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EMPIRICAL RESEARCH

Sensation Seeking and Substance use in Chinese Adolescents: Longitudinal Trajectories and Prospective Within-person Associations

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Abstract

Sensation seeking has been extensively demonstrated as a risk factor for substance use. Potential bidirectional associations between sensation seeking and substance use at the within-person level are incompletely understood. The present study examined longitudinal trajectories of sensation seeking and substance use and bidirectional longitudinal associations between sensation seeking and substance use in Chinese adolescents during a 3-year period over three time points. A total of 10,138 adolescents (59.8%) male; $M_{age} = 16.77$, $SD = 0.83$ at time (1) were surveyed. Sensation seeking and substance use frequency increased concomitantly over time. At the within-person level, sensation seeking and substance use were reciprocally predictable, and there were no evidence of sex difference in longitudinal associations. This study provides unique data concerning the relationship between sensation seeking and substance use in a sample of Chinese adolescents, and highlights the importance of identifying sensation seeking behaviors to prevent substance use.

Keywords Sensation seeking · Substance use · Chinese adolescents · Longitudinal trajectory · Within-person

Introduction

Substance use is defined as using any psychoactive compound that has the potential to cause health and social problems, including alcohol, tobacco and others (McLellan, 2017). Substance use behaviors increase in adolescence, peak in early young adulthood, and subsequently decline. Increased sensation seeking during adolescence is an important risk factor for substance use (Su et al., 2021). Although there is an increasing number of studies addressing how adolescent sensation seeking is reciprocally linked to substance use (Lac & Donaldson, 2021), few studies have concomitantly examined the developmental trajectories of both sensation seeking and substance use. Furthermore, the relationship between sensation seeking and substance use among Chinese adolescents is incompletely understood, as is the extent to which findings from prior studies in other racial and ethnic groups can be generalized to Chinese adolescents is unclear. The current longitudinal study analyzing three waves of data in Chinese adolescents investigated the within-person bidirectional associations between sensation seeking and substance use,

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concomitantly taking into account the longitudinal trajectories of sensation seeking and substance use, while also exploring sex differences over time.

Prospective Effects of Sensation Seeking on Substance Use

Sensation seeking is a personality trait that predisposes individuals to select and prefer experiences that are novel, rewarding, or exciting (Harden & Tucker-Drob, 2011). Sensation seeking typically becomes more prominent with the onset of adolescence, peaks in mid-adolescence, and declines in early adulthood (Freund et al., 2021). Compared to these normative overall trends, there are between-person differences in changes in trajectories (Schwaba and Bleidorn 2018). Prior studies have identified a strong association between sensation seeking and substance use (Su et al., 2021). Typically, the severity of sensation seeking is positively correlated with the severity of substance use in adolescence (Jamt et al., 2020). Studies examining the prospective effects of sensation seeking on future substance use have yielded relatively consistent findings, that is, sensation seeking was predictive of substance use, regardless of whether two or three longitudinal waves were sampled. A prior longitudinal study identified that sensation seeking has a prospective effect on alcohol consumption after 12 months in a sample of 1139 Canadian adolescents (45.0% male, grades 8–10) (Krank et al., 2011). Even after 20 months, the prospective effect of sensation seeking on substance use remained significant (Malmberg et al., 2012). This effect appears to be stable in adolescents and does not weaken with age. In a study of 525 American university students (48.0% male, $M_{age} = 18.95$) involving three waves of data, sensation seeking at each time point predicted subsequent alcohol use (Kaiser et al., 2018). The prospective effects of sensation seeking on substance use can be explained by the phenomenon that individuals with high levels of sensation seeking exhibit increased sensitivity to the reward sensations induced by psychoactive substances (Castellanos-Ryan & Conrod, 2012). The effect of sensation seeking on substance use is also probably mediated by enhancement motivation, which refers to the individual's expectation to enhance emotional experience or vitality through substance use (Woicik et al., 2009). Compared with the large number of studies on Western adolescents, few studies have investigated the trajectory of sensation seeking or evaluated the prospective effect of sensation seeking on substance use in Chinese adolescents. Only one prior study of Chinese college students (36.5% male, $M_{age} = 20.01$) demonstrated a positive cross-sectional association between sensation seeking and alcohol consumption (Xu et al., 2019). Cultural differences could limit the applicability of past findings from studies of Western adolescents to Chinese adolescents. It is necessary to further assess the prospective effect of sensation seeking on substance use in Chinese adolescents.

Prospective Effects of Substance Use on Sensation Seeking

According to the Corresponsive Principle, the traits individuals already possess are strengthened by the trait-related experiences they create (Caspi et al., 2005). Substance use would be predicted to have prospective effects on sensation seeking, but findings regarding the prospective effects of substance use on sensation seeking are varied. These seemingly inconsistent results could be explained by differences in the study design (for example timing and number of longitudinal waves, sample size, and individual study limitations), and the present study systematically examined these differences.

Research on the prospective effects of substance use on sensation seeking is scarce and has yielded inconsistent findings. Some studies have demonstrated prospective effects of substance use on sensation seeking, while other studies have identified that this effect was not present. The sample size, the age of the participants, different study methods, and culture may all be the potential reasons for the differences. A study of 1434 American high school graduates (36.0% male) identified that alcohol use predicted increased sensation seeking in a latent difference score model (LDSM) (Quinn et al., 2011). Despite drinking was assessed at three time points in the above study (Quinn et al., 2011), sensation seeking was only assessed at two time points, and the identified prospective effect of drinking on sensation seeking could have resulted from unmeasured increases in sensation seeking. A study of 525 American college students (48.0% male, $M_{age} = 18.95$) using the cross-lagged panel model (CLPM) yielded similar prospective effects of alcohol use on sensation seeking (Kaiser et al., 2018). Importantly, the population in the above study (Kaiser et al., 2018) did not represent the general population, as 23.1% of the sample was at high risk. Focusing on at-risk substance users could be more likely to identify significant effects of substance use on sensation seeking (Fernie et al., 2013). In fact, a study of a smaller general sample of 201 American college students (41.0% male, $M_{age} = 18.64$) did not identify a prospective effect of alcohol use on sensation seeking (Lac & Donaldson, 2021). More importantly, in studies that identified prospective effects of substance use on sensation seeking, the between-person and within-person effects could be confused, suggesting that longitudinal associations derived from previous research could reflect both the effects of stable individual differences between persons and changes within persons. If stable between-person effects could be distinguished from within-person associations, the findings could differ. A study of 1430 Spanish adolescents (53.9% male, $M_{age} = 13.02$) did not identify a within-person prospective effect of substance use on sensation seeking

(Fernández-Artamendi et al. 2018). Although data were collected at three longitudinal time points in the above study (Fernández-Artamendi et al., 2018), the participants were tracked for only 2 years, which limited assessment of longer-term effects of substance use on sensation seeking. It is unclear whether lack of the predicted within-person effects of substance use on sensation seeking is related to the age of adolescents. The within-person prospective effects of substance use on sensation seeking could only be present in a specific age group. Previous findings have demonstrated that the association between sensation seeking and substance use is most robust during adolescence (Lydon-Staley & Geier, 2018) and subsides in the late 20 s (Evans-Polce et al., 2018). Although previous studies focusing on the magnitude of associations between sensation seeking and substance use did not explore potential bidirectionality of the associations, these studies still provided substantial insights into understanding the effect of substance use on sensation seeking.

Sex Differences

One empirically documented source of individual differences in the development of sensation seeking in adolescence is sex. On average, male adolescents score higher than female adolescents in evaluations of sensation seeking (Mathijssen et al., 2021). Even across lifespan men score higher on sensation seeking than women (Cross et al., 2013). However, the mean level increase in sensation seeking was higher for girls than boys in adolescence (Mathijssen et al., 2021). Regarding the stability of sensation seeking during adolescence, higher stability of sensation seeking were found in girls (Malmberg et al., 2013), which can be explained by the fact that girls mature earlier than boys (Klimstra et al., 2009).

Prior findings also suggest that the severity and rate of substance use differ by sex, and that these sex differences vary during early adolescence and young adulthood. In early adolescence, female adolescents exhibit more serious substance use relative to their male counterparts (Chen & Jacobson, 2012). However, over time, male adolescents exhibit higher rates of changes in substance use behaviors (Chen & Jacobson, 2012), resulting in higher levels of substance use in male adolescents from middle adolescence to early adulthood (Johnston et al., 2012).

