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The association between reinforcement sensitivity and substance use is mediated by individual differences in dispositional affectivity in adolescents

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ABSTRACT

Background: Adolescence marks the onset of substance use experimentation and adolescents are particularly vulnerable to certain negative effects of substances. Some evidence indicates reinforcement sensitivity is associated with substance use, though little is known about mechanisms underlying such association.
Aims: in the current study were to examine, (1) associations between behavioral activation (BAS) and behavioral inhibition (BIS) system sensitivity, positive (PA) and negative affectivity (NA), and alcohol use and alcohol problems as well as tobacco, and marijuana use, and whether (2) associations are mediated by PA or NA.
Methods: Participants were a community sample of $N = 125$ adolescents ($M_{age} = 15.67$ years; $SD = 0.93$; 52% boys) who completed self-report measures.
Results: evinced associations, generally as expected, across variables (all $ps < 0.05$). In mediation analyses, an association emerged between BIS sensitivity and alcohol use, mediated by NA (95%CIs [0.034; 0.390]); greater BIS sensitivity was associated with greater NA and greater NA was associated with greater alcohol use. These findings were replicated with alcohol problems. An association also emerged between BAS sensitivity and marijuana use, mediated by PA (95%CIs [−0.296; −0.027]); greater BAS sensitivity was associated with greater PA and greater PA was associated with lower marijuana use. Finally, BIS sensitivity was associated with tobacco use through NA (95%CIs [0.023; 0.325]) and PA (95%CIs [0.004; 0.116]), with NA linked to greater, but PA linked to lower tobacco use. BAS sensitivity was also associated with tobacco use through PA (95%CIs [−0.395; −0.049]), with PA linked again to lower tobacco use.
Conclusions: There are unique and shared effects of domains of reinforcement sensitivity on adolescent substance use and these vary with index of dispositional affectivity and type of substance considered.

1. Introduction

Individual differences in reinforcement sensitivity are associated with substance use (e.g., Skidmore, Kaufman, & Crowell, 2016). Largely determining such differences is an architecture of attention- and motivation-regulating systems involving the Fight/Flight/Freeze (FFFS), the Behavioral Activation (BAS), and the Behavioral Inhibition (BIS) systems (Corr & McNaughton, 2012). Greater BAS sensitivity is related to greater alcohol use, abuse, and binge drinking (Skidmore et al., 2016; Tapper, Baker, Jiga-Boy, Haddock, & Maio, 2015; van

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Hemel-Ruiter, de Jong, Oldehinkel, & Ostafin, 2013), and cue-elicited alcohol craving (Serre, Fatseas, Swendsen, & Auriacombe, 2015). Greater BAS sensitivity is further associated with being a smoker (Garrison et al., 2017), and illicit substance use (Skidmore et al., 2016) and addiction (Balconi, Finocchiaro, & Canavesio, 2014). Some findings suggest the BIS is not related to substance use (Garrison et al., 2017) whereas others suggest a positive association (Grevenstein, Bluemke, & Kroeninger-Jungaberle, 2016; Widiger & Oltmanns, 2017). Although there is need for additional research on the association between reinforcement sensitivity and substance use, there is reason to believe that such association is particularly relevant in adolescence; a developmental phase that is characterized by heightened reinforcement sensitivity and that marks the onset of substance use experimentation.

Certain developmental changes in adolescent brain structure and function have implications for both reinforcement sensitivity and substance use. The maturation of motivation- and affect-generating (e.g., subcortical) systems begins and is complete earlier than that of regulatory (e.g., prefrontal) systems, creating a maturational discrepancy between these systems (Spear, 2018) – "a situation in which one is starting an engine without yet having a skilled driver behind the wheel" (Steinberg, 2005; p. 70). Likely partly due to this discrepancy, reward sensitivity peaks during adolescence and compared to adults, adolescents exhibit greater reward but lower punishment sensitivity (Cauffman et al., 2010). These characteristics, in turn, are associated with greater risk for risky behavior, e.g., substance use (Spear, 2018).

In the current research, substances most commonly used by adolescents across the U.S. and Europe, i.e., alcohol, nicotine, and marijuana (Johnston, O'Malley, Miech, Bachman, & Schulenberg, 2016; Kraus & Nociar, 2016), were of interest. Past month alcohol use rates in U.S. 8th, 10th and 12th grades are 7.9%, 18.4% and 29.3%, respectively, and nicotine use are 2.3%, 3.4% and 5.7%, respectively (NIDA, 2020). Regarding past month marijuana use rates, 12–17-year-old frequent users (i.e., on 21 or more days) represent 7–13% of all frequent marijuana users (Nock, Minnes, & Alberts, 2017).

The short- and long-term negative outcomes of adolescent substance use, accompanied by limitations of available interventions, underscore the need to investigate mechanisms through which individual differences in reinforcement sensitivity predispose youth to use. *First,* regarding negative outcomes, adolescents are particularly vulnerable to the negative effects of chemical substances (Salas-Gomez et al., 2016), as neuromaturation continues well into adolescence (Bunford, 2019), with white matter developing into the late 20s (Lebel & Beaulieu, 2011). In support, earlier alcohol and marijuana use is associated with reduced likelihood of high grades and regular class attendance (Patte, Qian, & Leatherdale, 2017) and greater likelihood of problematic sexual behavior (Agrawal et al., 2016). Relative to abstainers, those who engage in rare/ sporadic-to-weekly drinking or marijuana use aspire less to continue to higher education (Patte et al., 2017). Of note, marijuana is[2] the most commonly substantiated substance among youth suicide decedents (Choi, Marti, & DiNitto, 2019). *Second,* regarding negative outcomes, adolescent initiation of substance use is one of the strongest predictors of adult addiction (Morales, Jones, Kliamovich, Harman, & Nagel, 2020). Together, these findings indicate adolescence is a key developmental phase during which to assess predictors of – and implement prevention efforts targeting – substance use. Yet, although evidence-based interventions are available (Hogue, Henderson, Becker, & Knight, 2018), relatively low abstinence rates and reduction in substance use suggest there is room for improvement, with one possible avenue involving exploration of alternative intervention targets.

A first step in understanding relations between variables of interest is identification of associations. As the science advances, a subsequent step is identification of mechanisms through which (i.e., mediators) and boundary conditions of, or conditions under which (i.e., moderators), such relations operate (Hayes & Rockwood, 2020).

Regarding the former, that is, associations, findings with adolescents evince greater BAS sensitivity is associated with greater likelihood of alcohol, nicotine, and drug use (Knyazev, 2004) and predicts earlier initiation and greater quantity of use (Kim-Spoon et al., 2016; Urošević et al., 2015; Willem, Bijttebier, & Claes, 2010). Similar to the literature in adults, findings regarding the relation between BIS sensitivity and substance use in adolescents are mixed; in one study, BIS sensitivity was not associated with initiation and severity of substance use (Kim-Spoon et al., 2016) whereas in another study, greater BIS sensitivity was weakly related to greater (in males but lower in females) alcohol, nicotine, and drug use (Knyazev, Slobodskaya, Kharchenko, & Wilson, 2004).

Regarding the latter, that is, mechanisms that link and/ or modulate the association between reinforcement sensitivity and substance use, two limitations to the available literature are worthy of note. First, only a few mediating or moderating variables, social influences (parental and parenting characteristics, peer affiliation; (Knyazev, 2004; Knyazev et al., 2004)), inhibitory control (Kim-Spoon et al., 2016) and sex (Knyazev et al., 2004; Knyazev, 2004) have been examined to date in adolescents. This is problematic as epigenetic models of substance use suggest that reinforcement sensitivity will not be directly associated with a behavior pattern as complex as substance use. Rather, reinforcement sensitivity will affect proximal risk factors, which, in turn, will affect substance use (Knyazev, 2004). Second, in studies where mediators were explored, substance use was treated as a composite variable (Kim-Spoon et al., 2016; Knyazev, 2004). This assumes that associations between reinforcement sensitivity and substance use operate through the same mechanisms across substances. Yet, evidence indicates that different neurobiological and other risk factors are associated with different substances (Oleson & Cheer, 2012; Underwood et al., 2018), suggesting domains of reinforcement sensitivity and related variables may also show differential relations with those.

Taken together, despite some data on pairwise associations between reinforcement sensitivity and substance use in adolescents, comprehensive investigations of the mechanisms underlying the reinforcement sensitivity-substance use association in adolescents are limited, both with regard to number and to specificity (cf. (Kim-Spoon et al., 2016; Knyazev, 2004). Accordingly, the aim of the current investigation was to examine whether in adolescents, dispositional affectivity as a potential mechanism (proximal risk factor), mediates the association between domains of reinforcement sensitivity and substance use.

