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Dynamic transitions between marijuana use and cigarette smoking among US adolescents and emerging adults

Bin Yu, MD, MPH, Xinguang Chen, MD, PhD, and Yan Wang, PhD

Department of Epidemiology, University of Florida, Gainesville, FL 32610

Abstract

Background: Marijuana and tobacco are considered two closely related substances. It is of great significance to understand the mutual impact of marijuana and cigarette use when more and more states in the U.S. legalized marijuana use.

Objective: This study aims to investigate the transitions between marijuana and cigarette among adolescents and emerging adults.

Method: Guided by the probabilistic discrete events systems (PDES) theory, a five-stage model with 21 transition paths was constructed to quantify dynamic transitions between marijuana-cigarette use. The five stages were *NU*: Never-user, *MU*: Current marijuana user, *CU*: Current cigarette user, *MCU*: Current marijuana-cigarette user, and *FU*: Former-user. The proposed five-stage PDES model was tested using the 2013 National Survey on Drug Use and Health data (N=26,665, 50.45% male). Transition probabilities were estimated using the Moore-Penrose generalized inverse matrix method.

Result: Among the adolescents, 51.14% of the *CUs* transitioned to use marijuana (*MCU/MU*), higher than the proportion of those who first used marijuana and then transferred to cigarettes (*MCU/CU*) (41.66%). The quitting rates for *MUs*, *CUs* and *MCUs* were 29.38%, 25.93% and 27.76%, respectively. Of the total *FUs*, 31.90% transitioned to *MUs*, 17.06% to *CUs*, and 17.39% to *MCUs*. Among the young adults, more people progressed from *MUs* to *CUs*. Transition probabilities by single year of age were also estimated.

Conclusion: This is the first study to quantify marijuana-cigarette transitions. Study findings indicate more cigarette-to-marijuana transitions for adolescents and more marijuana-to-cigarette transitions for emerging adults. Future intervention programs should consider this age-related difference in marijuana-cigarette use transitions.

Keywords

PDES; Marijuana; Cigarette; Transition probability; State probability

Correspondence: Dr. Xinguang Chen, MD, PhD, Professor, Department of Epidemiology, University of Florida, 2004 Mowry Road, #4228, Gainesville, FL 32610, jimax.chen@phhp.ufl.edu, Phone: (352) 294-5945.

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1. Introduction

1.1 Marijuana and cigarette use among youth in the United States

Marijuana is the most commonly used illicit drugs among youth in the United States (U.S.) (1,2). To date, 29 U.S. states and the District of Columbia have established Medical Marijuana Laws (MML) (3), including eight states with laws for recreational marijuana use (4). Permitting marijuana use through state legislation may increase the likelihood of using marijuana (5–7). Marijuana-use is associated with increased risk of using other substances, including cigarettes (1,8,9). Reported studies indicate that using marijuana is associated with an 8-fold increased risk of cigarette initiation (8). Likewise, cigarettes could increase the risk of using marijuana (10).

A synergistic effect is likely seen between marijuana and cigarette use (8). The molecular biological changes in the brain of tobacco users suggest that smoking cigarettes increases the probability of using marijuana, and vice versa (11). In addition, using marijuana may alter individual's attitudes and perception of marijuana and other drugs, including reductions in perceived harm of drug use, which may increase the likelihood to smoke cigarettes (12,13). Social norms and stigma against drug users may also change along with marijuana legalization, increasing the acceptance and eventual use of marijuana and cigarettes (14).

In addition to the biopsychosocial consequences described above, using marijuana has been linked with a number of developmental, cognitive, and behavioral problems among adolescents (15); while tobacco use has long been recognized as one of the most preventable causes of morbidity and mortality (16). Therefore, understanding the mutual impact of marijuana and tobacco use is of great significance to prevent young people from misusing marijuana and to strengthen the current tobacco control strategy.

1.2. Marijuana-tobacco use transitions by stage

Distinguishing progression stages is essential for modeling the dynamics of substance use transitions (17–19). The development of substance use is not linear and continuous but complex and discrete, consisting of distinctive transition stages (20–22). For example, the development of cigarette smoking starts with people who have never smoked in lifetime – non-smoker. When smoking the first time they become initiators. If continue to smoke, they become current-smokers. Current-smoker can quit and become former-smoker (20). Similar stages can also be developed to characterize marijuana use (23–25).