Sex differences in the relationship between sensation seeking and substance use behaviors have not been fully evaluated, and conclusions have been inconsistent. Reviewing the design of several studies whose results seemingly conflicting supported the conclusion that sex differences in sensation seeking and substance use behaviors exhibit different or even opposite patterns with age. A cross-sectional study of 91,860 U.S. high school graduates detected no evidence of sex differences in the association between sensation seeking and substance use (Keyes et al., 2015). In a sample of 6002 Dutch college students (35.3% male, $M_{age} = 22.05$), the association between sensation seeking and substance use was stronger in male participants relative to female participants (de Haan et al., 2015). In participants in their late 20 s, the association between sensation seeking and substance use is significantly stronger in female participants (Evans-Polce et al., 2018). The cultural background of participants in these studies was different. This suggests that sex differences in the association between sensation seeking and substance use could vary according to the participants' cultural backgrounds.

Most of the previous studies evaluating sex differences in the associations between sensation seeking and substance use were conducted in adult participants, highlighting the relative lack of studies evaluating the critical period from adolescence to early adulthood. Prior studies of sex differences only evaluated cross-sectional associations and lack evaluations of sex differences in the longitudinal associations between sensation seeking and substance use. Additional work examining sex differences in the longitudinal associations between sensation seeking and substance use from adolescence to early adulthood is needed.

Differentiating Between- and Within-Person Change

Most studies investigating the relationship between sensation seeking and substance use used methods without the capacity to distinguish between-person changes from within-person changes. Some studies have longitudinally analyzed sensation seeking and substance use at two different time points (Krank et al., 2011; Malmberg et al., 2012). Because the autoregressive effect was not considered in these studies, the reliability of these research conclusions is uncertain. Some studies used CLPM, which has traditionally been used to characterize the temporal ordering relationship between two variables sampled longitudinally. CLPM considers the possibility that the two variables could interact in both directions and considers the autoregressive effect as well (Kojima et al., 2021). However, an important limitation of traditional CLPM is that findings reflect both between-person and within-person effects, and the two effects cannot be distinguished (Hamaker et al., 2015). Between-person effects focus on explaining the differences in outcome variables between persons using differences in antecedent variables between persons. On the other hand, the within-person effect focuses on explaining within-person variations of outcome variables relative to the individuals' baseline levels using the within-person variation of the antecedent variables. Therefore, it is necessary to have a differentiation of the between-person effect and within-person effect. The random intercepts cross-lagged panel model (RI-CLPM) is an extension of CLPM (Hamaker et al., 2015). In RI-CLPM, the between-person effect is introduced as a

random intercept, which then can be separated from the within-person effect (Hamaker et al., 2015).

Few studies have addressed the interrelationship between sensation seeking and substance use without confounding between- and within-person effects. A prior study detected a bidirectional relationship between sensation seeking and substance use with CLPM (Kaiser et al., 2018), while a study using RI-CLPM did not replicate this bidirectional relationship, finding only a one-way prospective effect of sensation seeking on substance use (Fernández-Artamendi et al. 2018).

To date, no studies have examined the within-person bidirectional prospective effects between sensation seeking and substance use in Chinese adolescents. The present study investigated the within-person effects of sensation seeking and substance use in Chinese adolescents using RI-CLPM and assessed the trajectories of sensation seeking and substance use with the latent growth model (LGM). The LGM can examine the development, trajectories, and dynamic interactions between multiple variables and is focused on between-person differences (Curran et al., 2014). Because sensation seeking and substance use tend to increase over adolescence, simultaneously modeling the trajectories of sensation seeking and substance use can determine the extent to which these changes are interrelated.

Current Study

Although extensive prior studies have investigated the association between sensation seeking and substance use, the applicability of these findings to Chinese adolescents is unknown. Integrative longitudinal research on the trajectories of sensation seeking and substance use during adolescence and interrelationships between sensation seeking and substance use at the within-person level in adolescents is lacking. Further, sex differences in the longitudinal associations between sensation seeking and substance use remain incompletely understood. To address these knowledge gaps, the present study sought to determine the trajectories of sensation seeking and substance use in Chinese adolescents within longitudinal settings using LGM, to explore bidirectional longitudinal associations between sensation seeking and substance use using RI-CLPM that accounted for within-person processes, and to investigate sex differences in the longitudinal associations between sensation seeking and substance use. Focusing on adolescence to early adulthood is of particular interest in helping to clarify the interrelation of sensation seeking and substance use, since during this period, adolescents are in a developmental stage regarding sensation seeking and substance use. It was expected that the trajectories of sensation seeking and substance use would exhibit linear growth (Hypothesis 1). It was predicted that sensation seeking and substance use would be reciprocally influenced over time at the within-person level (Hypothesis 2). Finally, it was expected that the longitudinal associations between sensation seeking and substance use would vary between sexes (Hypothesis 3).

Methods

Participants

Data were collected from a 3-year longitudinal study, the China Psychological Development Tracking Project. The initial sample at the first wave (Time 1 = T1, March–April 2017) comprised 12,089 adolescents (61.2% male, M_{age} = 16.90, SD = 1.12 at T1) enrolled in secondary vocational education programs, who were recruited from 18 schools in the Guangdong and Sichuan provinces. Each participant was coded with a unique identifier to match individual respondents from the three time points. Subsequent data were collected every year from this adolescent cohort, but the sample cohort was truncated to 11,065 participants at Time 2 (T2, 1 year from T1) due to the withdrawal of two schools. At Time 3 (T3, 2 years from T1), the sample cohort was truncated to 9797 participants because two more schools withdrew from the study. The reason for the four schools' withdrawal was to arrange students for internship.

The inclusion criteria for the study were: (a) aged 18 years or younger at T1, (b) participation in at least one wave, (c) no difficulties in understanding the Chinese language, and (d) enrollment in schools that did not withdraw from the study. Data from the four schools withdrew were not included because the management teams of the four schools did not allow the use of previously collected data.

Procedure

After the schools, students, and students' parents agreed to participate in the study, participants were surveyed in the computer classroom of their respective schools. Adolescents filled out online questionnaires, including sensation seeking, smoking, and drinking measures, as well as some demographic information. Students used the schools' computers under the supervision of psychology teachers, computer teachers, and graduate students who had been trained by the investigators or teachers.

Measures

Background information

The background questionnaire collected information such as age, sex, date of birth, grade, family structure (single-parent

families or not), and the family's socioeconomic status (SES). The SES included annual household income and maximum years of education for the father and mother. Annual household income was categorized as follows: 1 =<3000 RMB, 2 = 3001–6000 RMB, 3 = 6001–10,000 RMB, 4 = 10,001–30,000 RMB, 5 = 30,001–50,000 RMB, 6 = 50,001–100,000 RMB, 7 = 100,001–150,000 RMB, 8 = 150,001–200,000 RMB, and 9 > 200,000 RMB. SES was calculated using factor analysis. In addition, items were added to the background questionnaire to assess the testing environment and participants' status at the time of data collection (for example "Is there any noise in your current environment? If so, will it interfere with your answers?" and "Are you in a hurry to do something now?").

Sensation seeking

The Sensation Seeking Subscale from the Substance Use Risk Profile Scale (SURPS, Woicik et al., 2009) was used to assess sensation seeking. The scale contains six items (for example "I enjoy new and exciting experiences, even if they are unconventional"). Responses were made on a 4-point Likert-type scale (completely agree, agree, disagree, and completely disagree) and were summed across the six items to produce a total sensation seeking score ranging from 6–24, where higher total scores indicate more sensation seeking. The internal consistency coefficient of the scale in the original English version was 0.7. With the consent of the original author and the revisers, a Chinese version of the scale (Wang et al., 2019) was used in the study, and the internal consistency coefficients of the scale were 0.80 at T1, 0.85 at T2, and 0.90 at T3.

Substance use

To investigate the participants' substance use, the Substance Use Questionnaire (SUQ, Siu, 2011) was used. The original questionnaire asks participants to report the frequency of smoking, drinking, and illicit drug use (drugs such as analgesics and stimulants, including marijuana) in the past month. Due to the strict prohibition of drugs in China, it is difficult to conduct research concerning illegal drugs. Therefore, only the smoking and drinking items of the original questionnaire were used. Participants were asked the following two questions: "How many times did you smoke in the past month?" and "How many times did you drink in the past month?" The response options were 1 (never used), 2 (once or twice a month), 3 (3–10 times a month), and 4 (more than ten times a month). These data were self-reported, and the answers were not shared with parents or teachers. Generally, when substance use-associated problems are not severe in adolescents, the brief screening tool is sufficient to determine the level and modality of intervention required (Gray & Squeglia, 2018).

