}^*(t)^{-1/\beta_1}$ (Hogg & Craig 1978). Setting $E[S_{YM}^*(t)^{f(\theta)}]$ equal to the estimated marginal survival function for the NHSDA sample yields, $S_{YM}^*(t) = e^{(1 - \hat{S}_{YM}(t)^{-\beta_1})/\beta_1}$. Again, a similar procedure is used to estimate S_{YH}^* from the estimates of β_1 and $S_{YH}(t)$.

Estimation of π_M and π_H Since $\pi_M = \Pr\{Z_M < 9 \mid Y_M < 9\}$, we estimate this probability directly from the NHSDA as the sum of the weights from respondents who report marijuana initiation before age nine divided by the sum of the weights from respondents who report an opportunity to

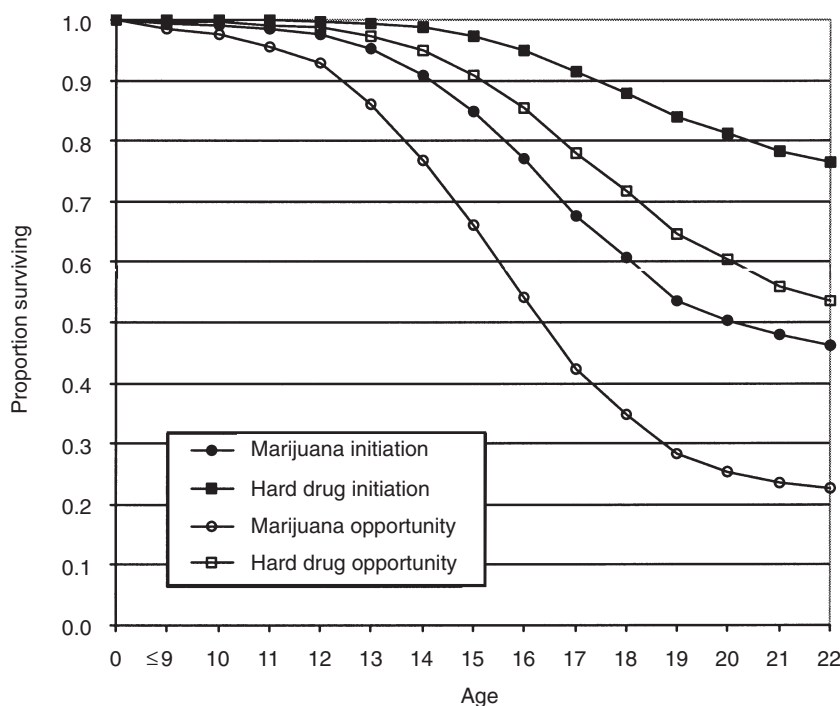


Figure 2 Survival functions estimated from the NHSDA describing the probability of surviving until age t without having the opportunity to use marijuana, the opportunity to use hard drugs, initiating marijuana and initiating hard drugs

use marijuana before age nine. The procedure is repeated for hard drugs.

Estimation of β_2 As noted earlier, we set β_2 so that the model correlation between L_M and L_H matches the NHSDA estimate. For all NHSDA respondents who reported using both marijuana and hard drugs by age 22, we calculated L_M and L_H and their correlation, r . We do not have a closed form for the correlation between L_M and L_H as a function of β_2 , $\rho(\beta_2)$ in our simulation model. Therefore, we estimated the function via simulation. For a given value of β_2 we simulated 10 000 observations from the distribution and calculated the correlation between L_M and L_H . We then used the bisection method to search over the values of β_2 to find the value that solved $\rho(\beta_2) - r = 0$.