Dispositional affectivity is a potential mechanism as the underlying reactivity of the RST systems contributes to individual differences in temperament (Derryberry & Rothbart, 1997) which, in turn, are related to substance use. Specifically, BAS sensitivity is positively associated with 'extraversion' (Corr & McNaughton, 2012) and positive affectivity (PA) (Martel, 2016) whereas BIS sensitivity is positively associated with 'neuroticism', or variously termed negative affectivity (NA) (Martel, 2016) (although closely linked and often conflated, extraversion and neuroticism are not synonymous with PA and NA, respectively; the former refer to dimensions of personality that capture average levels of affective states, attitudes, behavior, desires, and values (Geukes, Nestler, Hutteman, Küfner, & Back, 2017), whereas the latter refer to the stable tendency to experience positive/ negative emotions (Hamilton et al., 2017)). As such, indices of dispositional affectivity represent promising yet understudied individual difference variables – intermediate phenotypes – along which to parse heterogeneity in outcomes in youth. Regarding NA, available empirical data lend credence to this hypothesis, as findings indicate NA is implicated in virtually every form of psychopathology (Widiger & Oltmanns, 2017), including substance abuse (Kotov, Gamez, Schmidt, & Watson, 2010). Regarding PA, available empirical data are mixed, as results suggest PA is negatively associated with substance use (i.e., a composite variable of alcohol, marijuana, and tobacco use; Wills, Sandy, Shinar, & Yaeger, 1999) but PA-related traits such as extraversion and sensation-seeking are positively associated

[2] Between 2012 and 2015.

with alcohol use (Ayer et al., 2011; Kuntsche, Knibbe, Gmel, & Engels, 2006; MacPherson, Magidson, Reynolds, Kahler, & Lejuez, 2010).

1.1. Current study

Aims were to examine (1) associations between reinforcement sensitivity, indexed by BAS and BIS sensitivity, affectivity, indexed by PA and NA, and substance use, i.e., alcohol use and alcohol problems as well as tobacco and marijuana use, and whether (2) associations between reinforcement sensitivity and substance use are mediated by PA and NA.

PA and NA were examined separately as we were interested in the specificity of distinct aspects of dispositional affectivity. It was hypothesized that greater BAS sensitivity will be associated with greater substance use and greater BAS sensitivity will be associated with greater PA, which will mediate the former association. It was further hypothesized that greater BIS sensitivity will be associated with greater NA and greater NA will be associated with greater substance use. As the current study is the first wherein these complex associations are considered, PA and NA were both examined in all models. Further, there is insufficient prior data to formulate specific hypotheses regarding the direction of the effect between PA and substance use, or the nature (associated, mediated) or direction of the effect between BIS and substance use.

2. Method

2.1. Procedures

Data were collected in the context of a larger longitudinal study (A) project, the primary aims of which are to assess the effects of hypothesized adolescent predictors (e.g., reinforcement sensitivity and affective processing) of late adolescent/ young adult outcomes that are particularly key to such developmental phases and relevant to neurodevelopmental and externalizing disorders, such as problem/ risky behaviors and functional impairments. A community sample (without attention-deficit/hyperactivity disorder and externalizing symptoms) and an at-risk sample (with symptoms) of 14–17-year-old adolescents are being followed over several years. Data for the current project were collected at baseline. Adolescents between ages of 14–17 years were recruited from public middle- and high schools in Budapest, Hungary. This research was approved by the National Institute of Pharmacy and Nutrition (OGYÉI/17089-8/2019) and has been performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments. Participants' parents provided informed consent and participants provided assent. Assessments took place in laboratories of a research institute, and were conducted by master's and doctoral level clinicians/ psychologists, who were supervised by a team of clinical child psychologists and child psychiatrists. Assessment sessions were conducted either before (9:00am–12:00 pm) or after (13:30–17:00 pm) lunch and lasted approximately three hours.

2.2. Participants

Participants were 125 adolescents (M_{age} = 15.67 years; SD = 0.93; range: 14–17 years, 52% boys, 100% Caucasian, with average family net income falling in the 300 001–500 000 HUF range[3], and average level of highest primary caregiver education falling between vocational (short term) training courses for adults and bachelor's degree[4]). Recruitment took place in lower- and higher socioeconomic status (SES) Hungarian middle- and high schools in Budapest. Permission for recruitment was obtained from the principal of each school as well as the class teacher of each 8th, 9th, 10th and 11th grade classroom. Research staff informed students about the larger study, including its general goals and methods. Students interested in participating signed up and were contacted to schedule their appointment for assessments. Exclusionary criteria were the same as for the larger study and included: estimated IQ scores corresponding to a percentile rank < 8.9 (equivalent of FSIQ < 80) and diagnosis of bipolar, obsessive–compulsive, or psychotic disorder on the Structured Clinical Interview for DSM-5 (SCID-5) (First, Williams, Karg, & Spitzer, 2016). To estimate cognitive ability, abbreviated, age-appropriate versions of Wechsler Intelligence Scales (Wechsler, Coalson, & Raiford, 2008; Weschler, 2003) were used. Two Perceptual Reasoning Index (PRI) subtests, Matrix Reasoning and Picture Concepts (WISC) or Matrix Reasoning and Visual Puzzles (WAIS) and two Verbal Comprehension Index (VCI) subtests, Similarities and Vocabulary subtests (WISC and WAIS) were administered. These allow for estimation of PRI and VCI scores, and percentile ranks corresponding to estimated scores were used as indices of cognitive ability in the current study ($M_{\sim PRI\ percentile\ rank}$ = 54.58, SD = 25.21, $M_{\sim VCI\ percentile\ rank}$ = 67.33, SD = 21.44). For additional details on basic sample descriptives including history and heaviness of substance use, see Table 1.

2.3. Measures

2.3.1. Reinforcement Sensitivity Theory of Personality Questionnaire (RST-PQ) (Corr & Cooper, 2016)

The RST-PQ is a 79-item self-report measure of revised Reinforcement Sensitivity Theory (rRST) personality dimensions, comprised of three subscales: Flight-Fight-Freeze system (FFFS; 10 items), Behavioral Activation System (BAS; 32 items), and Behavioral Inhibition System (BIS; 23 items), and two additional subscales developed to complement the core RST-PQ: Defensive Fight (8 items) and Panic (6 items). Of interest to the current research, are the BAS subscale, which consists of four further subscales: Reward Interest (7 items), Goal-Drive Persistence (7 items), Reward Reactivity (10 items) and Impulsivity (8 items) and the BIS subscale (23 items). Respondents rate how accurately each item describes them on a four-point Likert-type response format scale (1 – 'not at all' to 4 – 'highly'). Higher scores indicate greater reinforcement sensitivity. Prior findings indicate that RST-PQ demonstrated good internal consistency (αs for BAS Reward Responsiveness, Drive, and Fun-Seeking were 0.84, 0.79, and 0.75, respectively and for BIS it was 0.79 (Corr & Cooper, 2016)) and adequate convergent and discriminant validity with other personality measures (e.g., Eysenck Personality Questionnaire-Revised [EPQ-R], BIS/BAS, State-Trait Anxiety Inventory [STAI]) (Corr & Cooper, 2016; Eriksson, Jansson, & Sundin, 2019; Pugnaghi, Cooper, Ettinger, & Corr, 2018).

For the current study, the English version of the RST-PQ was translated into Hungarian following evidence-based guidelines: (1) the English version was translated into Hungarian by three independent translators; (2) these three translations were combined into a single "summary translated" measure by a fourth independent translator, reconciling all discrepancies across the three translations/ors; (3) the "summary" was back-translated into English by two additional independent translators and (4) the two back-translations were combined into a single "summary back-translated" measure by members of the research team, reconciling all discrepancies in a manner that the "summary back-translation" measure best matches the Hungarian

[3] $M_{monthly\ family\ income}$=6.66, SD=1.148 on the following scale: 2: 50 001 – 99 000 Ft; 5: 200 001 – 300 000 Ft; 6: 300 001 – 500 000 Ft; 7: 500 001–700 000 Ft; 8: 700 000 – 800 000 Ft; 9: 800 000 – 1 000 000 Ft.

[4] $M_{monthly\ family\ income}$=6.58, SD=1.368 on the following scale: 3: trade school; 4: vocational secondary school; 5: high school; 6: vocational (short term) training courses for adults; 7: Bachelor's degree; 8: Master's degree; 9: PhD degree.

Table 1
Descriptive statistics of sample and variables.