Statistical Analysis

First, differences in background variables, sensation seeking, and substance use between the final and original sample were detected. Of the 10,138 adolescents that entered the study, 9797 participated at the final measurement wave, and 341 participants missed responses on one or several items. Response missing was principally due to students absent from school on the day of data collection or having moved schools. The practical significance of those differences was evaluated by the indices of effect size, which were measured using Cohen's d and φ, and were evaluated as small ($d = 0.20$, $\varphi = 0.10$), medium ($d = 0.50$, $\varphi = 0.30$), or large ($d = 0.80$, $\varphi = 0.50$) (Cohen, 1988). For background variables, statistically significant differences were identified between the final sample and the original sample in baseline age ($t = 10.846$, $p < 0.001$, Cohen's $d = 0.148$), maximum years of education for the mother ($t = 2.398$, $p = 0.016$, Cohen's $d = 0.036$), and percentage distribution of sex ($\chi^2 = 5.681$, $p = 0.020$, $\varphi = 0.015$). These analyses identified that annual household income ($t = 1.282$, $p = 0.199$), maximum years of education for the father ($t = 1.885$, $p = 0.059$), and the percentage distribution of the family structure ($\chi^2 = 3.7231$, $p = 0.052$) did not significantly differ. For sensation seeking and substance use, the analyses detected statistically significant differences in sensation seeking at T2 ($t = 9.164$, $p < 0.001$, Cohen's $d = 0.123$), sensation seeking at T3 ($t = 2.787$, $p < 0.01$, Cohen's $d = 0.037$), smoking frequency at T1 ($t = 7.269$, $p < 0.001$, Cohen's $d = 0.097$), smoking frequency at T2 ($t = 14.689$, $p < 0.001$, Cohen's $d = 0.196$), smoking frequency at T3 ($t = 6.572$, $p < 0.001$, Cohen's $d = 0.088$), drinking frequency at T1 ($t = 6.511$, $p < 0.001$, Cohen's $d = 0.087$), drinking frequency at T2 ($t = 15.368$, $p < 0.001$, Cohen's $d = 0.206$), and drinking frequency at T3 ($t = 6.777$, $p < 0.001$, Cohen's $d = 0.091$). The analyses detected no statistically significant difference in sensation seeking at T1 ($t = 1.871$, $p = 0.061$). For variables with statistically significant differences, all effect sizes were small, supporting the conclusion that these differences were of little practical significance. Additionally, missing value analysis was conducted. Little's missing completely at random (MCAR) test was significant ($p < 0.001$), indicating that the data were not missing completely at random (Little & Rubin, 2019). However, the normed chi-square (χ^2/df) was low (26.63/8 = 3.33), implying a small violation of the MCAR assumption (Mastrotheodoros et al., 2020).

Second, descriptive statistics were estimated for demographic characteristics, sensation seeking, and frequency of substance use. Statistical differences between male and

female participants in sensation seeking and substance use were examined by conducting independent sample t-tests. Correlations were calculated to determine the association and direction of relationships between sensation seeking and frequency of substance use.

Third, measurement invariance tests of Sensation Seeking Scale and Substance Use Questionnaire scores were performed using data from all participants to determine the extent to which measurement constructs remained equivalent across time and sex. The analyses were conducted as follows: (i) configural invariance was applied to evaluate whether the same factor structure was maintained for the three time points, as well as in both sexes; (ii) metric invariance was applied to examine the extent to which the magnitude of factor loading for particular items was the same; and (iii) scalar invariance tests were applied to determine if item intercepts were invariant. Model fit was evaluated using the following indices: the chi-square statistic (χ^2), the comparative fit index (CFI), the Tucker-Lewis index (TLI), and the root mean square error of approximation (RMSEA). There are no universally supported gold standards for the interpretation of these fit indices; so, the present study utilized graded fit criteria based on the recommended cutoffs of previous studies (Keefer et al., 2013; Kojima et al., 2021), which are as follows: CFI > 0.90, TLI > 0.90, and RMSEA < 0.08 for an acceptable fit; CFI > 0.95, TLI > 0.95, and RMSEA < 0.05 for a good fit. The measurement invariance testing process began with the configural model, and two increasingly restrictive models were then tested in successive order. Invariance was assumed to be maintained if the fit of the more restrictive model was not significantly different than that of the preceding, less restrictive model, then the next test was allowed. Relative fit of the models was evaluated based on changes in the CFI index (ΔCFI), with decreases < 0.02 indicating an acceptable fit (Cheung & Rensvold, 2002). The study did not refer to the results of the chi-square test to evaluate differences between models given the oversensitivity of the chi-square statistic in large samples. When the sample size is large, the results of the chi-square test are too conservative for the judgment of model fitting (Chen, 2007).

Next, the LGM for sensation seeking and substance use was used to identify these parameters' trajectories across time. A series of model tests was conducted to identify the best model explaining the trajectories of sensation seeking and substance use. For each variable, the linear growth model, indicating a linear change, was first conducted under an unconditional model to estimate the trajectories. In the example of sensation seeking, an intercept factor was created with a fixed loading of 1.0 to sensation seeking at each wave to represent the participants' baseline levels of sensation seeking. To represent the change of participants' sensation seeking over time, a slope factor was created with a fixed 0 loading to T1 sensation seeking, a fixed 1 loading to T2 sensation seeking, and a fixed 2 loading to T3 sensation seeking. Subsequently, two quadratic growth models, indicating non-linear change, were conducted under unconditional models for sensation seeking and substance use. A new slope factor, with the loadings be fixed to 0, 1, and 4 over the three waves, was added to the quadratic growth model based on the linear growth model. After determining the two univariate LGMs, a parallel process LGM was conducted under a conditional model with four covariates: sex, age, family structure, and SES to examine the dynamic relationship between sensation seeking and substance use. Goodness-of-fit statistics were used to determine model fit and the matching degree between the models and data.

Finally, RI-CLPMs were used to analyze temporal directional relationships between sensation seeking and substance use. The analyses were conducted as follows: (i) the relationship between sensation seeking and substance use was examined in the whole sample, and no constraints were imposed on the model; (ii) regression coefficients (over time) were constrained; (iii) a multiple group model was created, and the coefficients of male and female groups were constrained equal. By comparing models constraining these paths to be equal with models allowing them to be freely estimated, it can be revealed that whether a certain development process took place during the time span covered by the study (Mulder & Hamaker, 2021).

For the analyses, Mplus version 8.3 (Muthén & Muthén, 2019) and Statistical Product Service Solutions (SPSS) version 26 (International Business Machines Corp, Armonk, USA) were used. SPSS was used to produce descriptive statistics, difference analysis, correlation analysis, and factor analysis. Mplus was used to estimate the parameters of structural equation modeling, including LGMs, CLPMs, and RI-CLPMs. Sensation seeking was modeled as a latent factor with six indicators. Given the well-established widespread co-use of alcohol and tobacco, the two indicators, smoking frequency and drinking frequency, was combined into one indicator, substance use, which represents the frequency of adolescents smoking or drinking in the past month. Missing data were processed using the full information maximum likelihood (FIML) estimator (Muthén & Muthén, 2012).