Estimation of ψ_{Mt}^ and ψ_{Ht}^** To estimate ψ_{Mt}^* we first estimate from the NHSDA $Pr\{Z_M = t \mid Y_M \leq t, Z_M \geq t\}$ as the ratio of the sum of the weights for respondents who initiate use at age t to the sum of the weights of respondents with first opportunity to use marijuana before age $t + 1$ who did not initiate use prior to age t . We again did not have a closed form for $E[F_{\beta_2}(\psi_{Mt}^* - \theta_i)] = Pr\{Z_M = t \mid Y_M \leq t, Z_M \geq t\}$ as a function of ψ_{Mt}^* given a value for β_2 . Instead we used the bisection method to find a value ψ_{Mt}^* so the $E[F_{\beta_2}(\psi_{Mt}^* - \theta_i)]$ from the simulation model equals our estimate of $Pr\{Z_M = t \mid Y_M \leq t, Z_M \geq t\}$ from the NHSDA. Values for the corresponding hard drug parameter were calculated in a similar manner.

Estimation of the relative risk effect We estimate the risk of hard drug use by 21 using the sample of NHSDA respondents aged 22 or older. We estimate the probability of hard drug use separately for respondents who reported marijuana use by 21 and those who did not. Estimates equal the weighted proportion by stratum. The relative risk is the ratio of the risk for hard drug initiation for marijuana users to the risk for others.

Estimation of ordering effect We used life table methods to estimate the rate at which hard drug initiation precedes marijuana initiation. For each age, t , we summed the weights for respondents who had used neither marijuana nor hard drugs by age t . Call this sum E_t . We subtracted from E_t , C_t the sum of the weights for respondents who were surveyed at age t and had used neither marijuana nor hard drugs—i.e. the weights for censored observations. Let U_t equal the sum of the weights for youth who report initiating hard drugs at age t before initiating marijuana use. We then estimate the probability that hard drug use preceded marijuana use at age t as $P_t = A_t U_t / (E_t - C_t)$, where A_t equals our estimate of the probability that a youth's first use of hard drugs or mari-

juana is after age t . The survival curve for initiating hard drug use prior to marijuana use equals $S(t) = 1 - \sum_{j=1}^t P_j$.

Estimation of the dose-response effect To examine the marginal dose-response effect of the simulated marijuana use frequency on the age of hard drug initiation, a generalized linear model with a complimentary log-log link (Hosmer & Lemeshow 1999) was fitted to the marijuana use frequency and hard drug initiation data from a random sample of 30 000 simulated cases. Whether or not a case initiated hard drug use in a given year was modeled as a function of past year marijuana use intensity (no past year use, 1–2 times, 3–11 times, 12–51 times and 52 or more times) at age t ($t = 12 \dots 21$). Those who did not initiate hard drug use were censored after age 21.

To compute a corresponding hazard ratio for the NHSDA, we first selected the subset of respondents who reported no hard drug initiation prior to the year preceding the survey. We then stratified these respondents by age at the time of the survey. For each respondent age group we calculated the weighted proportion reporting initiation of hard drug use in the past year by past year marijuana use frequency. For example, we divided 12-year-old respondents into those who did not use marijuana in the past year, those who used marijuana 1–2 times, 3–11 times, 12–51 times or 52 or more times. Within each use group we estimate separately the proportion that initiated hard drugs. We repeat this for all other age groups. The resulting proportions define the hazard of hard drug initiation by age for each level of marijuana use. We assume that the five resulting hazard functions (one for each level of marijuana use) are age-specific, but that a single proportional hazards model describes the relative sizes of the five hazards at all ages. We compute the proportionality constants as the weighted average of the hazard ratios across ages in order to allow ages with less variability to have more weight in the calculation. This procedure for establishing dose-response hazards in the NHSDA is inaccurate, since marijuana use frequency could change after hard drug initiation in the past year. However, we use this NHSDA estimate only for purposes of comparison to analogous hazards observed in our modeled data, not to establish parameters for the model. For this comparison, our NHSDA dose-response estimates are sufficient.