	AUDIT total	AUDIT 1	AUDIT 2	AUDIT 3	ESPAD 1			ESPAD 2			ESPAD 3			Tobacco use total	Tobacco use 1	Tobacco use 2	Tobacco use 3	Marijuana
					a	b	c	a	b	c	a	b	c					
M	1.95	.802	.364	.281	3.394	2.692	1.548	1.731	1.500	1.144	2.163	1.856	1.221	13.116	1.256	14.593	6.111	.215
SD	2.549	.691	.753	.551	1.792	1.488	.787	1.108	.788	.380	1.673	1.361	.557	3.199	.725	1.010	7.526	.933
range	0-12	0-2	0-4	0-3	1-7	1-7	1-5	1-5	1-4	1-3	1-6	1-6	1-4	8-25	1-5	13-17	0-16	0-6

Note. AUDIT = Alcohol Use Disorder Identification Test – AUDIT 1: *How often do you have a drink containing alcohol?* (response options ranging from 0 = Never; 2 = 2–4 times a week; and 4 = 4 or more times a week); AUDIT 2: *How many drinks containing alcohol do you have on a typical day when you are drinking?* (response options ranging from 0 = 1 or 2; 2 = 5 or 6; and 4 = 10 or more); AUDIT 3: *How often do you have six or more drinks on one occasion?* (response options ranging from 0 = Never, 2 = Monthly; and 4 = Daily or almost daily). ESPAD = European School Survey Project on Alcohol and Other Drugs – ESPAD 1: *On how many occasions (if any) have you had any alcoholic beverage to drink? a: in your lifetime, b: in the past 12 months, c: in the past 30 days* (response options ranging from 1 = Never; 2 = 1–2 times; 3 = 3–5 times; 4 = 6–9 times; 5 = 10–19 times; 6 = 20–39 times; 7 = 40 or more); ESPAD 2: *On how many occasions (if any) have you been intoxicated from drinking alcoholic beverages, for example staggered when walking, not being able to speak properly, throwing up or not remembering what happened in your lifetime? a: in your lifetime, b: in the past 12 months, c: in the past 30 days* (response options ranging from1 = Never; 2 = 1–2 times; 3 = 3–5 times; 4 = 6–9 times; 5 = 10–19 times; 6 = 20–39 times; 7 = 40 or more); ESPAD 3: *How many times (if any) have you had five or more drinks on one occasion? (A 'drink' is one glass/bottle of beer [ca. 5 dl], one bottle of cider [ca. 5 dl], one glass of wine [ca. 5 dl] or one glass of concentrated alcohol, such as palinka [5 cl]) a: in your lifetime, b: in the past 12 months, c: in the past 30 days* (response options ranging from 1 = Never; 2 = Once; 3 = Twice; 4 = 3–5 times; 5 = 6–9 times; 6 = 10 or more); Smoking Behavior Questionnaire – Tobacco use 1: *During the past month, how many cigarettes have you smoked on an average day?* (response options ranging from 1 = None at all; or 4 = About half a pack a day; and 7 = About 12 packs or more a day); Tobacco use 2: *How old were you when you first smoked a cigarette?*; Tobacco use 3: *How old were you when you started smoking on a pretty regular basis, like one or two times a week?*. Marijuana – *In the past 12 months, how often did you use marijuana?* (response options ranging from 0 = Not at all; 3 = 8–11 times; 7 = 2–3 times a week; and 11 = Several times a day).
In the current sample, the average sample household income was around but somewhat higher than the 2018 Hungarian regional average https://www.ksh.hu/docs/hun/xstadat/xstadat_eves/i_zhc014c.html.

"summary translated" measure. This "summary back-translated" questionnaire was sent to the original author(s) who provided the research team with feedback and ultimately approved the translated measure (P. Corr, personal communication, May 29, 2019). In the current sample, the BAS subscale exhibited good (α = 0.869) and the BIS subscale exhibited excellent (α = 0.904) internal consistency.

2.3.2. *Positive and Negative Affect Schedule (PANAS) (Watson, Clark, & Tellegen, 1988b)*

The PANAS is a 20-item self-report measure of state and/or trait PA and NA, comprised of two corresponding subscales, reflecting the extent to which a person feels enthusiastic, active and alert, and reflecting a general dimension of subjective distress and a variety of aversive mood states such as anger, contempt, disgust, fear, guilt, and nervousness, respectively. Respondents rate the extent to which they are experiencing each mood state "right now" (i.e., state version) or "during the past two weeks" (i.e., trait version) on a five-point Likert-type response format scale (1 – 'very slightly or not at all' to 5 – 'very much'). Higher scores on the PA and NA subscales indicate greater positive and negative affect, respectively. Prior findings indicate that PANAS scales have good internal consistency (αs ranging from 0.86 to 0.90 for PA and from 0.84 to 0.87 for NA) and good convergent and discriminant associations with distress and psychopathology measures of the underlying affectivity factors (e.g., Beck Depression Inventory [BDI], Hopkins Symptom Checklist [HSCL], STAI) (Watson, Clark, & Tellegan, 1988a). The Hungarian translation (Rózsa et al., 2008) also demonstrated acceptable psychometric properties, including good internal consistency (PA α = 0.82, NA α = 0.83)[5] (Gyollai, Simor, Koteles, & Demetrovics, 2011). In the current study, the PANAS-trait was administered and the PA and NA subscales exhibited good internal consistency (α = 0.821 and α = 0.851, respectively).

2.3.3. *The European School Survey Project on Alcohol and Other Drugs (ESPAD) (Kraus & Nociar, 2016) master questionnaire*

The aim of the ESPAD is to collect data on substance use among 15–16-year-old European adolescents. Items of the master questionnaire assess alcohol consumption, cigarette smoking, drug use, energy drink consumption, gaming and internet use. In the current study, select items were used to assess alcohol use: "*On how many occasions (if any) have you had any alcoholic beverage to drink?*" (response options ranging from 0 to ≥ 40), "*How many times (if any) have you had five or more drinks on one occasion?*" (response options ranging from none to ≥ 10), and "*On how many occasions (if any) have you been intoxicated from drinking alcoholic beverages, for example staggered when walking, not being able to speak properly, throwing up or not remembering what happened?*" (response options ranging from 0 to ≥ 40). For each item, respondents are asked to respond by addressing the question as applied to (a) their lifetime, (b) during the last 12 months, and (c) during the last 30 days. As the ESPAD survey is administered anonymously, there is little empirical data on its psychometrics. Available relevant data indicate high internal consistency and test–retest reliability (Hibell, Guttormsson, Ahlström, Balakireva, Bjarnason, Kokkevi, & Kraus, 2012; Molinaro, Siciliano, Curzio, Denoth, & Mariani, 2012) and some evidence of validity, in the form of comparable responses across countries (Kraus & Nociar, 2016). In prior studies (Cheng & Anthony, 2017; Soellner, Göbel, Scheithauer, & Bräker, 2014), individual items were used as indices of substance use, with greater scores indicating greater use. In the current study, for the sake of parsimony and to thus reduce the number of models tested, we used a total score of each item, with each response category.

2.3.4. *Alcohol use disorders identification test (AUDIT) (Allen, Litten, Fertig, & Babor, 1997)*

The AUDIT is a 10-item self-report measure of alcohol use, comprised

[5] Authors of the cited article report α values with two decimals.

of 3 subscales, Hazardous Alcohol Use, Dependence and Harmful Alcohol Use. Items are rated on a five-point scale (0 – 'never' to 4 – 'four or more times a week'), with higher scores indicating greater difficulty with alcohol use. In adolescents, a total AUDIT score $\geq$ 5 indicates alcohol problems (Liskola et al., 2018). Prior findings indicate the AUDIT has well-established psychometric properties (Reinert & Allen, 2007), including high item-total correlations for the subscales ($\sim\alpha$s = 0.80), and at least acceptable internal consistency for the total score (αs > 0.7) (Allen et al., 1997; Bunford, Wymbs, Dawson, & Shorey, 2017). The Hungarian translation also demonstrated acceptable psychometric properties, including reliability (e.g., internal consistency α = 82; (Horváth et al., 2019)) and validity (Gerevich, 2006; Horváth et al., 2019; Kovács et al., 2020). In the current study, the total AUDIT was used in analyses and it exhibited acceptable (α = 0.712) internal consistency.

2.3.5. *Smoking Behavior Questionnaire (Donovan, Jessor, & Costa, 1991)*

The Smoking Behavior Questionnaire is a 13-item self-report measure of actual tobacco use (i.e., cigarette smoking and tobacco chewing) (e.g., "Have you smoked a cigarette?", "During the past month, how many cigarettes have you smoked on an average day?", "Have you ever tried chewing tobacco?") as well as attitude/ environmental influences promoting tobacco use (e.g., "How do your parents feel about someone your age smoking cigarettes?", "Does either of your parents (or stepparents or guardians) smoke cigarettes?", "How many of your friends smoke cigarettes on a pretty regular basis?", "Do you think smoking can have an effect on the health of young people your age?"). Prior findings indicate the Smoking Behavior Questionnaire has acceptable internal consistency (α = 0.76; (Donovan et al., 1991)). Of the 13 items, the 8 items applicable to all youth (and not only to those who have smoked or chewed at least a few times as indicated by respective screener items) were used to create a total tobacco use score as our goal was to assess use risk as reflected by actual use and general risk, both of which can be assessed in youth who do not regularly smoke cigarettes or chew tobacco. Higher scores indicate greater use risk.

For the current study, the English version of the Smoking Behavior Questionnaire was translated into Hungarian following identical steps as for the RST-PQ. The original author approved the translated measure (J. Donovan, personal communication, August 2, 2019).

2.3.6. *Illicit Drug Use (Wymbs, Dawson, Egan, & Sacchetti, 2016)*

The Illicit Drug Use Questionnaire is an 11-item self-report measure of the frequency of use of different substances – i.e., tobacco, marijuana, inhalants, hallucinogens, cocaine, opiates, tranquilizers, ecstasy, methamphetamine, club drugs and illegal use of prescription drugs – during the past year. Higher scores indicate greater use.