Results

Descriptive Statistics and Correlations

Means and standard deviations for the study variables are presented in Table 1 for the whole sample, male participants, and female participants. Significant sex differences in sensation seeking and substance use were detected at each

Table 1 Means and standard deviations for control variables, sensation seeking and substance use

Variable	Total ($N = 10,138$)		Male ($n = 6066$)		Female ($n = 4072$)		t	p	Cohen's d
	M	SD	M	SD	M	SD			
Age	16.77	0.83	16.79	0.83	16.74	0.83	2.972	0.003	0.060
Father's education	8.60	2.88	8.69	2.96	8.46	2.76	3.896	<0.001	0.079
Mother's education	8.10	3.10	8.21	3.18	7.95	2.97	4.214	<0.001	0.086
Annual household income	4.18	2.08	4.34	2.14	3.95	1.95	9.220	<0.001	0.189
T1 sensation seeking	14.90	3.59	15.51	3.59	14.01	3.39	21.080	<0.001	0.430
T2 sensation seeking	15.98	3.86	16.51	3.97	15.20	3.55	16.853	<0.001	0.348
T3 sensation seeking	17.06	4.41	17.55	4.52	16.33	4.13	13.461	<0.001	0.283
T1 smoking frequency	1.43	0.92	1.58	1.04	1.20	0.64	20.886	<0.001	0.442
T2 smoking frequency	1.69	1.08	1.89	1.17	1.38	0.85	23.929	<0.001	0.504
T3 smoking frequency	1.99	1.24	2.21	1.28	1.67	1.09	21.119	<0.001	0.447
T1 drinking frequency	1.51	0.84	1.62	0.91	1.35	0.68	16.260	<0.001	0.339
T2 drinking frequency	1.72	1.01	1.89	1.07	1.47	0.85	20.852	<0.001	0.436
T3 drinking frequency	2.03	1.19	2.22	1.22	1.75	1.07	19.190	<0.001	0.405

Father's and mother's education refers to the maximum years of education for the father and mother. T1 = Time 1, March–April 2017; T2 = Time 2, one-year interval from T1; T3 = Time 3, two-year interval from T1

Table 2 Correlations of sensation seeking and substance use

Variable	1	2	3	4	5	6	7	8	9
1. T1 sensation seeking	–	0.32	0.13	0.34	0.17	0.09	0.33	0.18	0.09
2. T2 sensation seeking	0.22	–	0.16	0.12	0.41	0.13	0.13	0.41	0.13
3. T3 sensation seeking	0.09	0.10	–	0.06	0.08	0.49	0.05	0.08	0.47
4. T1 smoking frequency	0.28	0.09	0.05	–	0.29	0.10	0.70	0.26	0.09
5. T2 smoking frequency	0.13	0.38	0.09	0.31	–	0.15	0.23	0.87	0.14
6. T3 smoking frequency	0.06	0.07	0.51	0.14	0.18	–	0.08	0.13	0.92
7. T1 drinking frequency	0.31	0.08	0.04	0.68	0.22	0.11	–	0.27	0.10
8. T2 drinking frequency	0.14	0.41	0.09	0.21	0.83	0.15	0.23	–	0.15
9. T3 drinking frequency	0.05	0.07	0.53	0.10	0.15	0.90	0.10	0.16	–

Male adolescents' measures are below the diagonal and female adolescents' measures are above the diagonal. All correlations were significant at $p < 0.01$. T1 = Time 1, March–April 2017; T2 = Time 2, one-year interval from T1; T3 = Time 3, two-year interval from T1

time point ($ps < 0.001$), with male participants scoring higher than female participants, and small to medium effect sizes (Cohen's $d = 0.283$–0.504).

The bivariate correlations of sensation seeking and substance use are presented separately for male and female participants in Table 2. Cross-sectional and longitudinal associations between sensation seeking and substance use were low to moderately positive ($r = 0.04$–0.53, all $ps < 0.01$).

Measurement Invariance Tests

Sensation seeking

Longitudinal measurement invariance of sensation seeking was examined (Table 3). As anticipated, the configural invariance model provided an acceptable fit for sensation seeking data, CFI = 0.963, TLI = 0.950, RMSEA = 0.052 (90% confidence interval [CI] [0.050, 0.053]), which allowed for further tests. The metric invariance model provided a good fit to the data, CFI = 0.960, TLI = 0.955, RMSEA = 0.051 (90% CI [0.050, 0.053]). Sensation seeking exhibited metric invariance across the three time points (ΔCFI = 0.003). Although the fit of the scalar invariance model was significantly different from that of the metric invariance model (ΔCFI = 0.026), it was still acceptable, CFI = 0.934, TLI = 0.931, RMSEA = 0.060 (90% CI [0.059, 0.062]).

Measurement invariance of sensation seeking across sexes was tested (see Table 3). The baseline test model provided an acceptable fit for the male and female data, CFI = 0.929, TLI = 0.917, RMSEA = 0.066 (90% CI

Table 3 Model fit indices for measurement invariance testing models of sensation seeking and substance use

Model	χ^2	*df*	CFI	ΔCFI	TLI	RMSEA	90% CI
Sensation seeking							
Longitudinal Invariance							
Configural	3159.767	120	0.963	–	0.950	0.052	[0.050, 0.053]
Metric	3251.599	130	0.960	0.003	0.955	0.051	[0.050, 0.053]
Scalar	5219.463	142	0.934	0.026	0.931	0.060	[0.059, 0.062]
Invariance across sex							
Configural	5649.262	264	0.929	–	0.917	0.066	[0.065, 0.067]
Metric	5950.341	279	0.929	0.000	0.921	0.063	[0.062, 0.065]
Scalar	6432.588	294	0.923	0.006	0.919	0.065	[0.064, 0.067]
Substance use							
Longitudinal Invariance							
Configural	61.273	2	0.999	–	0.991	0.051	[0.039, 0.063]
Metric	68.143	4	0.998	0.001	0.994	0.039	[0.031, 0.048]
Scalar	566.786	8	0.987	0.011	0.964	0.090	[0.089, 0.103]
Invariance across sex							
Configural	549.384	12	0.985	–	0.966	0.093	[0.086, 0.100]
Metric	658.587	15	0.984	0.001	0.968	0.092	[0.085, 0.098]
Scalar	690.123	18	0.983	0.001	0.973	0.085	[0.080, 0.091]

χ^2 chi-square, *df* degrees of freedom, *CFI* comparative fit index, *TLI* Tucker–Lewis Index, *RMSEA* root mean square error of approximation, *CI* confidence Interval

[0.065, 0.067]). The metric invariance model provided an acceptable fit, CFI = 0.929, TLI = 0.921, RMSEA = 0.063 (90% CI [0.062, 0.065]) and did not differ from the configural invariance model (ΔCFI = 0.000). The results for scalar invariance of sensation seeking across sexes was upheld, CFI = 0.923, TLI = 0.919, RMSEA = 0.065 (90% CI [0.064, 0.067]), ΔCFI = 0.006.

Substance use

Longitudinal measurement invariance of substance use was estimated (see Table 3). The configural invariance model provided an acceptable fit to the data, CFI = 0.999, TLI = 0.991, RMSEA = 0.051 (90% CI [0.039, 0.063]), allowing further tests. The metric invariance model provided a good fit, CFI = 0.998, TLI = 0.994, RMSEA = 0.039 (90% CI [0.031, 0.048]) and did not significantly differ from the configural invariance model (ΔCFI = 0.001), which demonstrated metric invariance across time. When intercepts were constrained (i.e., assessment of scalar invariance), the change in the CFI index was below the threshold, CFI = 0.987, TLI = 0.964, RMSEA = 0.090 (90% CI [0.089, 0.103]), ΔCFI = 0.011. Thus, the model was deemed invariant.

Measurement invariance of substance use across sexes was tested (Table 3). Both CFI and TLI of the configural model exhibited a good model fit, CFI = 0.985, TLI = 0.966, but the RMSEA showed an unacceptable fit, RMSEA = 0.093 (90% CI [0.086, 0.100]). When the three indices were combined, the fit remained acceptable. Thus, the metric invariance test was conducted. The metric invariance model revealed no significant difference from the configural invariance model, CFI = 0.984, TLI = 0.968, RMSEA = 0.092 (90% CI [0.085, 0.098]), ΔCFI = 0.001, which indicated metric invariance across sexes. Scalar invariance of substance use across sexes was supported, CFI = 0.983, TLI = 0.973, RMSEA = 0.085 (90% CI [0.080, 0.091]), ΔCFI = 0.001.

Trajectories of Sensation Seeking and Substance Use Across Time

Whole-cohort analysis

Unconditional models of sensation seeking and substance use were analyzed to identify the patterns of both behaviors over time using LGMs (Table 4). The quadratic growth models of sensation seeking and substance use showed no convergence. The coefficients were not standardized because the values of the means are relevant for interpretation, and the means would automatically become 0 in a standardized solution.