Behavioral progression becomes more complex when two or more substances are considered. A simple three-stage model for marijuana or cigarettes can include never-user, current-user, and former-user. To model the two substance simultaneously, a minimum of five transition stages are needed: (a) Never-user: people never used marijuana *and* cigarettes in lifetime, (b) Current marijuana user: people currently use *only* marijuana, (c) Current cigarette user: people currently use *only* cigarettes, (d) Current marijuana-cigarette user: people currently use both marijuana and cigarettes, and e) Former-user: people previously used either marijuana or cigarettes or both but use neither currently.

1.3 PDES modeling in estimating the transition probabilities

With defined behavior progression stages, transition models can be constructed to quantify the impact of one substance on another. Using the marijuana-cigarette transition as an example, a path linking current marijuana users to current cigarette smokers makes it possible to quantify the likelihood of people who use marijuana progress to smoking cigarettes; paths linking current-users of marijuana, cigarettes and dual marijuana-cigarettes to former-user make it possible to assess which types of users are more likely to quit. Information of polysubstance use transition is essential for prevention; however, conducting such modeling analyses requires longitudinal data, which are not often available.

Another reason for the lack of studies on stage-based polysubstance use transitions is the lack of appropriate methodology (20–22,26). Recently, a method based on the probabilistic discrete event systems (PDES) was reported (27–29). An important advantage of this method is that it requires no longitudinal data but only one wave cross-sectional data. PDES model has been successfully used in modeling single behavior, including cigarette smoking (20,22) and alcohol consumption (21). In a recent study, we successfully modeled mutual transitions of conventional-electronic cigarette smoking among U.S. adolescents (30). This study aims to use PDES method to model mutual transitions between marijuana and cigarette use with cross-sectional data.

1.4. Age and laws affecting marijuana-cigarette transition

Age patterns of substance use progression provide useful information for understanding the substance use development. Substance uses during adolescence are often associated with imbalanced developments with cognitive function being lagged behind physical growth (14,31,32). In one study, the risk of marijuana initiation was related to biological age with the likelihood peaked at age 18 (14). In another study, a sudden and dramatic increase of alcohol transition from never-users to users was observed in age 18–20 (21). However, few studies have investigated issues related to polysubstance use transitions. One aim of this study is to investigate the age patterns of marijuana-cigarette transition. We hypothesized that biological age plays an important role in affecting marijuana-cigarette transitions.

Substance use behaviors are greatly influenced by laws and policies. Laws regulating substances not only affect individual's behaviors, but also attitudes, perceptions and values towards the substances (5,6,33,34). For example, the legal age to purchase tobacco, as well as the smoking-free campus, health warnings on cigarette packages, and tobacco taxations (35) have shown significant effects in reducing tobacco use. People must be at least 18 years old to purchase and use tobacco products legally, preventing those younger than 18 from accessing and using tobacco.

However, limited laws and policies have been established at the local and state levels to govern substance use among adolescents, such as tobacco vaping. While marijuana use is illegal by federal laws, but in states with marijuana laws, using marijuana is protected. Although no minimum legal age has been established for marijuana, the minimal legal age for purchasing tobacco at age 18 (36) may affect marijuana use and marijuana-cigarette transitions. In addition, the MML in the U.S. may increase acceptability to and reduce the

perceived harm from marijuana, and it may also increase the availability and accessibility of marijuana among adolescents (37,38). When adolescents have limited access to cigarettes below age 18, they might pick up marijuana instead, which does not have a minimum legal age to use (37,38).

1.5 Purpose of the study

This study aims to investigate the mutual marijuana-cigarette transitions by age from adolescence to emerging adulthood. The ultimate purpose is to provide data in deepening our understanding of marijuana-cigarette transitions and informing future policy and behavioral interventions to prevent marijuana use among young people and to deal with new challenges in tobacco control emerging from marijuana legalization.

2. Materials and Methods

2.1 Data source and study sample

Data were derived from the 2013 National Survey on Drug Use and Health (NSDUH) (<https://nsduhweb.rti.org/respweb/homepage.cfm>). NSDUH is an ongoing annual cross-sectional survey sponsored by the Substance Abuse and Mental Health Services Administration (SAMHSA) to monitor substance use and health in the U.S. Participants were selected with a multi-stage stratified cluster sampling method (39). We included participants aged 12–21 in our study to assess transition probabilities by single age. Among the total 55,160 participants, those aged 22 and above were excluded because of lack of data by single age, yielding a final sample of 26,665 participants.