For the current study, the English version of the Illicit Drug Use Questionnaire was translated into Hungarian following identical steps as for the RST-PQ. The original author approved the translated measure (B. T. Wymbs, personal communication, August 16, 2019). In the current study, the marijuana item was used in analyses.

2.4. Analytic plan

To examine associations among variables, bivariate correlations were computed. To examine whether associations between reinforcement sensitivity and substance use are mediated by PA and NA as parallel mediators, we used PROCESS (Hayes, 2013) to calculate 95% CIs around the total and individual (for negative and positive affectivity) indirect effects with 1,000 bootstrap resamples[6], implementing a heteroscedasticity-consistent standard error estimator[7]. As is commonly done in – and recommended for – atemporal/ mathematical mediation studies (Agler & De Boeck, 2017; Bunford et al., 2018, 2015; Danner, Hagemann, & Fiedler, 2015; Rinsky & Hinshaw, 2011), to establish unidirectionality of observed effects (i.e., that models are supported in the hypothesized direction, but not the reverse), in case of significant models, we also tested the alternative model with dispositional affectivity as the predictor, reinforcement sensitivity as the mediator, and substance use variables as the outcome.

In the larger study, ESPAD items were added later. Accordingly, data on alcohol use was available for the current study – and thus analyzed – on a subsample (103 of the total sample of 125 adolescents).

Age and sex differences in reinforcement sensitivity (Kühn, Mascharek, Banaschewski, Bodke, Bromberg, Büchel, Quinlan, Desrivieres, Flor, Grigis, Garavan, Gowland, Heinz, Ittermann, Martinot, Nees, Orfanos, Paus, Poustka, Millenet, Fröhner, Smolka, Walter, Whelan, Schumann, Lindenberger, & Gallinat, 2019; Vervoort et al., 2010) and in substance use (Pagliaccio et al., 2016; Substance Abuse and Mental Health Services Administration, 2014) as well as comorbidity-related differences in substance use (Englund & Siebenbruner, 2012) underscore importance of adjusting for these variables in analyses involving these characteristics. Accordingly, as a follow-up to supported mediational models, we tested whether age, sex, or comorbid internalizing or externalizing symptoms (conceptualized as a sum of all symptoms on all assessed internalizing, i.e., major depressive disorder, persistent depressive disorder, agoraphobia, panic disorder, generalized and social anxiety disorder and externalizing, i.e., attention-deficit/ hyperactivity, oppositional defiant, and conduct disorders) moderate the mediational models. To this end, we tested two moderated mediation models (one for each supported mediational model with each potential moderator) wherein age, sex, internalizing, and externalizing symptoms were examined as moderators of the indirect path (from reinforcement sensitivity to substance use through affectivity) and the direct path (from reinforcement sensitivity to substance use) in the mediational model, using PROCESS (Hayes, 2013) and 1000 bootstrap resamples, implementing a heteroscedasticity-consistent standard error estimator.

2.5. Data availability

Datasets generated and/or analyzed for the current study are available from the corresponding author on reasonable request.

[6] The macros provide a 95% confidence interval around the indirect effect. When zero is not in that interval (i.e., both numbers fall on the same side of 0), it can be concluded that the indirect effect is significantly different from zero at $p<.05$ (two tailed).

[7] A post hoc power analysis using Monte Carlo Power Analysis for Indirect Effects (Schoemann et al., 2017) indicated that, with sample size and parameter estimates derived from the current dataset, Monte Carlo draws per replications set to 5000, alpha set to 0.1, in case of *alcohol use*, for the BIS>alcohol use model, power was 0.2 (a1b1 path) and 0.8 (a2b2 path and for the BAS>alcohol use model power was 0 (a1b1 path) and 0 (a2b2 path). In case of *alcohol problems*, for the BIS>alcohol problems model, power was 0.2 (a1b1 path) and 0.4 (a2b2 path) and for the BAS>alcohol problems model power was 0.2 (a1b1 path) and 0 (a2b2 path). For *tobacco use*, for the BIS>tobacco use model power was 0.4 (a1b1 path) and 0.6 (a2b2 path) and for the BAS>tobacco use model power was 0.8 (a1b1 path) and 0.2 (a2b2 path). In case of marijuana use, for the BIS>marijuana use model power was 0.2 (a1b1 path) and 0 (a2b2 path) and for the BAS>marijuana use model power was 0.8 (a1b1 path) and 0 (a2b2 path).

3. Results

3.1. Bivariate correlation analyses

Findings evince bivariate associations across variables, with greater BAS sensitivity associated with greater PA and greater BIS sensitivity associated with lower PA and greater NA. Neither BAS nor BIS sensitivity was associated with substance use but greater PA was associated with lower tobacco use and greater NA was associated with greater alcohol problems and greater tobacco use (Table 2). Greater BIS sensitivity, greater NA, and greater alcohol use and alcohol problems were associated with greater age and greater BIS sensitivity and greater alcohol problems were associated with sex, in that girls exhibited greater BIS sensitivity but lower alcohol problems (Table 2).

Table 2
Bivariate correlations among study variables.

			1.	2.	3.	4.	5.	6.	7.	8.	9.
1. BAS	*r (p)*		–								
	Bootstrap	Bias	–								
		(SE)									
		95% CI	–								
2. BIS	*r (p)*		.086 (.341)	–							
	Bootstrap	Bias	.002 (.095)	–							
		(SE)									
		95% CI	−.107; .272	–							
3. PA	*r (p)*		**.675** (.000)	**−.212** (.018)	–						
	Bootstrap	Bias	−.002	.001 (.095)	–						
		(SE)	(.051)								
		95% CI	.563; .766	−.400; −.022	–						
4. NA	*r (p)*		.018 (.841)	**.699** (.000)	−.155 (.085)	–					
	Bootstrap	Bias	.001 (.099)	−.005	.001 (.097)	–					
		(SE)		(.047)							
		95% CI	−.177; .209	.593; .779	−.339; .037	–					
5. Alcohol use	*r (p)*		−.007 (.946)	.072 (.470)	−.047 (.635)	.187 (.059)	–				
	Bootstrap	Bias	.004 (.104)	−.002	.006 (.102)	−.003	–				
		(SE)		(.105)		(.100)					
		95% CI	−.202; .211	−.130; .276	−.250; 158	−.008; .371	–	.			
6. Alcohol problems	*r (p)*		.100 (.267)	.069 (.448)	.050 (.579)	**.207** (.021)	**.753** (<.001)	–			
	Bootstrap	Bias	.001 (.087)	.000 (.115)	−.001	.000 (.101)	.002 (.052)	–			
		(SE)			(.088)						
		95% CI	−.063; .276	−.160; .290	−.131; .209	.004; .386	645; .847	–			
7. Tobacco use	*r (p)*		.038 (.681)	.153 (.093)	**−.196** (.031)	**.230** (.011)	**.450** (<.001)	**.407** (<.001)	–		
	Bootstrap	Bias	−.007	.004 (.080)	−.006	.003 (.082)	−.001	.002 (.076)	–		
		(SE)	(.099)		(.080)		(.083)				
		95% CI	−.176; .231	.002; .320	−.355; −.046	.058; .394	.278; .600	.248; .552	–		
8. Marijuana use	*r (p)*		−.019 (.836)	.154 (.088)	−.144 (.111)	.126 (.164)	**.322** (.001)	**.259** (.004)	**.325** (.000)	–	
	Bootstrap	Bias	−.002	−.006	−.002	.001 (.106)	−.007	−.005	.001 (.057)	–	
		(SE)	(.105)	(.081)	(.075)		(.128)	(.131)			
		95% CI	−.213; .191	−.014; .301	−.292; .008	−.090; .332	.061; .556	−.001; .498	.207; .434	–	
9. Age	*r (p)*		−.003 (.973)	**.203** (.023)	.017 (.852)	**.223** (.013)	**.274** (.005)	**.280** (.002)	.163 (.070)	.076 (.402)	
	Bootstrap	Bias	.000 (.094)	−.002	.000 (.089)	−.003	.001 (.096)	−.004	.000 (.091)	−.002	–
		(SE)		(.090)		(.087)		(.095)		(.051)	
		95% CI	−.188; .174	.018; .371	−.165; .192	.048; .388	.068; .456	.088; .453	−.007; .340	−.039; .171	–
10. Sex	*r (p)*		.079 (.383)	**.273** (.002)	.027 (.766)	.077 (.395)	−.183 (.064)	**−.232** (.009)	−.037 (.685)	.130 (.149)	−.157 (.082)
	Bootstrap	Bias	.000 (.087)	.000 (.084)	.000 (.094)	−.001	−.004	−.004	−.002	−.012	.001 (.085)
		(SE)				(.092)	(.100)	(.088)	(.090)	(.075)	
		95% CI	−.095; .249	.110; .438	−.166; .210	−.099; .251	−.371; .023	−.395; −.063	−.209; .140	−.071; .240	−.314; .015

Note. BAS = Behavioral Activation System; BIS = Behavioral Inhibition System; PA = positive affectivity; NA = negative affectivity. Alcohol use = ESPAD (select items) Total; Alcohol problems = AUDIT Total.