MODEL RESULTS

We drew 1 000 000 observations from the joint distribution, from which three sets of outputs are recorded: simulated marijuana and drug initiation survival functions, $\hat{S}_{ZM}(t)$ and $\hat{S}_{ZH}(t)$; relative risk of initiating hard drugs by

age 21 for cases with and without prior marijuana initiation, and the percentage of simulated cases for which hard drug use preceded marijuana use by at least 1 year prior to age 22. Because the NHSDA and our simulated cases record age of drug use initiation in whole years, it is not possible to determine if hard drug initiation preceded marijuana initiation if both occurred in the same year. Therefore, we describe hard drug initiation as preceding marijuana initiation only if $Y_H < Y_M$.

Model precision

By design, modeled marijuana and hard drug initiation survival functions, $\hat{S}_{ZM}(t)$ and $\hat{S}_{ZH}(t)$, closely matched those for the US population shown in Fig. 2. Indeed, actual and modeled survival rates differed by 0.009 or less for each drug at every age.

Gateway effects

Relative risk

In our model, by age 21, users of marijuana were 157 times more likely than non-users to have initiated a hard drug. In comparison, respondents aged 22 or older in our NHSDA sample who initiated marijuana use by age 21 were just 24 times more likely than non-marijuana users to initiate hard drugs. Thus, our model produces a relative risk phenomenon even greater than that observed in the US data, even though the model incorporates no gateway effect. We attribute little significance to the fact that our model produces a relative risk substantially greater than that observed in the NHSDA. The denominator in this ratio is so small that even a slight imprecision in its estimate could more than account for the difference between observed and modeled risk ratios. Thus, for instance, if the true value of $P_r \{Z_H < 22 \mid Z_M > 21\}$ differs from our NHSDA estimate by as little as 0.013, the true relative risk could be greater than 190.

In addition, the elevated relative risk of hard drug initiation among younger marijuana initiators vs. older ones is also reproduced in the model. Among those aged 22 and older in our NHSDA sample, those who initiate marijuana by age 15 have 1.60 times greater risk of becoming a hard drug user by age 22 than those whose marijuana initiation occurs after age 15. Our model produces the larger, but still comparable, relative risk for these groups of 3.44.

Ordering

The proportion of simulated cases for which hard drug initiation preceded marijuana initiation was 0.011. This compares with the corresponding estimate of 0.016 from the NHSDA. Thus, initiation of hard drugs before mari-

juana was even more rare in our model than in the US household data, suggesting that no gateway effect is required to explain the strong ordering effect observed in youths' drug initiation experiences.

Dose-response

Hazard ratios for hard drug initiation among users of marijuana vs. those who did not use it in the past year are presented in Fig. 3. The figure exhibits a strong dose-response relationship between marijuana use frequency and the hazard of hard drug initiation at each hypothesized correlation between the marijuana use intensity random effect, ξ_i , and propensity, θ_i . Indeed, even assuming zero correlation between these effects, a rising dose-response curve is found, with the heaviest users of marijuana having hazards of hard drug initiation more than 10 times greater than those of non-users.

The corresponding dose-response curve from the NHSDA data is plotted as a series of stars in Fig. 3. This curve bears a striking resemblance to those produced by the model. For the first two levels of marijuana use frequency the US data corresponds closely to the assumption that marijuana use frequency and drug use propensity have a moderate correlation ($r = 0.4$). For the highest marijuana frequencies, US hazard ratios fall between the moderate and high ($r = 0.8$) correlation assumptions.