2.2 Measurement of marijuana use and cigarette smoking

Two questions were used to assess marijuana use. Data from the first question was related to lifetime use: “Have you ever, even once, used marijuana or hashish?” (Yes/No). Individuals who responded positively to this question were further asked: “During the past 30 days, that is since [date of 30 days ago], on how many days did you use marijuana or hashish?” (Enter the number days).

Likewise, two similar questions were used to assess cigarette smoking, including one asking for lifetime use: “Have you ever smoked part or all of a cigarette? (Yes/No)”; and another asking for 30-day use for those who responded positively to the first question: “During the past 30 days, that is since [date of 30 days ago], on how many days did you smoke part or all of a cigarette?” (Enter the number days).

2.3 Stages of marijuana-cigarette transitions and state probabilities

Using data from the four questions described above, five stages were defined to quantify the complex mutual marijuana-cigarette transitions:

1. Participants were categorized as “never-users” (*NU*) if they responded negatively to the two questions asking for lifetime use of marijuana and cigarettes.
2. Participants were categorized as “current marijuana users” (*MU*) if they responded positively to the lifetime marijuana use question, used marijuana at

least one day in the past 30 days, and did not smoke cigarettes during the past 30 days.

3. Participants were categorized as “current cigarette users” (*CU*) if they responded positively to the lifetime cigarette smoking question, smoked cigarettes at least one day in the past 30 days, and did not smoke marijuana during the past 30 days.
4. Participants were categorized as “current marijuana and cigarette users” (*MCU*) if they responded positively to the lifetime use questions for both marijuana and cigarette and used both of them at least one day during the past 30 days.
5. Participants were categorized as “former-users” (*FU*) if they responded positively to the lifetime use questions for marijuana, cigarette or both and used neither during the past 30 days.

With the five *mutually exclusive progression stages* defined above, proportions of participants in individual stages were calculated as “state probabilities”. The state probabilities were calculated first by single age to assess annual transitions from age 12 to 21. The state probabilities were then calculated across two consecutive age-groups, 12–16 years and 13–17 years, and used to assess transitions for all adolescents aged 12–16 advanced to age 13–17 in one-year period. Likewise, state probabilities were also calculated for participants aged 18–20 and 19–21, and were used to assess one-year transitions for emerging adults aged 18–20 as they advanced to ages 19–21.

State probabilities were calculated using the PROC SURVEYFREQ from the statistical software SAS, considering the multi-stage clustering sampling design used in NSDUH. These probabilities provided a snapshot of the stage-based marijuana-cigarette transition, and were used as data to estimate the transition probabilities through PDES modeling analysis.

2.4. Construction of PDES transitional models

Figure 1 depicts the dynamics of mutual marijuana-cigarette transitions with transition paths linking the five transition stages *NU*, *MU*, *CU*, *MCU* and *FU*. A total of 21 transition probabilities σ_1 to σ_{21} were used to quantify the complex nonlinear dynamic transition process. These probabilities were estimated with the state probabilities as described in Section 2.3. For example, σ_2 describes the probability of people who never used marijuana and cigarettes to progress to cigarette smokers; and σ_9 describes the probability of a cigarettes smoker to progress to marijuana user.

Guided by the proposed PDES model in Figure 1, the following 10 equations were constructed by introducing age (*a*) of the participants as a time variable to describe transitions across different stages during one-year period, i.e., from age/year (*a*) to age/year (*a*+1).

$$NU(a + 1) = NU(a) - NU(a)*\sigma_2 - NU(a)*\sigma_3 - NU(a)*\sigma_4 - NU(a)*\sigma_5 \quad (1)$$

$$\begin{aligned} \text{MU}(a+1) = & \text{MU}(a) + \text{NU}(a) * \sigma_3 + \text{CU}(a) * \sigma_7 + \text{MCU}(a) * \sigma_{15} + \text{FU}(a) * \sigma_{19} - \text{MU}(a) * \sigma_{10} - \\ & \text{MU}(a) * \sigma_{12} - \text{MU}(a) * \sigma_{13} \end{aligned}$$

(2)

$$\begin{aligned} \text{CU}(a+1) = & \text{CU}(a) + \text{NU}(a) * \sigma_2 + \text{MU}(a) * \sigma_{10} + \text{MCU}(a) * \sigma_{14} + \text{FU}(a) * \sigma_{18} - \text{CU}(a) * \sigma_7 - \\ & \text{CU}(a) * \sigma_8 - \text{CU}(a) * \sigma_9 \end{aligned}$$