For the linear growth model of sensation seeking, both CFI and TLI exhibited a good fit to the model, CFI = 0.933, TLI = 0.932, and RMSEA exhibited an acceptable fit, RMSEA = 0.059 (90% CI [0.058, 0.061]). The mean value of the intercept was significantly positive ($b = 2.567$, SE = 0.007, $p < 0.001$) and the mean value of the slope was significantly positive ($b = 0.175$, SE = 0.005, $p < 0.001$),

Table 4 Model fit indices and results of univariate latent growth models

Univariate latent growth model	Growth parameter			Model fit indices					
	b	SE	*p*	χ^2	*df*	CFI	TLI	RMSEA	90% CI
Sensation seeking				5522.751	151	0.933	0.932	0.059	[0.058, 0.061]
Intercept mean	2.567	0.007	<0.001						
Slope mean	0.175	0.005	<0.001						
Intercept variance	0.047	0.006	<0.001						
Slope variance	0.027	0.004	<0.001						
Substance use				17.409	1	0.990	0.970	0.040	[0.025, 0.058]
Intercept mean	1.615	0.009	<0.001						
Slope mean	0.231	0.007	<0.001						
Intercept variance	0.101	0.024	<0.001						
Slope variance	0.037	0.020	<0.001						

SE standard error, χ^2 chi-square, *df* degrees of freedom, *CFI* comparative fit index, *TLI* Tucker–Lewis Index, *RMSEA* root mean square error of approximation, *CI* confidence interval

Table 5 Model fit indices and results of univariate multigroup latent growth models

Univariate multigroup latent growth model	Parameter						Difference tests		Model fit indices					
	Male			Female										
	b	SE	*p*	*b*	SE	*p*	Δ *b*	*p*	χ^2	*df*	CFI	TLI	RMSEA	90% CI
Sensation seeking									5633.064	303	0.932	0.931	0.059	[0.058, 0.060]
Intercept mean	2.660	0.008	<0.001	2.421	0.010	<0.001	0.239	<0.001						
Slope mean	0.165	0.006	<0.001	0.194	0.007	<0.001	0.029	0.001						
Substance use									30.942	2	0.976	0.927	0.053	[0.038, 0.071]
Intercept mean	1.782	0.013	<0.001	1.370	0.011	<0.001	0.413	<0.001						
Slope mean	0.261	0.010	<0.001	0.184	0.010	<0.001	0.077	<0.001						

SE standard error, χ^2 chi-square, *df* degrees of freedom, *CFI* comparative fit index, *TLI* Tucker–Lewis Index, *RMSEA* root mean square error of approximation, *CI* confidence interval

indicating that the initial level of sensation seeking was significantly higher than 0, and that sensation seeking linearly over the three years of measurement. The variance of the intercept was significant ($b = 0.047$, $SE = 0.006$, $p < 0.001$) and the variance of the slope was significant ($b = 0.027$, $SE = 0.004$, $p < 0.001$), indicating significant individual differences in the initial level and change rate of sensation seeking.

For the linear growth model of substance use, CFI, TLI, and RMSEA exhibited a good fit to the model, CFI = 0.990, TLI = 0.970, RMSEA = 0.040 (90% CI [0.025, 0.058]). The mean value of the intercept was significantly positive ($b = 1.615$, $SE = 0.009$, $p < 0.001$) and the mean value of the slope was significantly positive ($b = 0.231$, $SE = 0.007$, $p < 0.001$), indicating that the initial level of substance use was significantly higher than 0, and that substance use linearly increased over the three years of measurement. The variance of the intercept was significant ($b = 0.101$, $SE = 0.024$, $p < 0.001$), as was the variance of the slope ($b = 0.037$, $SE = 0.020$, $p < 0.001$), indicating that there were significant individual differences in the initial level and change rate of substance use.

The linear growth models provided a good fit to explain the trajectories of sensation seeking and substance use, supporting the conclusion that the trajectories of sensation seeking and substance use were linear.

Multiple group analysis

To examine potential differences in the trajectories of sensation seeking and substance use between male and female participants, multiple group analysis was conducted. Intercept and slope factors were estimated respectively for male and female participants, and difference tests were conducted for the intercept and slope factors in the two groups (Table 5).

For the linear growth model of sensation seeking, both CFI and TLI exhibited a good fit, CFI = 0.932, TLI = 0.931, and RMSEA exhibited an acceptable fit, RMSEA = 0.059 (90% CI [0.058, 0.060]). In male participants, the mean value of the intercept was significantly positive ($b = 2.660$, $SE = 0.008$, $p < 0.001$) and the mean value of the slope was significantly positive ($b = 0.165$, $SE = 0.006$, $p < 0.001$). In female participants, the mean value of the intercept was significantly

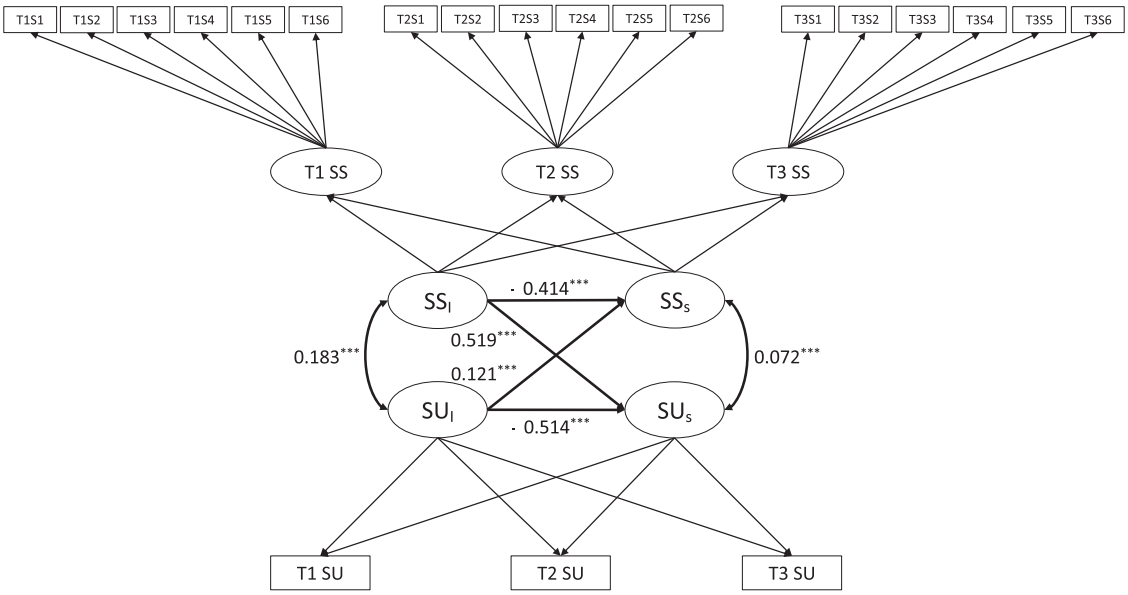

Fig. 1 Parallel process latent growth model. Bolded lines indicate paths of interest. SS = Sensation Seeking, SU = Substance Use, I = Intercept, S = Slope. T1 = Time 1, March–April 2017; T2 = Time 2, one-year interval from T1; T3 = Time 3, two-year interval from T1. *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

positive ($b = 2.421$, SE = 0.010, $p < 0.001$), as was the mean value of the slope ($b = 0.194$, SE = 0.007, $p < 0.001$). These findings suggest that in both male and female participants, the initial level of sensation seeking was significantly higher than 0, and sensation seeking linearly increased over the three years of measurement. The initial level of sensation seeking in male participants was higher than that in female participants ($\Delta\ b = 0.239$, $p < 0.001$), but the increase rate of sensation seeking in female participants was higher than that of male participants ($\Delta\ b = 0.029$, $p < 0.01$), and the differences were statistically significant.

For the linear growth model of substance use, both CFI and TLI showed a good fit, CFI = 0.976, TLI = 0.927, and RMSEA showed an acceptable fit, RMSEA = 0.053 (90% CI [0.038, 0.071]). In male participants, the mean value of the intercept was significantly positive ($b = 1.782$, SE = 0.013, $p < 0.001$), as was the mean value of the slope ($b = 0.261$, SE = 0.010, $p < 0.001$). In female participants, the mean value of the intercept was significantly positive ($b = 1.370$, SE = 0.011, $p < 0.001$), as was the mean value of the slope ($b = 0.184$, SE = 0.010, $p < 0.001$). This suggests that in both male and female participants, the initial level of substance use was significantly higher than 0, and substance use linearly increased over the three years of measurement. The initial level ($\Delta\ b = 0.413$, $p < 0.001$) and increase rate (($\Delta\ b = 0.077$, $p < 0.001$)) of substance use in male participants were higher than that of female participants, and the differences were statistically significant.