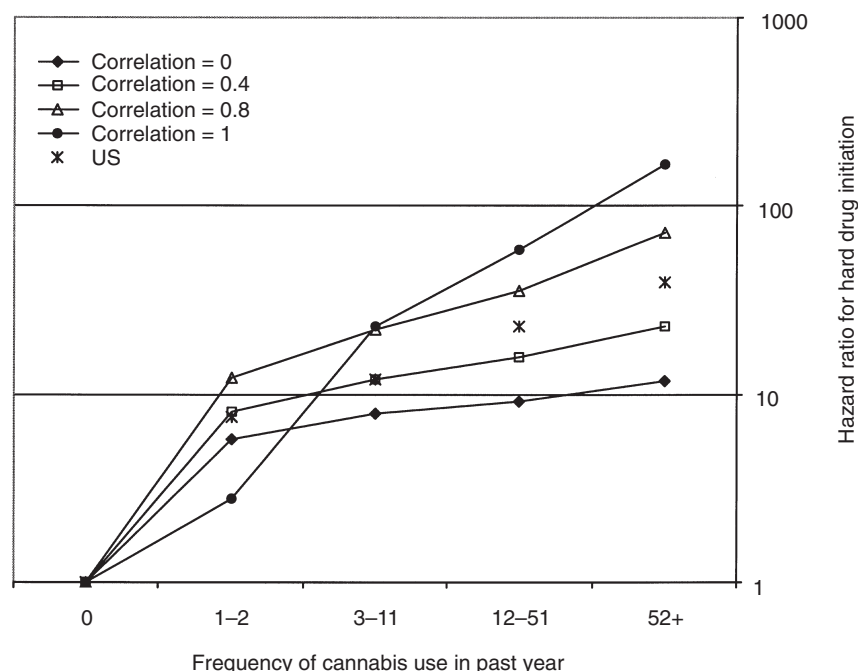
DISCUSSION

Adolescent drug use initiation

The results reported here demonstrate that a simple common-factor model with population-based parameters can reproduce each of the phenomena previously used to support claims of a marijuana gateway effect. Thus, the strong relative risk, ordering and dose-response relationships observed between marijuana use and hard drug initiation do not require an assumption that marijuana initiation, or even the first opportunity to use it, increases the risk of either hard drug initiation or the opportunity to use hard drugs. While not disproving the existence of a marijuana gateway effect, our findings demonstrate that the primary evidence supporting gateway effects is equally consistent with an alternative model of adolescent drug use initiation in which use, *per se*, of marijuana has no effect on the later use of hard drugs.

Once a general propensity to use drugs is posited, the relative risk of hard drug use among marijuana users vs. non-users can be completely accounted for as a simple consequence of the fact that users of any drug are likely to have higher drug use propensities than non-users. Indeed, our model produced hard drug initiation risk

Figure 3 Hard drug initiation hazards, given past-year marijuana use frequency (expressed as a proportion of the hazard given no past year marijuana use) under four assumptions concerning the correlation between the marijuana use intensity random effect and the drug use propensity random effect



ratios greater than those observed in the NHSDA both for users vs. non-users of marijuana and for younger vs. older initiates of marijuana.

With the assumption that use of any drug is conditioned only on an individual's age, drug use propensity and opportunity to use drugs, the observed ordering in drug initiation can be attributed to the fact that opportunities to use marijuana routinely precede opportunities to use hard drugs—often by many years. Using just these assumptions, our model produced rates of hard drug use preceding marijuana use of just 11 per 1000 individuals, reflecting an even more invariant ordering than that found in our NHSDA sample, in which 16 of every 1000 individuals try hard drugs before marijuana.

Finally, even without the reasonable assumption of a correlation between marijuana use intensity and the more general propensity to use drugs, the assumptions of the model suffice to produce a strong dose-response relationship between marijuana use frequency and the risk of hard drug initiation. However, introducing such a correlation strengthens the dose-response relationship considerably. Indeed, as demonstrated by our sensitivity analysis, adjustments to the correlation between marijuana use intensity and drug use propensity suffice to account for the magnitude of the dose-response relationship observed for populations of youths. Again, the observed dose-response relationship between marijuana use frequency and the risk of hard drug initiation requires no marijuana gateway effect for its explanation.