(3)

$$\begin{aligned} \text{MCU}(a+1) = & \text{MCU}(a) + \text{NU}(a) * \sigma_4 + \text{CU}(a) * \sigma_8 + \text{MU}(a) * \sigma_{12} + \text{FU}(a) * \sigma_{20} - \text{MCU}(a) * \sigma_{14} \\ & - \text{MCU}(a) * \sigma_{15} - \text{MCU}(a) * \sigma_{17} \end{aligned}$$

(4)

$$\begin{aligned} \text{FU}(a+1) = & \text{FU}(a) + \text{NU}(a) * \sigma_5 + \text{CU}(a) * \sigma_9 + \text{MU}(a) * \sigma_{13} + \text{MCU}(a) * \sigma_{17} - \text{FU}(a) * \sigma_{18} - \\ & \text{FU}(a) * \sigma_{19} - \text{FU}(a) * \sigma_{20} \end{aligned} \quad (5)$$

$$\sigma_1 + \sigma_2 + \sigma_3 + \sigma_4 + \sigma_5 = 1 \quad (6)$$

$$\sigma_6 + \sigma_7 + \sigma_8 + \sigma_9 = 1 \quad (7)$$

$$\sigma_{10} + \sigma_{11} + \sigma_{12} + \sigma_{13} = 1 \quad (8)$$

$$\sigma_{14} + \sigma_{15} + \sigma_{16} + \sigma_{17} = 1 \quad (9)$$

$$\sigma_{18} + \sigma_{19} + \sigma_{20} + \sigma_{21} = 1 \quad (10)$$

2.5. Solving the PDES marijuana-cigarette transition model

It is challenging to solve the constructed PDES marijuana-cigarette transition model using equations (1) to (10) (20–22). This is because the system model is not directly identifiable given that the model consists of 21 unknown transition probabilities σ_{1-21} but has only 10 equations. To overcome this challenge, Moore-Penrose (M-P) generalized inverse matrix method was developed to obtain solutions for under-determined equation systems (40,41). We implemented the M-P method using R packages “limSolve” and “MASS”. In the modeling analysis, three sets of transition probabilities were estimated, one for adolescents aged 12–17, one for emerging adults aged 18–21, and one by single age for the whole adolescent-emerging adulthood age range. The first two sets of probabilities were used to describe the overall patterns of marijuana-cigarette transitions and the last set was used to describe age-patterns of the mutual marijuana-cigarette transitions.

3. Results

3.1 Characteristics of the study sample

Among the 26,665 participants, 50.45% were male, 55.60% White, 13.83% Black, 19.77% Hispanic, 4.02% Asian, and 4.79% multi-racial. The mean age (not shown in the table) was 16.20 (SD=2.79). More detailed information about the study sample is presented in Table 1.

3.2 State probabilities, overall and by age groups and single years of age

Table 2 summarizes the state probabilities for the five stages of marijuana-cigarette transition. Overall, 61.82% of the participants were *NU* with 6.19% *MU*, 8.19% *CU*, 6.69% *MCU*, and 17.12% *FU*. The state probabilities for the two adolescent groups with one-year interval (12–16 and 13–17) were used for modeling transitions during adolescence; the state probabilities for the two emerging adults groups also with one-year interval (18–20 and 19–21) were used for modeling transitions during emerging adulthood; and state probabilities by single year of age were used for modeling mutual marijuana-cigarette transitions by single years of age.

Results in Figure 2(a) indicate that within one-year period, an adolescent *CU* had 51.14% chance to progress to using marijuana (24.39%: *CU*→*MCU* and 26.75%: *CU*→*MU*). The transition from *MU* to cigarette smoking were 41.76%, lower than that from *CU* to marijuana use. *MUs* had a 20.56% chance of transition from *MU* to *MCU* by picking up cigarettes and 21.10% chance of transition from *MU* to *CU* by dropping marijuana and picking up cigarettes. The chances to quit and become *FU* were 29.38% for *MU* (the highest), 27.76% for *MCU* (the second highest) and 25.93% for *CU* (the lowest). Lastly, *FU* had 31.90% chance to become *MU* (the highest), 17.39% to become *MCU* (the second highest) and 17.06% to become *CU* (the lowest).