Parallel Process Latent Growth Model for Sensation Seeking and Substance Use

The parallel process LGM was used to investigate the influence processes between sensation seeking and substance use, treating the behaviors as two parallel development processes, and sex, age, SES, and family structure were treated as covariates to control (Fig. 1). Model fit indices and results are shown in Table 6. Both CFI and TLI showed a good model fit, CFI = 0.924, TLI = 0.920, and RMSEA showed an acceptable fit, RMSEA = 0.057 (90% CI [0.056, 0.058]). The initial level of sensation seeking positively and significantly correlated with the initial level of substance use ($b = 0.183$, SE = 0.006, $p < 0.001$). The change rate of sensation seeking was significantly and positively correlated with the change rate of substance use ($b = 0.072$, SE = 0.003, $p < 0.001$). The initial level of sensation seeking had a significant positive effect on the change rate of substance use frequency ($b = 0.519$, SE = 0.033, $p < 0.001$). The initial level of substance use had a significant positive effect on the change rate of sensation seeking ($b = 0.121$, SE = 0.011, $p < 0.001$). The initial level of sensation seeking was negatively correlated with sensation seeking change rate ($b = -0.414$, SE = 0.020, $p < 0.001$). The initial frequency of substance use had a significant negative effect on substance use change rate ($b = -0.514$, SE = 0.022, $p < 0.001$).

In addition, the parallel process LGM of smoking frequency and sensation seeking and the parallel process LGM of drinking frequency and sensation seeking were estimated

Table 6 Model fit indices and results of parallel process latent growth model

Parallel process latent growth model	Parameter			Model fit indices					
	b	SE	*p*	χ^2	*df*	CFI	TLI	RMSEA	90% CI
				6860.230	201	0.924	0.920	0.057	[0.056, 0.058]
Covariances									
Sensation seeking intercept ↔ Substance use intercept	0.183	0.006	<0.001						
Sensation seeking slope ↔ Substance use slope	0.072	0.003	<0.001						
Regression path									
Sensation seeking intercept → Sensation seeking slope	−0.414	0.020	<0.001						
Substance use intercept → Substance use slope	−0.514	0.022	<0.001						
Sensation seeking intercept → Substance use slope	0.519	0.033	<0.001						
Substance use intercept → Sensation seeking slope	0.121	0.011	<0.001						

SE standard error, χ^2 chi-square, *df* degrees of freedom, *CFI* comparative fit index, *TLI* Tucker–Lewis Index, *RMSEA* root mean square error of approximation, *CI* confidence interval

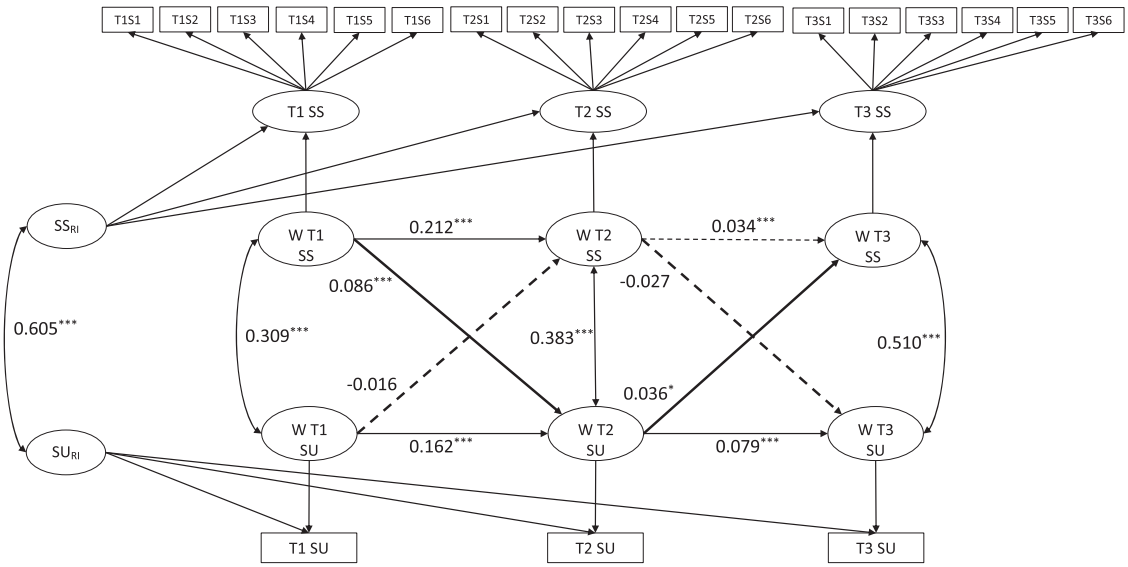

Fig. 2 Random intercepts cross-lagged panel model.Bolded lines indicate paths of interest and dotted lines indicate paths with non-significant coefficients. RI = random intercept, W = within-person component, SS = Sensation Seeking, SU = Substance Use. T1 = Time 1, March–April 2017; T2 = Time 2, one-year interval from T1; T3 = Time 3, two-year interval from T1. $*p < 0.05$, $**p < 0.01$. $***p < 0.001$

respectively, and the results of the two models were similar to that in the parallel process LGM of overall substance use and sensation seeking (Supporting Fig. 1). Thus, a parallel process LGM that was not separated by types of substance use was the final model.

Within-Person Effects of Sensation Seeking and Substance Use

Whole-cohort analysis

RI-CLPM was conducted to investigate the within-person relationships between sensation seeking and substance use (Fig. 2). The most appropriate model was selected via model comparison (Table 7). Both CFI and TLI showed a good fit with the unconstrained model, CFI = 0.928, TLI = 0.919 and RMSEA showed an acceptable fit, RMSEA = 0.058 (90% CI [0.057, 0.059]). The auto-regressive and cross-lagged paths were then constrained to be equivalent over time. Compared with the unconstrained model, the fit of the constrained model was significantly decreased, CFI = 0.769, TLI = 0.755, RMSEA = 0.101 (90%) CI [0.100, 0.103], ΔCFI = 0.159. Thus, the final model was unconstrained.

Standardized parameter estimates of RI-CLPM are shown in Table 8. At the between-person level, a significant positive covariance was detected between the random intercepts ($\beta = 0.605$, SE = 0.052, $p < 0.001$), suggesting

Table 7 Model fit indices for random intercepts cross-lagged panel models

RI-CLPM	Constraints	χ^2	*df*	CFI	ΔCFI	TLI	RMSEA	90% CI
Whole sample								
	Freely estimated	6497.584	188	0.928	–	0.919	0.058	[0.057, 0.059]
	Constraints over time	20503.599	198	0.769	0.159	0.755	0.101	[0.100, 0.103]
Multiple group (male/female)								
	Freely estimated	7324.443	438	0.919	–	0.915	0.056	[0.055, 0.058]
	Constrained lagged parameters	7339.493	446	0.919	0.000	0.916	0.055	[0.054, 0.056]

χ^2 chi-square, *df* degrees of freedom, *CFI* comparative fit index, *TLI* Tucker–Lewis Index, *RMSEA* root mean square error of approximation, *CI* confidence interval

Table 8 Results of random intercepts cross-lagged panel model

Path	β	SE	*p*
Covariances			
RI sensation seeking ↔ RI substance use	0.605	0.052	< 0.001
T1 sensation seeking ↔ T1 substance use	0.309	0.017	< 0.001
T2 sensation seeking ↔ T2 substance use	0.383	0.012	< 0.001
T3 sensation seeking ↔ T3 substance use	0.510	0.010	< 0.001
Autoregressive path			
T1 sensation seeking → T2 sensation seeking	0.212	0.020	< 0.001
T2 sensation seeking → T3 sensation seeking	0.034	0.019	< 0.001
T1 substance use → T2 substance use	0.162	0.017	< 0.001
T2 substance use → T3 substance use	0.079	0.017	< 0.001
Cross-lagged path			
T1 sensation seeking → T2 substance use	0.086	0.017	< 0.001
T2 sensation seeking → T3 substance use	0.027	0.016	0.093
T1 substance use → T2 sensation seeking	−0.016	0.016	0.313
T2 substance use → T3 sensation seeking	0.036	0.016	0.022

T1 = Time 1, March–April 2017; T2 = Time 2, one-year interval from T1; T3 = Time 3, two-year interval from T1

RI random intercept, *SE* standard error

that in general, individuals with higher sensation seeking levels had more frequent substance use. At the within-person level, in relation to cross-lagged paths, sensation seeking at T1 positively affected substance use at T2 ($\beta = 0.086$, SE = 0.017, $p < 0.001$), and substance use at T2 positively affected sensation seeking at T3 ($\beta = 0.036$, SE = 0.016, $p < 0.05$). These findings suggest that relative to the individuals' own mean, individuals with lower sensation seeking levels at T1 would likely use substances less frequently at T2, and individuals who used substances more frequently at T2 would likely experience more sensation seeking at T3. Other cross-lagged path coefficients were not significant.