Exhibiting gateway effects by controlling for common factors

Earlier studies have sought to support claims of a gateway effect by showing that marijuana use, *per se*, remains a powerful predictor of hard drug initiation, even after controlling for a wide range of candidate 'common factors' such as individuals' background characteristics, their risk behaviors and the behaviors of their peers (Yamaguchi & Kandel 1984b; Fergusson & Horwood 2000). This approach presumes that the included factors are sufficiently powerful indicators of any unobserved drug use propensity that their inclusion should eliminate any spurious appearance of a relationship between marijuana use and hard drug initiation. Since we know drug use propensities in our simulation model, we can examine the limits of this assumption using a random sample of cases drawn from our model. To do so, we construct variables that are more or less reliable indicators of drug use propensity, where the variances of the normally distributed error terms are used to control the correlation between the drug use propensity and its indicator. These indicators are next included as covariates along with a marijuana use indicator, m , in the following logistic model of hard drug initiation by age 22:

$$P_r \{Z_H < 22\} = \frac{1}{1 + e^{-(a + bm + cX_1)}} \quad (5)$$

Figure 4 presents the hard drug initiation odds ratios for marijuana users vs. non-users, after controlling for drug use propensity indicators (X) with reliabilities ranging

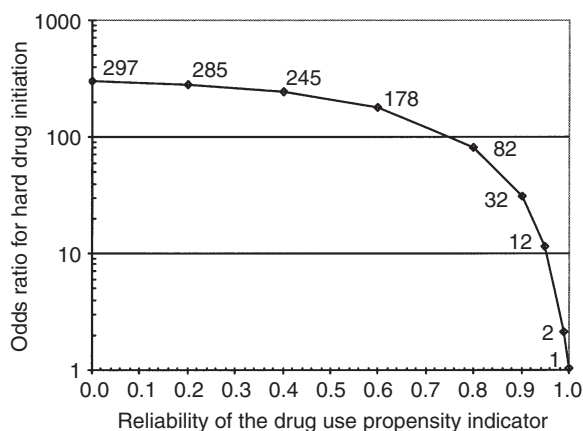


Figure 4 Odds ratios for initiating hard drugs given marijuana use (vs. non-use), after controlling for presumptive 'common-factor' variables, as a function of these variables' reliability as indicators of true drug use propensity

between 0 and 1. This figure demonstrates that drug use propensity indicators need to be almost perfectly correlated with true drug use propensity before strong relationships between marijuana use and hard drug use are eliminated. Even when the indicator fails to capture just 2% of the variance in drug use propensity (i.e. its reliability is 0.99), marijuana users appear to have odds of initiating hard drugs that are twice as great as non-users of marijuana. Because it is very unlikely that the covariates included in prior studies have anything like a 0.99 correlation with drug use propensity, it is hardly surprising that controlling for these covariates does not eliminate the association between marijuana and hard drug use.

Model limitations

Several limitations and clarifications on the results are warranted. Firstly, our model relies on a number of untested assumptions and simplifications, such as a normal distribution for propensity and the frailty model for the joint distribution of age of first opportunity to use marijuana or hard drugs. To the extent these assumptions do not approximate corresponding phenomena in the population of youths, the model represents the process of adolescent drug use initiation less well. However, to the extent the model assumptions are plausible, we have demonstrated one possible process of drug use initiation that produces all of the gateway phenomena without requiring a gateway effect. The plausibility of our model is demonstrated through comparisons with estimates from the NHSDA. However, our estimates of the rate at which gateway phenomena occur in the NHSDA also depend on assumptions that may be wrong, like that the hazards of hard drug initiation for different marijuana use frequency groups remain proportional across

age groups. If the assumptions are wrong, our NHSDA estimates will be biased and the comparisons provide less good evidence for the plausibility of our simulation model.

Secondly, we have produced a plausible model of adolescent drug use initiation that derives many of its parameter estimates from the NHSDA, a survey of US residents. However, it is quite clear that many of these parameters, like marijuana use prevalence, are specific to the population of youths in the US during the period in which the data used in this study were collected. As such, our estimates of the rate at which gateway effects occur in the NHSDA should not be expected to generalize to other places or times. Similarly, our model is calibrated to correspond to this US data, and might produce quite different results if parameter estimates from a different country or a different time were substituted for those estimates we used.