Results in Figure 2(b) indicate that the probability for an emerging adult *CU* progressing to marijuana was 37.53% (22.39%: *CU*→*MCU*, and 15.14%: *CU*→*MU*). The probability for *MU* progressing to cigarette was 50.44% (27.19%: *MU*→*CU*, and 23.25%: *MU*→*MCU*). The probabilities for transitions of *MU*, *CU* and *MCU* to *FU* were 30.42%, 32.71%, and 31.81%, respectively; while the probability for *FU* progressing back to *MU*, *CU* and *MCU* were 10.29%, 30.14% and 21.29%.

Comparing results in Figure 2(a) with 2(b) indicates that probabilities were higher for adolescents than emerging adults to progress from *CU* to *MU* (26.75% vs. 15.14%, $p<0.001$) and *MCU* (24.39% vs. 22.39%, $p<0.001$); and the probabilities were lower for adolescents than for emerging adults progressing from *MU* to *CU* (21.10% vs. 27.19%, $p<0.001$) and *MCU* (20.56% vs. 23.25%, $p<0.001$). The probabilities were lower for adolescents than emerging adults progressing from *MU* (29.38% vs. 30.24%, $p=0.15$), *CU* (25.93% vs. 32.71%, $p<0.001$), and *MCU* (27.76% vs. 31.81%, $p<0.001$) to *FU*; while the probabilities were also lower for adolescents than emerging adults progressing from *FU* to *CU* (17.06% vs. 30.14%, $p<0.001$) and *MCU* (17.39% vs. 21.29%, $p<0.001$) but higher for *FU* to *MU* transition (31.90% vs. 10.29%, $p<0.001$). It is worth noting that an adolescent *NU* had a 9.51% chance of progressing to *FU* within one year (by using either marijuana or cigarettes or both and then stopping) and the probability was 13.38% for emerging adults.

3.3 Age patterns of marijuana-cigarette use transitions

Figure 3(a) contrasts the age-specific probabilities of transition from *MU* to cigarette use (*CU*/*MCU*) (solid line) and *CU* to marijuana use (*MU*/*MCU*) (dashed line). The probability for *CU*-marijuana use (*MU*/*MCU*) transition remained at around 50% in age 12–16 before it suddenly dropped and ended at the lowest level at 25.78% by age 20. The probability for *MU*-cigarette use (*CU*/*MCU*) transition, started at 48.38%, declining from age 12 and reaching the lowest level by age 16; after age 16, the probability increased, forming a peak at age 18 before it declined again, and ended at 48.52% by age 20. The two curves crossed each other at around age 17. Up to age 17, *CU*-marijuana transition was more likely than *MU*-cigarette transition; after age 17, *MU*-cigarette transition was more likely than *CU*-marijuana transition.

Results in Figure 3(b) present the probabilities for *MCU*-*CU* transition (solid line) and *MCU*-*MU* transition (dashed line) respectively. The two transition probability curves started at a similar level (25.07% vs. 25.56%) and formed a crossover in age 16–17. Prior to age 17, the probability was higher for *MCU*-*MU* transition than for *MCU*-*CU* transition; and after age 17, the transition was reversed.

Figure 3(c) presents the probabilities for *MU*, *CU* and *MCU* progressing to *FU*. The three probabilities all started at around 25–27%, gradually increased up to age 17 and accelerated from age 17 to 20. At age 16, the probability was the highest for *MU*-*FU* transition and the lowest for *CU*-*FU* transition; the three probabilities became close to each other at age 18 and differed thereafter; by age 20 the probability was the highest for *CU*-*FU* transition, lowest for *MU*-*FU* transition with *MCU*-*FU* in between.

Results in Figure 3(d) depict the probabilities for transitions from *FU* to *MU* (dashed black line), *CU* (solid black line) and *MCU* (dashed grey line). At age 12, the probability was high for both *FU-MU* and *FU-CU* transitions; prior to age 16, the probability for *FU-MU* transition fluctuated at high levels while the probabilities for both *FU-CU* and *FU-MCU* fluctuated at low levels. Starting from age 16, the probability for *FU-MU* transition declined progressively while the probability for *FU-CU* and *FU-MCU* transitions increased progressively. By age 20, the transition probability was the highest for *FU-CU* transition, the lowest for *FU-MU* transition with *FU-MCU* in between.