3.2. Mediation analyses with BAS sensitivity

The model with affectivity mediating the association between BAS sensitivity and alcohol use was not supported (95%CIs [−0.043; 0.062]). The model with affectivity mediating the association between BAS sensitivity and alcohol problems was not supported (95%CIs [−0.104; 0.173]).

Affectivity mediated the association between BAS sensitivity and tobacco use (point estimate = −0.209; SE = 0.088; 95%CIs [−0.388; −0.024])[8], with this effect driven by PA mediating such association (point estimate = −0.213; SE = 0.087; 95%CIs [−0.395; −0.049]). Greater BAS sensitivity was associated with greater PA and greater PA was associated with lower tobacco use (the BAS-tobacco use association was positive but nonsignificant, $p = .195$) (Table 3). Follow-up mediation analyses with just the actual tobacco use items pooled together indicated affectivity mediated the association between BAS sensitivity and tobacco use (point estimate = −0.019; SE = 0.70; 95%CIs [−0.033; −0.006]) (direction of effects was the same as in the overall model). Follow-up mediation analyses with the attitude/ environmental influences items pooled together indicated affectivity mediated the association between BAS sensitivity and attitude/ environmental influences promoting tobacco use (point estimate = −0.017; SE = 0.01; 95%CIs [−0.031; −0.004]) (direction of effects was the same as in the overall model).

Affectivity also mediated the association between BAS sensitivity and marijuana use (point estimate = −0.141; SE = 0.071; 95%CIs [−0.295; −0.010]), with this effect driven by PA mediating such association (point estimate = −0.143; SE = 0.068; 95%CIs [−0.296; −0.027]). Greater BAS sensitivity was associated with greater PA and greater PA was associated with lower marijuana use at the trend level (the BAS-marijuana use association was positive but nonsignificant, $p = .442$) (Table 3).

3.3. Mediation analyses with BIS sensitivity

Affectivity mediated the association between BIS sensitivity and alcohol use (point estimate = 0.210; SE = 0.099; 95%CIs [0.022;0.399]), with this effect driven by NA mediating such association (point estimate = 0.202; SE = 0.092; 95%CIs [0.034;0.390]). Greater BIS sensitivity was associated with greater NA and greater NA was associated with greater alcohol use (the association BIS-alcohol use association was negative but nonsignificant, $p = .253$) (Table 3).

Affectivity mediated the association between BIS sensitivity and alcohol problems (point estimate = 0.209; SE = 0.065; 95%CIs [0.090;0.337]), with this effect driven by NA mediating such association (point estimate = 0.224; SE = 0.062; 95%CIs [0.107;0.359]). Greater BIS sensitivity was associated with greater NA and greater NA was associated with greater alcohol problems (the association BIS-alcohol problems association was negative but nonsignificant, $p = .253$) (Table 3).

Affectivity also mediated the association between BIS sensitivity and tobacco use (point estimate = 0.215; SE = 0.083; 95%CIs [0.055;0.382]), with both PA and NA mediating such association (point estimate = 0.038; SE = 0.027; 95%CIs [0.004;0.116] and point estimate = 0.177; SE = 0.076; 95%CIs [0.023;0.325], respectively). Greater BIS sensitivity was associated with lower PA but greater BIS sensitivity was associated with greater NA. Greater PA was associated with lower tobacco use whereas greater NA was associated with greater tobacco use. (The BIS-tobacco use association was negative but nonsignificant, $p = .552$) (Table 3). Follow-up mediation analyses with just the actual tobacco use items pooled together (i.e., items assessing actual cigarette smoking and tobacco chewing as opposed to attitude/ environmental influences promoting tobacco use) indicated affectivity mediated the association between BIS sensitivity and tobacco use, with NA driving this effect (point estimate = 0.019; SE = 0.01; 95%CIs [0.003;0.035]) (direction of effects was the same as in the overall model). Follow-up mediation analyses with the attitude/ environmental influences items pooled together indicated affectivity mediated the association between BIS sensitivity and attitude/ environmental influences promoting tobacco use, with PA driving this effect (point estimate = 0.003; SE = 0.01; 95%CIs [0.013;0.009]) (direction of effects was the same as in the overall model).

The model with affectivity mediating the association between BIS sensitivity and marijuana use was not supported (95%CIs [−0.175;0.257]).

For visual summary of mediation results, see Fig. 1.

The indirect effects of all alternative models (i.e., wherein the roles of the independent and mediator variables were reversed) were unsupported, indicating that only models in the hypothesized direction were supported (95% CIs: NA > BIS > alcohol use [−0.360;0.116]; NA > BIS > alcohol problems [−0.041;0.009]; PA > BIS > tobacco use [−0.015;0.001]; NA > BIS > tobacco use [−0.152;0.134]; PA > BAS > tobacco use [−0.001;0.066]; PA > BAS > marijuana use [−0.012;0.051]). In case of follow-up moderated mediational models, none of the indirect effects corresponding to highest order interactions were significant (all 95% CIs contained zero), indicating insufficient support for moderation by age, sex, or comorbid internalizing or externalizing symptoms.

4. Discussion

Adolescence marks the onset of substance use experimentation and is a particularly vulnerable developmental phase with regard to such use (Colder et al., 2013; Spear, 2018). First, differences in reinforcement – in particular heightened reward – sensitivity (Cauffman et al., 2010) increases likelihood of adolescent substance use (Patel et al., 2013; Peters et al., 2011; Schneider & Shiffrin, 1977). Second, ongoing neuromaturation (Bunford, 2019; Sowell, Trauner, Gamst, & Jernigan, 2002) is linked to greater vulnerability to negative effects of such use (Monti et al., 2005; Spear, 2000). The focus of this study was on heterogeneity in mechanistic pathways to adolescent substance use *vis-à-vis* individual differences in reinforcement sensitivity and dispositional affectivity. Our goals were to examine 1) associations between reinforcement sensitivity as indexed by BAS and BIS sensitivity, dispositional positive and negative affectivity, and adolescent substance use, i.e., alcohol, tobacco, and marijuana use and 2) dispositional affectivity as mediator of the association between reinforcement sensitivity and adolescent substance use.

In bivariate analyses, as expected and consistent with theory and earlier findings, greater BAS sensitivity was associated with greater PA (Smillie, 2013) and greater BIS sensitivity was associated with greater NA (Bunford, Roberts, Kennedy, & Klumpp, 2017; Hundt et al., 2013). Greater BIS sensitivity was also associated with lower PA. Regarding the relation between reinforcement sensitivity and substance use, neither BAS nor BIS sensitivity was associated with substance use. The former finding is inconsistent with hypotheses and prior results (Kim-Spoon et al., 2016; Urošević et al., 2015; Willem et al., 2010) but the latter is in line with other data indicating no (Colder et al., 2013; Kim-Spoon et al., 2016) and weak (Knyazev, 2004) relations between BIS sensitivity and adolescent substance use. Regarding the relation between dispositional affectivity and substance use, greater PA was associated with lower tobacco use. This finding replicates earlier results of a negative longitudinal association between PA and adolescent substance use (Wills et al., 1999) and underscores the importance of considering not only NA but also PA in understanding youth substance use, in particular, tobacco use. Greater NA was associated with greater alcohol use and greater tobacco use and this also replicates earlier results of a positive longitudinal association between NA and adolescent substance use (Wills et al., 1999).

[8] Data reported correspond to completely standardized indirect effects of X on Y.

Table 3
Model coefficients for parallel mediation models testing effects of reinforcement sensitivity through affectivity on substance use