Smoking and drinking frequency was included separately as the indicator for substance use, and the relationship between smoking and drinking frequency and sensation seeking was explored. Results revealed that the paths between smoking frequency and sensation seeking and paths between drinking frequency and sensation seeking were similar to paths between overall substance use and sensation seeking (Supporting Fig. 2). Thus, a RI-CLPM that was not separated by types of substance use was the final model.

Multiple group analysis

Multiple group analysis was conducted to examine whether the within-person effects between sensation seeking and substance use differed between male and female participants (Table 7). Both CFI and TLI showed a good fit in the freely estimated model, CFI = 0.919, (TLI = 0.915), and RMSEA showed an acceptable fit, RMSEA = 0.056 (90% CI [0.055, 0.058]), and the freely estimated model was compared to a model in which autoregressive and cross-lagged coefficients were set equally for male and female participants, which had an acceptable or good fit (CFI = 0.919), TLI = 0.916, RMSEA = 0.055 (90% CI [0.054, 0.056], ΔCFI = 0.000). This indicated that imposing constraints on the coefficients

Table 9 Model fit indices for alternative models

Model	Constraints	χ^2 (*df*)	*df*	CFI	ΔCFI	TLI	RMSEA	90% CI
CLPM								
Whole sample								
	Freely estimated	6643.111	191	0.926	–	0.919	0.058	[0.057, 0.059]
	Constraints over time	21928.591	198	0.752	0.174	0.737	0.104	[0.103, 0.106]
Multiple group (male/female)								
	Freely estimated	7258.802	402	0.919	–	0.916	0.058	[0.057, 0.059]
	Constrained lagged parameters	22902.885	417	0.736	0.183	0.734	0.103	[0.102, 0.105]
RI-CLPM (WLSMV)								
Whole sample								
	Freely estimated	3090.026	203	0.923	–	0.912	0.037	[0.036, 0.038]
	Constraints over time	16737.510	210	0.559	0.364	0.515	0.088	[0.087, 0.090]
Multiple group (male/female)								
	Freely estimated	3223.598	435	0.925	–	0.920	0.036	[0.035, 0.037]
	Constrained lagged parameters	2614.854	443	0.941	0.016	0.939	0.031	[0.030, 0.032]
LCSM								
	Constraints over time	10642.869	207	0.881	–	0.879	0.071	[0.070, 0.072]

CLPM cross-lagged panel model, *RI-CLPM* random intercepts cross-lagged panel model, *WLSMV* mean- and variance-adjusted robust weighted least squares, *LCSM* latent change score model, χ^2 chi-square, *df* degrees of freedom, *CFI* comparative fit index, *TLI* Tucker–Lewis Index, *RMSEA* root mean square error of approximation, *CI* confidence interval

across groups did not significantly change model fit. Hence, the constrained model was selected, and no sex differences were detected in within-person effects of sensation seeking and substance use.

Alternative Models

Further analyses were conducted to investigate whether other models could provide a better fit to the data. These models included: (1) standard CLPMs, (2) RI-CLPMs estimated by mean- and variance-adjusted robust weighted least squares (WLSMV) estimator in which substance use data was treated as ordinal, and (3) a latent change score model (LCSM) in which random intercepts and slopes were both contained. The fit indices of alternative models are shown in Table 9. The parameter estimates for alternative models with acceptable fit are shown in Tables S2, Table S3, and Table S5 in the Supplementary Material. In LGM and LCSM, substance use was also tried to be treated as an ordinal variable, and the WLSMV estimator was used to estimate the models, but there was no convergence. In CLPM, substance use was both an independent variable and a dependent variable, but Mplus does not allow the independent variable to be ordinal, so substance use was not treated as ordinal variable.

In CLPM, significant sex differences were detected in the longitudinal associations between sensation seeking and substance use. In male participants, significant positive cross-lagged effects were detected from sensation seeking at T1 to substance use at T2, and from substance use at T2 to sensation seeking at T3, while other cross-lagged paths were not significant. Contrastingly, in female participants, sensation seeking at T1 had a positive effect on substance use at T2, and sensation seeking at T2 had a positive effect on substance use at T3, but there was no evidence that substance use affected subsequent sensation seeking.

Discussion

Adolescence is a formative period during which sensation seeking and substance use fluctuate dramatically. Prior studies have suggested that sensation seeking personality is related to substance use behaviors in adolescents (Kaiser et al., 2018). The relationship between sensation seeking and substance use has not been thoroughly investigated in Chinese adolescents, and most developmental research thus far has not focused adequately on within-person processes. In addition, Sex differences in longitudinal associations between sensation seeking and substance use were not previously explored. The present study investigated the trajectories of sensation seeking and substance use using LGM, examined within-person effects between sensation seeking and substance use over time using RI-CLPM, and investigated sex differences in these relationships. During the 3-year study period, sensation seeking and substance use increased linearly in adolescents, and significant bidirectional associations were found at the within-person level. No evidence was detected for sex difference at the within-

person level. This study provides unique data concerning the relationship between sensation seeking and substance use in a sample of Chinese adolescents.

Trajectories of Sensation Seeking and Substance Use in Chinese Adolescents

Adolescents with higher initial levels of sensation seeking reported higher initial substance use frequency, consistent with prior studies demonstrating associations between sensation seeking and substance use (Fernández-Artamendi et al., 2018). As in the present study, sensation seeking and substance use increased concomitantly across adolescence (Hypothesis 1). This finding is consistent with prior findings (Freund et al., 2021; Biglan, 2004), suggesting that sensation seeking and substance use follow the same developmental trajectories in Chinese adolescents as in Western adolescents. Adolescents with higher initial sensation seeking levels had lower rates of sensation seeking increase. Adolescents' sensation seeking gradually reached its peak over three years measurement. The higher the sensation seeking level was, the closer it was to the peak, and sensation seeking would increase less rapidly. For the same reason, adolescents with higher initial substance use frequency had decreased rates of substance use increase in the follow-up period. Importantly, there were significant individual differences in the change of sensation seeking, and substance use was a predictor of this change, providing important evidence for substance use as a risk factor of sensation seeking and vice versa. This may indicate that following the normal increase in sensation seeking, adolescents that initiate substance use could develop a mutually reinforcing cycle in which sensation seeking and substance use are mutually exacerbated (Quinn et al., 2011). This cycle could be difficult to overcome.

The shapes of the developmental trajectories of sensation seeking and substance use were similar between sexes, but different initial levels and rates of change were detected. The initial level of sensation seeking was higher in male participants than in female participants, but the increase rate of sensation seeking in female participants was higher than that of male participants. This finding is consistent with previous research (Mathijssen et al., 2021), and suggests girls are more likely to develop internalizing problems during adolescence, concurrent with pubertal development (Paus et al., 2008). The initial substance use level was higher in male participants than in female participants, and male participants exhibited higher rates of substance use increase than did female participants, consistent with prior studies (Chen & Jacobson, 2012). These sex differences could be due to sex-specific changes in social roles and contexts (Schulenberg & Maggs, 2002), and suggests that intervention programs should place more emphasis on male adolescents from adolescence to early adulthood.

Bidirectional Associations among Sensation Seeking and Substance use at Within-Person Level

Sensation seeking and substance use were expected to be bidirectionally associated at the within-person level (Hypothesis 2), which was supported by the data. The prospective effect of sensation seeking on substance use occurred earlier than did the prospective effect of substance use on sensation seeking, suggesting that sensation seeking is a precursor to substance use, but that the two behaviors, once developed, have bidirectional prospective effects. Sensation seeking level at T1 predicted the frequency of substance use at T2, but sensation seeking at T2 did not predict substance use at T3, indicating that the effect of sensation seeking on substance use frequency diminished over time during adolescence. A previous study that collected three waves of data and used RI-CLPM analysis identified that sensation seeking at each time point predicted subsequent substance use (Fernández-Artamendi et al., 2018). Contrary to the previous study, the present study did not identify a stable pattern of sensation seeking influence on substance use at the within-person level in Chinese adolescents. It is noted that participant age in the present study is different from the previous study. The average baseline participant age in previous study (Fernández-Artamendi et al., 2018) was 13.02 years, and baseline age in the present study was 16.77 years. The findings of the present study are consistent with a prior study identifying that sensation seeking was more weakly associated with binge drinking and cigarette use in the late 20 s compared with age 18 (Evans-Polce et al., 2018). However, it is not clear when this trend emerges. One potential explanation is that adolescents are more likely to develop substance use behavior due to addiction, which contributes to the decreased influence of sensation seeking on substance use (Benowitz, 2010; Hasin et al., 2015). Addiction may be an important confounder and/or mediator in the influence of sensation seeking on substance use. Another important consideration regarding age variation is adolescents' psychological development. As individuals make the transition from adolescence to adulthood, the functions and purposes of substance use could change, such that substance use is less related to sensation seeking (Evans-Polce et al., 2018). With increased age, adolescents could gradually find that substance use is not novel, as in China, social smoking and drinking are very common. After developing substance use behavior, adolescents are likely to use substances in the course of social interactions (Neighbors et al., 2006).