4. Discussion

In this study, we successfully modeled the nonlinear dynamics of mutual marijuana-cigarette transitions using a five-stage PDES model. PDES model is a useful tool to quantify mutual transitions of using two substances. To our knowledge, this is the first study to model the dynamics of mutual transitions of marijuana and cigarette with cross-sectional data and PDES method. Findings of this study add new data deepening our understanding of the complex dynamic transitions underpinning polysubstance use behavior, and provide new evidence informing future policy and behavioral intervention research for tobacco and marijuana use prevention.

4.1 PDES modeling in substance use research

Understanding the transitions by stages of one or more substances is important to develop effective interventions. Traditionally, the transitional probabilities are estimated using longitudinal data which is expensive and time-consuming with a high attrition rate (22). The PDES modeling enables researchers to derive longitudinal information from one wave cross-sectional data. One previous study demonstrated the validity of PDES method by comparing the transitional probabilities estimated from cross-sectional data with the results from longitudinal data (20). Based on findings from this and another study on conventional-electronic cigarette smoking transitions (30), we can conclude that PDES method is a useful tool not only to model the progression of one behavior but also two or more behaviors.

4.2 Differences in marijuana-cigarette transitions between adolescence and emerging adulthood

Using marijuana is associated with increased risk of cigarette use, and vice versa (1,8–10). This study expanded the previous knowledge by investigating mutual marijuana-cigarette transitions across multiple progression stages linked by 21 progression steps. People who never used marijuana/cigarettes in life can start using them separately or together in one year. Marijuana-users can pick up cigarettes, becoming dual-marijuana and cigarette users, they may also quit marijuana and pick up cigarettes and become cigarette-only users. Likewise, cigarette-smokers may also pick up marijuana and become dual marijuana-cigarette users or drop cigarettes and become marijuana-only users. Single or dual-users of marijuana/cigarettes could have different probabilities to quit and become former-users, while former-users have different probabilities to re-use marijuana, cigarettes or both.

During adolescence, transitions of cigarettes-to-marijuana and from former-users to marijuana were more dominant. According to tobacco related policies, adolescents less than 18 years old are not allowed to purchase and use cigarettes (36). Stores are requested to check ID before selling tobacco to youth. Meanwhile, the decriminalization and legalization movements of marijuana have reduced the perceived risk, altered the attitudes, and increased the accessibility of marijuana (33,34). Studies showed a high proportion (about 50%) of middle/high schools students have access to marijuana through different approaches (37,38). Therefore, facing the situation of illegal use of cigarettes versus acceptable use of marijuana, adolescents might prefer to drop cigarettes and pick up marijuana.

During the emerging adulthood, initiation of cigarette-use and transitions from marijuana-to-cigarettes were more prevalent. When entering adulthood at age 18, young people acquire their legal rights to buy and smoke cigarettes. Relative to marijuana, cigarettes are cheaper (approximately \$7 per gram of marijuana vs. \$5–7 per pack of cigarettes), and much easier to get access to in market. All these features may make people more likely to switch to cigarettes.

4.3 Age patterns of marijuana-cigarette transitions

Consistent with the differences in the susceptibility to substance use between adolescence and emerging adulthood, the observed marijuana-cigarette transitions showed distinguished patterns by age from age 12 to 21 with a crossover occurring around ages 17–18. Prior to age 18, cigarette-to-marijuana transitions were more likely than transitions from marijuana-to-cigarette; after age 18, a reverse pattern was true. The observed differences in transitions by single age demonstrate the continuous impact over time of laws, policies, social norms and perceptions on the availability, accessibility and actual use of marijuana and cigarettes during adolescence–emerging adulthood (8).

In addition, there is a sudden increase in transitions to cigarettes from marijuana-use only, dual marijuana-cigarette use, and former use during ages 15–19. This pattern is consistent with the imbalanced physical and cognitive developments during this period (42). Curiosity (43) and peer influence (44) are two most commonly factors affecting adolescent substance use. By age 15, most students have experienced their freshmen year in high school and experienced increased peer influences. After completing high school by age 18, students either enter college or find a job. The sudden increases in personal freedom and the social and financial burden and the lack of maturity may put them at increased risk of substance use. Additional studies are needed to investigate the mechanisms of substance use during adolescence-emerging adulthood.