	Consequent					
	M (PA)		*M* (NA)		*Y* (alcohol use)[a]	
Antecedent	*b*	SE	*b*	SE	*b*	SE
X (BAS)	.313***	.039	.011	.064	.001	.094
M (PA)	–	–	–	–	−.024	.198
M (NA)	–	–	–	–	.231§	.122
Constant	6.645§	3.576	17.522**	5.812	13.814*	6.623
	R^2=.43, F(1,101)=64.064***		R^2=.01, F(1,101)=1.198		R^2=.04, F(1,99)=1.199	
	Consequent					
	M (PA)		*M* (NA)		*Y* (alcohol use)[a]	
Antecedent	*b*	SE	*b*	SE	*b*	SE
X (BIS)	−.111*	.05	.385***	.04	−.092	.091
M (PA)	–	–	–	–	−.046	.151
M (NA)	–	–	–	–	.353*	.155
Constant	39.973***	2.429	−1.544	1.978	17.170*	7.04
	R^2=.05, F(1,101)=4.899*		R^2=.52, F(1,101)=93.019***		R^2=.04, F(1,99)=1.827	
	Consequent					
	M (PA)		*M* (NA)		*Y* (alcohol problems)	
Antecedent	*b*	SE	*b*	SE	*b*	SE
X (BAS)	.304***	.031	.011	.052	.016	.019
M (PA)	–	–	–	-	.012	.046
M (NA)	–	–	–	–	.086§	.044
Constant	7.807***	2.729	17.608***	4.616	−1.399	1.692
	R^2=.45, F(1,123)=98.553***		R^2=.01, F(1,123)=.045		R^2=.06, F(3,121)=2.127	
	Consequent					
	M (PA)		*M* (NA)		*Y* (alcohol problems)	
Antecedent	*b*	SE	*b*	SE	*b*	SE
X (BIS)	−.103*	.046	.376***	.036	−.029	.026
M (PA)	–	–	–	–	.030	.039
M (NA)	–	–	–	–	.128**	.040
Constant	39.358***	2.252	−.821	1.746	.109	1.976
	R^2=.05, F(1,123)=5.055*		R^2=.49, F(1,123)=108.870***		R^2=.06, F(3,121)=3.394*	
	Consequent					
	M (PA)		*M* (NA)		*Y* (tobacco use)	
Antecedent	*b*	SE	*b*	SE	*b*	SE
X (BAS)	.306***	0.033	.020	.053	.067	.042
M (PA)	–	–	–	–	−.193*	.078
M (NA)	–	–	–	–	.085§	.043
Constant	7.616	2.945**	16.717***	4.737	12.313***	2.306
	R^2=.44, F(1,123)=87.115***		R^2=.01, F(1,123)=.143		R^2=.11, F(3,121)=4.872**	
	Consequent					
	M (PA)		*M* (NA)		*Y* (tobacco use)	
Antecedent	*b*	SE	*b*	SE	*b*	SE
X (BIS)	−.093	.048	.373***	.037	−.012	.029
M (PA)	–	–	–	–	−.095*	.048
M (NA)	–	–	–	–	.119§	.060
Constant	38.969***	2.329	−.698	1.795	14.768***	2.206
	R^2=.04, F(1,123)=3.769§		R^2=.49, F(1,123)=10.756***		R^2=.08, F(3,121)=4.209**	
	Consequent					
	M (PA)	*M* (NA)	*Y* (marijuana use)			
Antecedent	*b*	SE	*b*	SE	*b*	SE
X (BAS)	.304***	.031	.011	.052	.009	.012
M (PA)	–	–	–	–	−.034§	.020
M (NA)	–	–	–	–	.013	.018
Constant	7.807**	2.729	17.608***	4.616	.361	.371
	R^2=.45, F(1,123)=98.553***		R^2=.01, F(1,123)=.046		R^2=.04, F(3,121)=1.537	
	Consequent					
	M (PA)		*M* (NA)		*Y* (marijuana use)	
Antecedent	*b*	SE	*b*	*b*	SE	*b*
X (BIS)	−.103*	.046	.376***	.036	.008	.008
M (PA)	–	–	–	–	−.109§	.011
M (NA)	–	–	–	–	.005	.019
Constant	39.360***	2.252	−.821	1.746	.334	.284
	R^2=.05, F(1,123)=5.055 *		R^2=.49, F(1,123)=108.870***	R^2=.49, F(1,123)=108.870***	R^2=.04, F(3,121)=1.055	

Note. ***: p<.001; **: p<.01; *: p<.05; §: .1>p>.05. [a]: n=103. Alcohol use = ESPAD (select items) Total; Alcohol problems = AUDIT Total.

Analyses with age revealed that older adolescents were more likely to exhibit greater conflict detection, monitoring, and resolving system (i.e., BIS) sensitivity and were also more likely to exhibit greater trait-like tendency to react frequently and intensely with negative emotions to frustrations, threats, and other challenges (i.e., NA). These data are consistent with the literature suggesting a positive association between age and BIS sensitivity (Vervoort et al., 2010) and age-related increases in NA (Mason, Hitch, & Spoth, 2009) and indicators of NA (Costello et al., 2002). Not surprisingly, age was also positively related to alcohol use (Kühn et al., 2019) and girls exhibited greater BIS sensitivity

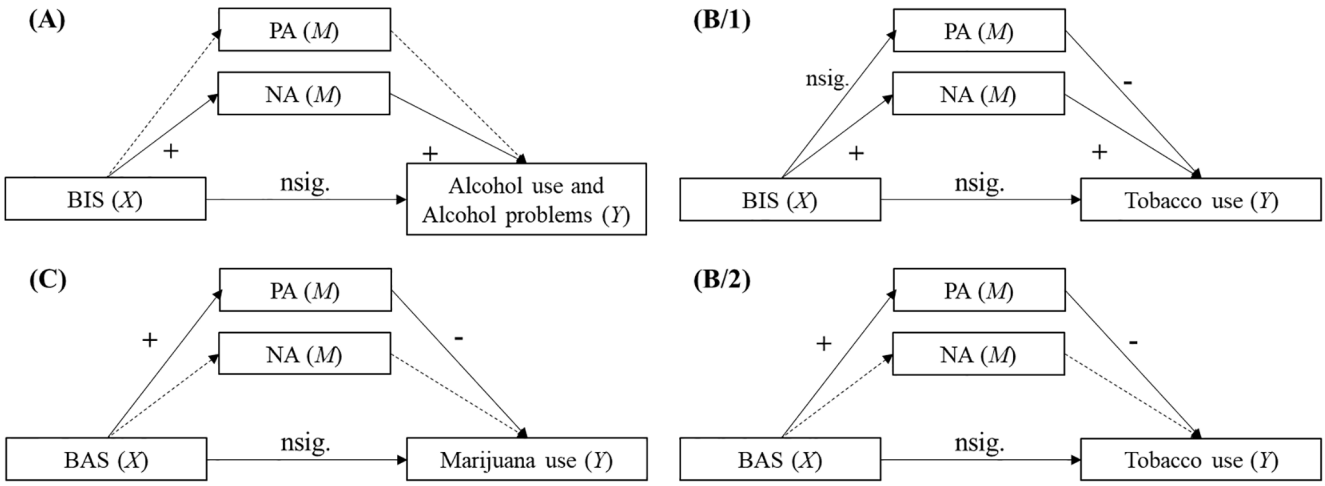

Fig. 1. Visual summary of parallel mediation results: (A) The association between both BIS and alcohol use and between BIS and alcohol problems was mediated by NA. (B/1) The association between BIS and tobacco use was mediated by positive and negative affectivity. (B/2) The association between BAS and tobacco use was mediated by positive affectivity. (C) The association between BAS and marijuana use was mediated by positive affectivity. Note. BAS = Behavioral Activation System; BIS = Behavioral Inhibition System; PA = positive affectivity; NA = negative affectivity; + = a positive effect, where greater scores on one variable are associated with greater scores on the other variable; - = a negative effect, where greater scores on one variable are associated with lower scores on the other variable; nsig. = a nonsignificant effect. Solid lines represent supported indirect effects, dashed lines represent non-supported indirect effects. Alcohol use = ESPAD (select items) Total; Alcohol problems = AUDIT Total.

(Pagliaccio et al., 2016) but lower alcohol problems (Substance Abuse and Mental Health Services Administration, 2014).

A greater number of associations were observed when more complex relationships among variables (i.e., mediation) were considered, adding to the available but meager literature (Kim-Spoon et al., 2016; Knyazev, 2004) on mechanisms through which individual differences in reinforcement sensitivity are associated with adolescent substance use. Specifically, although still no association emerged between BAS sensitivity and alcohol use, one emerged between both BIS sensitivity and alcohol use and BIS and alcohol problems, with NA (but not PA) mediating such associations. As hypothesized and consistent with theory and earlier findings, greater BIS sensitivity was linked to greater NA (Bunford, Roberts, Kennedy, & Klumpp, 2017; Hundt et al., 2013), and greater NA was linked to greater alcohol use and alcohol problems. Accordingly, it is through greater tendency to experience negative emotions (Watson and Clark) that the conflict (e.g., approach-avoidance conflict) detecting, monitoring, and resolving system (Bunford, Kujawa et al., 2017; Corr & McNaughton, 2012) exerts its effect on alcohol use/problems but, at least in the current sample, not independent of that association. Others also found that the BIS did not show a direct association with substance use (a composite measure of alcohol, tobacco, and any drug use) but did show an indirect effect on this outcome, through educational aspiration and subjective well-being (Knyazev et al., 2004). Of note, serotonin has been implicated in all three characteristics of the BIS > NA > alcohol use/ problems mediational model, indicating alterations in serotonergic activity may underlie and perhaps explain the relations we observed here. First, the BIS functions through serotonergic activity in the septohippocampal system (Gray, 1994). Second, alcohol drinking in humans and rats is associated with serotonin depletion (Virkkunen & Linnoila, 1990) and alcohol-reinforced behavior in rats is suppressed by pharmacological compounds targeting the serotonergic system (Johnson, 2008). Third, negative affective biases in anxiety and depressive disorders are mitigated by serotonergic medications (Robinson et al., 2013).