A third clarification concerns the possible effects of response bias on the appearance of gateway effects in this study, and every other study relying primarily on self-reports of drug use to demonstrate gateway effects. Suppose, for instance, that the likelihood of initiating hard drugs is, in fact, independent of whether or not someone has initiated marijuana or the frequency with which they use it. If there was a systematic under-reporting bias that led some marijuana users to claim to have never used either marijuana or hard drugs, or to under-report their marijuana use frequencies and their use of hard drugs, these biases could lead to the appearance of both the relative risk and dose-response gateway phenomena, although neither truly existed. If response bias accounts for the gateway phenomena, then the propensity factor we include in our model may correspond more to some heterogeneous response bias trait than it does to a true propensity to use drugs. It is for this reason that we have been careful to define propensity in terms of the likelihood of reporting drug use, rather than of engaging in drug use.

Fourthly, we constructed the model in such a way that use of hard drugs is independent of use of marijuana, except insofar as they share a common propensity to use drugs. This feature of the model holds true regardless of the particular values selected for drug use opportunities, use given opportunities or the correlation parameters. Therefore, even though the data set we use to derive these parameters might reflect the operations of a true gateway effect (the NHSDA), we can be certain that model's outputs do not result from any such effects.

The status of the marijuana gateway effect

The model and analyses described above do not disprove the gateway effect. Instead, they demonstrate that each

of the phenomena that appear to support such an effect are, in fact, equally consistent with a plausible alternative that accounts for the known general liability to use drugs and the known differences in when youths receive their first opportunities to use drugs.

Something like a marijuana gateway effect probably does exist, if only because marijuana purchases bring users into contact with a black market that also increases access to hard drugs (Goode 1970). However, this observation does not refute the analysis presented above, since there are at least two ways that gateway effects could exist without undermining a model of drug use initiation that fails to include them. Firstly, it is possible that any true marijuana gateway effects can explain only a tiny fraction of individuals' risk of hard drug use in comparison with the risk attributable to their propensities to use drugs, and is therefore a negligible factor in our model. A second possibility is that marijuana use could increase the risk of hard drug use for some youths, while decreasing the risk for others. As such, true marijuana gateway effects may be counterbalanced in the population by negative marijuana gateway effects, with the net effect of marijuana use on hard drug use being insignificant. Negative gateway effects could occur if, for instance, marijuana sated some youths' desires to experiment with illicit drug use, or if unsatisfying (or penalized) marijuana use experiences discouraged drug use progression among some youths.

The purported marijuana gateway effect is frequently invoked by policy makers as among the primary reasons to resist efforts to relax marijuana policies, such as permitting the medicinal use of marijuana (US Department of Health and Human Services 1999). Whereas social scientists often acknowledge that relative risk, ordering in drug use initiation and dose-response phenomena do not prove the existence of a marijuana gateway effect, they too have frequently drawn policy conclusions that presuppose such an effect. For instance, many have concluded that by postponing youths' marijuana initiation, prevention efforts will reduce the likelihood of hard drug use and abuse (Yamaguchi & Kandel 1984b; Kandel *et al.* 1992; Golub & Johnson 2001). Our model demonstrates how the observed correlations in the use of marijuana and hard drugs may be entirely due to individuals' propensity to use drugs and their opportunities to use them. As such, marijuana policies would have little effect on hard drug use, except insofar as they affected either an individuals' propensity to use any drugs (as might be the case with drug use prevention programs) or they resulted in hard drugs becoming less available or available later in youths' lives.

Because our model provides a straightforward, parsimonious and plausible explanation for each of the phenomena used to support claims of a marijuana gateway

effect, we believe the validity of that effect must remain uncertain until new evidence is available directly comparing it with the alternative common-factor model.

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