5. Conclusion

Mutual marijuana-cigarette transitions among adolescents and emerging adults are complex. PDES-based model provides a powerful method to investigate the complex mutual transitions. Findings of this study indicate that ages 17–18 are a critical time by which marijuana-cigarette transitions substantially differ. This age-related difference reflects the impact of intra-personal developmental imbalance and the external factors of substance-related laws and policies. Intervention researchers and public health practitioners might

think of strengthening current intervention measures or developing new intervention programs for effective substance use control and prevention.

6. Limitations

There are limitations to this study. First, participants older than 21 years are excluded because data by single age were not publicly available. Second, data for marijuana and cigarette were based on self-report, and recall bias cannot be ruled out. Third, the modeling analysis focused on transitions occurring within one year, transitions occurring over a period shorter than one year will not be captured. Lastly, caution is needed when interpreting the estimated transition probabilities. The PDES models are mathematically unidentifiable. Although solutions for PDES models are obtained using the M-P method, this does not mean the identifiability problem has been resolved.

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Figure 1.

Probabilistic discrete events systems Model of the Nonlinear Dynamics of Mutual Marijuana-Cigarette Use Transitions for Adolescents and Emerging Adults Note: NU=Never-user, MU=Current marijuana user, CU=Current cigarette user, MCU=Current marijuana and cigarette user, FU=Former user

(a) Adolescence

(b) Emerging adulthood

Figure 2.
PDES modeling of marijuana-cigarette transitions during (a) adolescence and (b) emerging adulthood

Figure 3. Age pattern of transition probabilities between cigarettes and marijuana use (a) CU→M and MU→C (b) MCU→CU and MCU→MU (c) CU→FU, MU→FU and MCU→FU, and (d) FU→CU, FU→MU and FU→MCU

Table 1.

Characteristics of the study sample and prevalence rates of marijuana and cigarette smoking

Variables	Sample, n (%)	Lifetime smoking (%)		
		Cigarettes	Marijuana	Marijuana & Cigarette
Total	26665 (100.00)	28.85	28.07	36.62
Gender				
Male	13452 (50.45)	30.25	29.24	37.85
Female	13213 (49.55)	27.42	26.87	35.36
Age in years				
12	2725 (10.22)	2.64	1.65	3.49
13	2925 (10.97)	6.70	4.92	8.41
14	3039 (11.40)	12.57	10.33	15.86
15	3006 (11.27)	19.33	19.93	26.61
16	3058 (11.47)	25.64	29.66	36.82
17	2983 (11.19)	34.19	37.45	46.90
18	2343 (8.79)	40.67	42.85	54.03
19	2122 (7.96)	51.08	46.65	61.31
20	2244 (8.42)	56.28	50.80	65.78
21	2220 (8.33)	61.13	55.14	70.86
Race				
White	14827 (55.60)	31.15	27.74	37.38
Black	3689 (13.83)	21.12	29.68	35.21
Hispanic	5273 (19.77)	27.54	27.46	35.37
Asian	1071 (4.02)	17.93	17.74	23.90
Multi-racial	1278 (4.79)	34.59	35.21	43.82
Others	527 (1.98)	39.66	35.67	45.73

Table 2.

State probabilities for five PDES-model based marijuana and cigarette use stages, overall and stratified by age and age groups, NSDUH, 2013

Age (a)	NU	MU	CU	MCU	FU
Adolescence					
12–16 years	83.31	3.47	1.96	1.98	9.27
13–17 years	75.39	5.03	3.21	3.25	13.12
Emerging adulthood					
18–20 years	39.72	8.98	15.43	11.64	24.23
19–21 years	34.37	8.59	17.66	13.30	26.07
Single age					
12 years	97.17	0.36	0.25	0.14	2.09
13 years	92.91	0.72	0.90	0.46	5.01
14 years	85.55	3.44	1.14	1.39	8.48
15 years	75.84	4.02	3.23	3.21	13.70
16 years	66.55	8.41	4.16	4.53	16.34
17 years	55.48	8.64	6.66	6.80	22.42
18 years	46.61	9.56	11.36	9.53	22.94
19 years	38.96	8.83	15.70	12.77	23.74
20 years	32.86	8.49	19.66	12.85	26.13
21 years	31.29	8.45	17.59	14.30	28.36
Overall	61.82	6.19	8.19	6.69	17.12

Note: *NU*=Never used marijuana and/or cigarette, *MU*=Current marijuana user, *CU*=Current cigarette smoker, *MCU*=Current marijuana and cigarette user, *FU*=former marijuana or cigarette user.