The relationship between reinforcement sensitivity and marijuana use was also specific to one domain of reinforcement sensitivity and one domain of dispositional affectivity. However, unlike with alcohol use, where an association emerged between BIS sensitivity and alcohol use/problems, in case of marijuana, an association emerged between BAS sensitivity and marijuana use, with PA (but not NA) mediating such association. As hypothesized and in line with prior results, greater BAS sensitivity was linked to greater PA (Smillie, 2013) and interestingly and in line with Wills (1999), greater PA was linked to lower marijuana use, indicating PA may provide a degree of protection. That BAS was directly not but indirectly was related to substance use is consistent with earlier findings insofar as those also underscore the importance of considering third variables. Specifically, earlier, an association between BAS and earlier initiation of substance use (a composite measure of alcohol, tobacco, and any drug use) was not observed in adolescents with high inhibitory control but was observed in adolescents with low inhibitory control (Kim-Spoon et al., 2016). That BAS was indirectly, negatively linked to marijuana use is inconsistent with prior results of BAS being indirectly, positively linked to substance use (Knyazev et al., 2004). Specifically, in a large sample of adolescents and young adults, greater BAS sensitivity was related to greater affiliation with peers, disobedience to adults, and tolerant attitude toward illegal activity, and greater scores on these variables were related to greater substance use (Knyazev et al., 2004). Certainly, both the current and these earlier findings will need to be replicated. Nevertheless, as an explanatory hypothesis reconciling seemingly discrepant findings across these studies, the effect of BAS on substance use may be complex and dependent on additional variables with which BAS sensitivity is associated. When paired with greater PA, the outcome may be lower marijuana use but when paired with certain socio-cognitive characteristics, the outcome may be greater substance use.

A similar argument as for the BIS > NA > alcohol relationship can be made for the neurobiological bases of the BAS > PA > marijuana relationship; the BAS functions through the dopaminergic reward pathways (Pickering, 1997) and Δ9-tetrahydrocannabinol, the primary psychoactive component of *Cannabis sativa*, exerts its effects by increasing dopamine concentrations in terminal regions of the mesolimbic dopamine system (Oleson & Cheer, 2012). As per the dopaminergic theory of positive affect, the psychological effects of positive emotion are specifically linked to increased dopamine release via the substantia nigra and ventral tegmental area (Ashby, Isen, & Turken, 1999). Taken together, alterations in the dopaminergic system may contribute to or underlie the BAS > PA > marijuana relationship. Both the serotonergic hypothesis on the BIS > NA > alcohol use relationship and the dopaminergic hypothesis of the BAS > PA > marijuana use relationship are testable hypotheses for future research.

Finally, unlike with alcohol and marijuana use, the reinforcement sensitivity-tobacco use relationship was not specific to any given domain of reinforcement sensitivity or affectivity: the association between BIS sensitivity and tobacco use was mediated by both NA and PA and the association between BAS sensitivity and tobacco use was mediated by PA (but not NA). Of note, when assessed with actual tobacco use items and attitude/ environmental influences promoting tobacco use separately, the association between BIS sensitivity and actual use was mediated by NA whereas the association between BIS sensitivity and attitude/ environmental influences was mediated by PA. The association between BAS sensitivity and both actual use and attitude/ environmental influences was mediated by PA. Thus, similar to alcohol use, NA (in the context of greater BIS sensitivity) only plays a role in actual use and is a potential risk factor for such use. Conversely, PA (in the context of reinforcement sensitivity) plays a role in both actual use and in risk factors for actual use, such as parental/ peer influences and beliefs about health effects and is a potential protective factor in relation to these outcomes.

The link between reinforcement sensitivity and smoking is likely quite complex. Smoking may be associated with mixed (reward and punishment) motivational cues (e.g., tension-reducing effects vs. negative health outcomes of smoking). As such, smoking may activate – as would also be suggested by our current findings – both the conflict detecting and the approach system. Indeed, the joint subsystems hypothesis of BIS/BAS effects suggests that the final effect of one system on outcome behavior depends on the activity of the other system (Corr, 2002). This is another testable hypothesis to explore in the context of the effects of affectivity on these proposed mechanisms.

Across models, as hypothesized and consistent with theory and earlier findings, greater BIS sensitivity was linked to greater NA (Bunford, Roberts, Kennedy, & Klumpp, 2017; Hundt et al., 2013), greater BAS sensitivity was linked to greater PA (Smillie, 2013) and greater NA was linked to greater substance (i.e., alcohol and tobacco) use. Interestingly, greater PA was linked to lower substance (i.e., marijuana and tobacco) use. Importantly, with regard to supported mediation models, none of the alternative models were supported wherein the roles of reinforcement sensitivity and dispositional affectivity variables were reversed, indicating a unidirectional relationship between the predictors and mediators.

4.1. Conceptual and practical implications

In the current study, bivariate analyses did not, but mediational tests did reveal relations between indices of reinforcement sensitivity and substance use. In other words, it was only when potential third variables were considered that the assessed relation was observed. This is consistent with contemporary thinking about associations between variables indexing human behavior and development that accounting for relevant mechanisms and influences may reveal previously undetected effects (Hayes, 2013).

Regarding the nature of the observed relationships, individual differences in reinforcement sensitivity exert unique (BIS on alcohol and BAS on marijuana) and shared (BIS and BAS on tobacco use) effects on adolescent substance use and a mechanism through which they exert this effect is dispositional affectivity. In terms of unique influences, it is through greater NA that greater BIS sensitivity may predispose youth to alcohol use/ problems. Conversely, it is through greater PA that greater BAS sensitivity may reduce likelihood of youth marijuana use. Thus, in addition to domains of reinforcement sensitivity, domains of affectivity and type of substance are also important to consider when specifying the nature of the relationships across these characteristics. In the context of the effects of reinforcement sensitivity, different domains of affectivity may have opposite effects on substance use: negative affect may increase whereas positive affect may decrease use. Further, and still in the context of reinforcement sensitivity, whether a given aspect of affectivity plays a role in substance use varies: NA appears to be more relevant in case of alcohol use/ problems whereas PA appears to be relevant in case of marijuana use. In terms of shared influences, both domains of reinforcement sensitivity and through both domains of affectivity may alter risk for tobacco use, with directions of these effects consistent with those observed with alcohol and marijuana. Greater BIS sensitivity exerts its effect through greater NA on greater tobacco use whereas greater BAS sensitivity exerts its effect through greater PA on lower tobacco use.

Together, findings are novel contributions to the literature suggesting that beyond affiliation with peers, disobedience to adults, and a tolerant attitude toward illegal activity (Knyazev, 2004), dispositional affectivity is a mechanism through which reinforcement sensitivity is associated with adolescent substance use. As such, individual differences in affectivity may be promising substance use prevention targets. Decreasing the influence of BIS sensitivity on negative affect and reducing negative affect may be beneficial for reducing alcohol and tobacco use. Capitalizing on the influence of BAS sensitivity on positive affect and increasing positive effect may be beneficial for preventing marijuana and tobacco use. Although evidence-based, well-established interventions targeting adolescent substance use are available (Hogue et al., 2018), relatively low abstinence rates and reduction in substance use suggest room for improvement, such as via identification of alternative intervention targets. Although in the current study, effectiveness of interventions was not assessed, identification of mechanisms of adolescent substance use may ultimately have implications in this regard.

When considered through the revised RST (Corr & McNaughton, 2012), links between the BIS and NA and BAS and PA are relatively well-understood. The same cannot be said about the links between affectivity and substance use, as mechanisms underlying their association are far from unequivocal. The long-standing self-medication hypothesis for example, suggests that alleviation of dysphoria and negative affect is the aim of substance use (Khantzian, 1985). One limitation to this hypothesis is that it is restricted to explaining the association between NA and substance use but does not explain the association between PA and substance use, despite some prior and the current results indicating that PA may influence vulnerability for use. A relevant explanatory hypothesis is that high PA is inconsistent with attributing a coping function to substance use (Wills et al., 1999). Certainly, the relationship between affectivity and substance use is more complex than these hypotheses suggest. In support, findings show that self-medication processes operate under some but not other conditions (Mason et al., 2009) and also that PA may serve not only as a protective but also as a risk factor for substance use, as positive affect enhancement may also be an aim of use (Wills & Hirky, 1996). Relevant differential effects of sex have also been reported, with enhancement (of PA) motives mediating the relationship between childhood abuse and alcohol use in men, but attenuation (of NA) motives mediating this relationship in women (Goldstein, Flett, & Wekerle, 2010). Beyond characteristics examined in the current study and as described above, these and other variables will be informative in further refining and thus personalizing prevention and treatment methods aimed at problematic substance use.

4.2. Differences in policy/regulatory environments

As compared to the U.S. adolescent substance use prevalence rates, the Hungarian rates are generally higher. Findings of a recent Hungarian national survey show lifetime prevalence of alcohol use in 5th–11th graders is 60.7%, of alcohol intoxication 36.9%, of past month use 39.5%, and of past month intoxication, it is 18.7% (Paki, 2019). Regarding cigarette smoking, 55% of adolescents (M_{age} = 15.7 years) smoked during the past year, 29% smoked during the past month and 3–6% used cannabis during the past month (Kraus & Nociar, 2016). Of 9th and 11th graders, 24.6% had used an illegal and/ or a legal substance in their lifetime; 39.4% used illegal substances on $\geq$ 10 days, whereas 20–25% are frequent users, i.e., have used illegal substances on

≥ 30 days (Paki, 2019).