A previous study using RI-CLPM reported that drinking frequency did not have prospective effects on sensation seeking (Fernández-Artamendi et al. 2018). Contrastingly, the present study suggested that in Chinese adolescents, although substance use at T1 did not have a significant within-person prospective effect on sensation seeking at T2, substance use at T2 had a prospective effect on sensation seeking at T3. The lack of an effect of T1 substance use behaviors on sensation seeking at T2 could be due to the relatively low level of substance use at baseline (White et al., 2011). The threshold levels for substance use severity and duration to significantly affect personality are not clearly defined (Kroencke et al., 2021). The influence of substance use at T1 on sensation seeking at T2 might not have reached threshold levels. Unfortunately, previous studies used different measuring tools to evaluate substance use; so, it is difficult to directly compare the level of substance use in different studies. Furthermore, little is known about how long alcohol and tobacco use must occur for adolescents' personality traits to be measurably affected (Fernie et al., 2013; MacKillop et al., 2007; Malmberg et al. 2012). It is plausible that alterations in personality traits from T1 to T2 did not meet detectable thresholds (Peeters et al., 2014; Riley et al., 2016). While at T2, the severity of substance use in adolescents could have reached threshold levels required for changes in personality traits to be detected at T3.

Effect of Biological Sex on Sensation Seeking and Substance Use

Counter to the Hypothesis 3, the study did not detect evidence of sex differences in bidirectional associations between sensation seeking and substance use at the within-person level. Applying CLPM as an alternative approach to investigate sex differences in the associations between sensation seeking and substance use in adolescents, significant sex differences were found in the path from sensation seeking at T2 to substance use at T3, and in the path from substance use at T2 to sensation seeking at T3. For male participants, sensation seeking at T1 predicted the frequency of substance use at T2, and the frequency of substance use at T2 predicted sensation seeking at T3. Contrastingly, the bidirectional effect of sensation seeking and substance use was not detected in female participants. Substance use at each point did not predict subsequent sensation seeking. However, in female participants, the effect of sensation seeking on substance use did not disappear with time as in male participants. Sensation seeking at T1 predicted the frequency of substance use at T2, and sensation seeking at T2 predicted the frequency of substance use at T3. These findings are inconsistent with previous studies also not disaggregate the effects into between-person and within-person levels, which failed to detect significant sex differences in the relationship between sensation seeking and substance use during late adolescence (Evans-Polce et al., 2018; Keyes et al., 2015). This could be due in part to differences in racial and ethnic backgrounds, as adherence to traditional gender roles could be greater in China. The presence of significant sex differences in cross-lagged effects in the CLPMs indicate that sex differences in the relationship between sensation seeking and substance use could be due to stable differences between individuals. Although the interpretation of CLPM results remains controversial (Berry & Willoughby, 2017), the present findings are still helpful in identifying sex differences in the relationship between sensation seeking and substance use.

Limitations

The strengths of the study include use of longitudinal data, large sample size, and distinguishing effects at the within-person level from those at the between-person level. However, some limitations need to be acknowledged. First, the study investigated the number of times adolescents used substances in the last month, which could have varied from month to month. Investigating the number of days that participants had consumed alcohol or smoked cigarettes could be more readily standardized. In addition, adolescents' substance use levels could be characterized more specifically, for example by considering frequency in combination with the quantity of substances used. Second, the frequency of substance use was analyzed as continuous data, and it was unfortunate that although data could be analyzed at a continuous level, analysis at an ordinal level did not have a good model fit. Third, the samples were from 18 secondary vocational schools, and adolescent substance use in vocational schools is often more severe than in ordinary high schools. The applicability of findings in this cohort to general adolescent populations remains unknown.

Conclusion

Studies using longitudinal designs to distinguish within-person associations from between-person associations are needed to better understand the interrelationships between sensation seeking and substance use in Chinese adolescents. This study not only found that increases in sensation seeking co-occurred with increases in substance use, but also identified within-person associations between sensation seeking and substance use. It is noteworthy that sensation seeking was identified as a precursor to substance use. In Chinese adolescents, the effect of sensation seeking on substance use was not long-term, and it diminished within 1 year. The effect of substance use on sensation seeking is likely to depend on the amount of substance use, such that substance use must reach a

certain threshold to have prospective effects on sensation seeking. The lack of sex differences in within-person associations should be emphasized. There was some evidence that sensation seeking was more stable in female participants; so, the sensation seeking personality trait in female participants could thus have been less sensitive to substance use (Malmberg et al., 2013; Mathijssen et al., 2021). However, it appears to be approximately equally true for male and female adolescents in the present study. The results of the present study provide an important step in elucidating within-person relationships between sensation seeking and substance use in Chinese adolescents. The findings highlight the importance of identifying sensation seeking behaviors to prevent substance use. Parents and teachers of adolescents during this developmental period should be able to identify rapid development of sensation seeking in adolescents, such that interventional programs can help adolescents debunk the belief that substance use is novel and exciting. Targeting both substance use and sensation seeking could protect adolescents from the mutually reinforcing effects of increased substance use and more problematic personality changes.

Authors' Contributions T.S. conceived of the study, coordinated the data entry, performed the statistical analyses, interpreted the results, and drafted the manuscript; C.C. helped with the performance of analyses, was involved in the interpretation of results, and revised the manuscript; S.T. helped with the performance of analyses, was involved in the interpretation of results, and revised the manuscript; Y.G. participated in the interpretation of the data and helped to revise the manuscript; C.W. was involved in the interpretation of the results and revised the manuscript critically; S.T. coordinated the data collection, performed data collection, and was involved in the interpretation of results; D.W. coordinated the data collection, performed data collection, performed data entry, was involved in the interpretation of the results and drafted the manuscript critically. All authors contributed significantly to the current manuscript. All authors read and approved the final manuscript.

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Data Sharing and Declaration The datasets generated and/or analyzed during the current study are not publicly available but are available from the corresponding author on reasonable request.

Compliance with Ethical Standards

Conflict of Interest The authors declare no competing interests.

Ethical Approval All procedures performed in the current study involving human participants were in accordance with the ethical standards with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. Ethics Committee of Beijing Normal University approved the study.

Informed Consent Before data collection, oral consent of school, parents of each student and students themselves was obtained. Also, written consent was obtained from each participant. When collecting data, researchers informed all student participants about the study aims and the confidentiality and anonymity principles of data collection and analysis.

Appendix

Questionnaire Items

Sensation Seeking Subscale

1. I would like to skydive.
2. I enjoy new and exciting experiences, even if they are unconventional.
3. I like doing things that frighten me a little.
4. I would like to learn how to drive a motorcycle.
5. I am interested in experience for its own sake even if it is illegal.
6. I would enjoy hiking long distances in wild and uninhabited territory.

Substance Use Questionnaire

1. How many times did you smoke in the past month?
2. How many times did you drink in the past month?

Computation of Socioeconomic Status

SES was calculated based on three indicators which were the maximum years of education for father, the maximum years of education for mother, and annual household income using principal components analysis. First, three indicators were standardized as z-scores (w_1, the maximum years of education for father; w_2, the maximum years of education for mother; w_3, annual household income). Second, the principal components were calculated by the z-scores of three indicators. If the characteristic value (λ_i) of one principal component (Z_i) was greater than or equal to 1, this principal component would be retained, otherwise, it would be removed. After calculation, one principal component was retained. According to the eigenvectors (x_i) of the principal component on the three indicators, the principal component was calculated using Eq. (1):

$$Z_i = x_1 w_1 + x_2 w_2 + x_3 w_3 \quad (1)$$

Finally, the formula of SES (Eq. (2) was constructed with the variance contribution rate of each principal component ($c_i = \lambda_i / m$) as the weight:

$$SES = c_1 Z_1 + c_2 Z_2 + \cdots + c_p Z_p \quad (2)$$

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