Differences in substance use prevalence rates suggest there may be differences in policy/ regulatory environments around the substances examined here that have implications for the generalizability and interpretation of our results. Alcohol, tobacco and other drugs, such as marijuana, are subject to different regulatory measures across countries and geographic areas. Differences in regulatory measures, in turn, are associated with factors that may influence susceptibility to substance use, such as differences in ease of access, norms, and use of substances. In support, findings suggest that a higher minimum sales age for alcohol and tobacco is associated with less use in youth (Callaghan et al., 2018; Kessel Schneider, Buka, Dash, Winickoff, & O'Donnell, 2016; Wagenaar & Toomey, 2000), though data also indicate enforcement of these laws is necessary for them to have such an effect (Voas, Tippetts, & Fell, 2000).

Taking Hungary, another European country with different policies, i.e., Austria, and the United States as examples, differences in policy are as follows. In Hungary, the legal age for alcohol use is 18 years, with enforcement of the corresponding law focused on the retailer (penalties most frequently take the form of fines or written notices), rather than on the user (International Alliance for Responsible Drinking, 2020). In some Austrian states, the legal age for drinking is 16 years (in some others, it is 18) ("Austria tobacco use/consumption age laws," 2020). Primary responsibility is on adults with a penalty of fines or up to 6 weeks of imprisonment. Noncompliant youth over the age of 14 years are simply informed about the law, though repeat offenders may incur a smaller fine (Wiener JugendschutzgesetzDocument, 2020). The United States allows the consumption of alcoholic beverages from 21 years and there is a zero-tolerance law (especially with regard to driving under the influence), with possible legal consequences, depending on state, including fines, license suspension, jail time, alcohol awareness classes and community service (International Alliance for Responsible Drinking, 2020). Regulations regarding tobacco use follow a similar pattern; in Hungary, purchasing and consuming tobacco is legal from 18 years of age, with enforcement of the corresponding law again focused on retailers or parents (International Alliance for Responsible Drinking, 2020). In Austria, tobacco can be purchased by 16-year-olds but can be consumed only from 18 (FRA, 2020). Primary responsibility is on adults, with penalties the same as for alcohol for both adults and noncompliant youth (Wiener JugendschutzgesetzDocument, 2020). The United States recently enacted a law through all states, setting the legal age for tobacco consumption to 21 years. However, contrary to underage alcohol consumption in the United States and similar to Hungary, enforcement of the law is focused on retailers, not on underage youth (Marynak et al., 2020).

Although many drugs are illegal in most countries, marijuana is a controversial drug, with many countries or states declaring it legal or illegal along a continuum – decriminalized, legal exclusively for medical use, or legal for recreational use (Marijuana overview, 2019). Legislation in many countries takes into account the amount in possession, the location of possession (e.g., in places that minors frequently locate), and whether distribution or minors were involved (Marijuana overview, 2019).

Hungarian law does not distinguish between types of illegal drugs and with all types of marijuana possession and use being illegal, possession and trade of marijuana falls under the same legal category as of other drugs. Possession- and trade-related legal consequences depend on the total amount of active ingredient found in possession or distributed (Hungary, 2018). Possession can result in written notice, fines, mandatory community service or jail. Distributing near to, giving to, or selling to minors is more harshly penalized, with up to 5–10 years in jail (Hungary, 2018). For first time offenders consuming marijuana or possessing a minimal amount, there is a possibility to attend drug-awareness sessions or 6 months of drug addiction therapy, in lieu of penalty (Hungary, 2018). In Austria, medical marijuana was legalized in 2008 (EMCDDA, 2020) and recreational marijuana use is distinguished from recreational other drug use. Involving a minor in illegal activity (possession, selling) regarding marijuana may increase the sentence, which is usually a fine or jail time (generally up to 6 months, but if a minor is involved, up to 3 years). The United States has different laws by state regarding marijuana possession and use, ranging from illegal to legal for recreational purposes (in small doses) for adults – over 18 or 21 years of age (Marijuana overview, 2019; State Medical Marijuana Laws, 2020). Legislation also distinguishes between marijuana and other drugs and legal consequences of marijuana use vary by state. For example, in Massachusetts, underage possession of minimal marijuana has the same legal consequence (civil citation and a fine) as for those above 18, but minors must also attend an approved drug awareness program (Contant Law, 2019).

Taken together, although comparing Hungarian policy/ regulatory environment to several countries is beyond the scope of this study, that environment appears neither as strict – in some regards – nor as lenient as certain aspects of legislation in some U.S. states. However, as our cursory review of the issue indicates, it is difficult to make overarching comparisons across geographic regions regarding substance use. The conclusions of any such comparison would depend on type of substance and aspect of legislation considered (e.g., legal age to purchase vs. legal age to consume vs. party held responsible, etc.). Nevertheless, there is a somewhat consistent pattern where European regulations regarding legal age of consumption are more lenient than U.S. regulations. Whether this corresponds to differences in adolescents' susceptibility to substance use remains an empirical question that will be informative to address in future studies.

4.3. Future directions

We restricted our analyses to most common indices of adolescent substance use. Reinforcement sensitivity and temperamental predictors of use of other classes of substances will be important to examine in the future. Related, we assessed marijuana use with a single item and a more comprehensive assessment of this outcome may be indicated as a next step in this line of research. When accounting for factors known to confound the examined associations during adolescence (i.e., age, sex, and comorbid mental health symptoms), we did not find support for moderation by such factors, potentially due to the relatively low number of adolescents with more severe substance use and/ or relatively low number of comorbid symptoms. Support for moderation may be detectable in more severe and/ or comorbid samples. Related, the range of alcohol problems in our sample was below the cutoff for alcohol problems, limiting ability to interpret corresponding findings as reflecting alcohol problems in the clinical sense. Further related, lack of ethnicity variability also limits generalizability of our research to non-Caucasian groups.

Mediation can be demonstrated in cross-sectional research (Winer et al., 2016), but only via statistical criteria (Baron & Kenny, 1986; Hayes & Scharkow, 2013; Hayes, 2013; Mackinnon & Dwyer, 1993; MacKinnon, Fairchild, & Fritz, 2007). Accordingly, we established atemporal mediation, mathematically/ statistically. As we tested but did not find support for reversed models – as recommended e.g., in cross-sectional designs, where temporal precedence is not definitively established (Agler & De Boeck, 2017; Bunford et al., 2018, 2015; Danner et al., 2015; Rinsky & Hinshaw, 2011), our findings evince unidirectionality of observed effects and indicate additional research is warranted, e.g., experimental or prospective studies, to establish temporal mediation and thus causation (Bunford, Kujawa, Fitzgerald, Monk, & Phan, 2018; Shadish, Cook, & Campbell, 2002).

In case of some relations, our study appears to have been sufficiently powered to find statistically significant mediation when there is one, whereas in case of other relations, it was not. As such, to determine their robustness, it will be important to determine whether our findings can be replicated with larger samples. (Though in some cases, the sample size necessary to detect an effect, given the observed correlation coefficients between certain variables, is extremely large, e.g., for the BAS

> alcohol use and alcohol problems models, we would have needed over 3000 participants to detect an effect with 0.6 power, indicating such effect is likely simply not there (Schoemann, Boulton, & Short, 2017)). Of note, to some extent, bootstrapping guards against issues related to low power; as a result of resampling, it refines the approximation to the *null* distribution of test statistics and a more accurate approximation correspond to more accurate size for a test or more accurate coverage probability for a confidence interval (Kulesa, Krzywinski, Blainey, & Altman, 2015).

We defined adolescence based on chronological age without accounting for biological age or pubertal status, though these may not necessarily correspond. It thus remains an outstanding question whether these findings replicate if adolescence is defined based on biological maturity. Finally, it will also be beneficial to supplement self-report with additional, e.g., objective measures of substance use in future studies.

4.4. Conclusion

There are unique and shared effects of reinforcement sensitivity on adolescent substance use and these vary not only with domain of reinforcement sensitivity but also with aspect of dispositional affectivity and type of substance considered. Thus, the herein examined intermediate phenotypes are a promising individual difference variable along which to parse heterogeneity in youth substance use outcomes.

CRediT authorship contribution statement

Alexandra Rádosi: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing - original draft, Writing - review & editing. **Bea Pászthy:** Conceptualization, Methodology, Supervision, Writing - review & editing. **Tünde É. Welker:** Data curation, Formal analysis, Project administration, Investigation, Writing - review & editing. **Evelin A. Zubovics:** Investigation, Project administration, Writing - review & editing. **János M. Réthelyi:** Conceptualization, Writing - review & editing. **István Ulbert:** Conceptualization, Writing - review & editing. **Nóra Bunford:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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