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Exploring associations between affect and marijuana use in everyday life via specification curve analysis

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Although frequently hypothesized, the evidence for associations between affect and marijuana use in everyday life remains ambiguous. Inconsistent findings across existing work may be due, in part, to differences in study design and analytic decisions, such as study inclusion criteria, the operationalization of affect, or the timing of affect assessment. We used specification curves to assess the robustness of the evidence for affect predicting same-day marijuana use and marijuana use predicting next-day affect across several hundred models that varied in terms of decisions that reflect those typical in this literature (e.g., whether to average affect prior to marijuana use or select the affect report closest in time to marijuana use). We fitted these curves in data from two ecological momentary assessment studies of regular marijuana and/or alcohol using college students (N = 287). Results provided robust evidence that marijuana use was slightly *less* likely following experiences of negative affect, and slightly *more* likely following positive affect. Specification curves suggested that differences in previous findings are most likely a function of the specific emotion items used to represent affect rather than differences in inclusion criteria, the temporal assessment and modeling of affect, or the covariates added to the model. There was little evidence for an association between marijuana use and next-day affect. Overall, our findings provide evidence against the predictions made by affect reinforcement models in college students, and suggest that future research should model the associations of marijuana use with discrete emotional states rather than general negative and positive affect.

Data, analysis code, supplementary material: https://osf.io/tds7h/

Keywords: affect, marijuana use, motivation, ecological momentary assessment, specification curve analysis

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Substance use has long been proposed to be preceded and followed by changes in negative and positive affect, which are considered two general feeling states that can be composed of a variety of discrete emotions (e.g., NA: angry, distressed; PA: enthusiastic, energized) in different moments (Russell, 2003; Watson et al., 1988). For example, researchers have long been interested in the idea that substance use might be a form of emotion regulation (Cloninger, 1987; Conger, 1956). Multiple affect reinforcement models by Cox and Klinger (1988), Cooper and colleagues (1995), and Simons and colleagues (2005) all propose in some way that people consume substances, such as marijuana, with the hopes of increasing positive feelings and/or decreasing negative ones. Although some of these models have initially been proposed to explain alcohol use, similar motivational processes are expected to underlie marijuana use (Cooper et al., 2016). One of the broad predictions that these models make is that increases in affect should result in increases in marijuana use, meaning that people should be more likely to consume marijuana following increases in emotional experiences (especially negative ones). This association is theorized to develop as marijuana use should lead to short-term improvements in mood (i.e., for the duration that subjective intoxication is experienced; Wachtel et al., 2002).

Theoretical models differ in the population in which they expect negative affect to motivate substance use (e.g., marijuana use). The motivational models by Cox and Klinger (1988) and Cooper and colleagues (1995, 2016) state that people *in general* are motivated to use marijuana to cope with negative affect. Later models by Baker and colleagues (2004) and Koob and Le Moal (2008) specifically state that negative affect should motivate substance use in people with substance use disorders. These two models hypothesize that negative affect is a key component of withdrawal that motivates further use, implying that marijuana use might also be associated with worsened mood on the day following use. The goal of the present study is thus to test two key hypotheses derived from affect reinforcement theories: that higher negative and positive affect should precede marijuana use episodes, and that marijuana use leads to changes in affect on the day following use.

Cross-sectional, prospective, and experimental research appears to support the notion that affect motivates marijuana use in people *with and without cannabis use disorder*. In apparent support of affect reinforcement models, varied populations of marijuana users (e.g., regularly using high-school, college students, and young adults, individuals meeting criteria for DSM-5 cannabis use disorder) often report the desire to cope with negative emotions or enhance positive emotions as major motivations for their use (Blevins et al., 2016; Lee et al., 2007; Moitra et al., 2015; Simons et al., 1998). Studies also find consistently that young adults who report higher enhancement and coping motives consume marijuana more frequently (Bresin & Mekawi, 2019; Zvolensky et al., 2007), and that young adults use more marijuana on days they report higher enhancement and coping motives (Bonar et al., 2017). Affect reinforcement of marijuana use also seems well-supported in cross-sectional research (e.g., Bravo et al., 2020; Denson & Earleywine, 2006; Farris et al., 2016; Metrik et al., 2016). For example, a survey study with more than 2,000 college students across ten universities found that participants who reported higher negative affect also reported higher marijuana use (Bravo et al., 2020). Evidence for affect reinforcement of marijuana use also comes from experimental research (Hunault et al., 2014), in which recreational marijuana users reported decreased anxiety following administration of a low and moderate dose of THC compared to a placebo (anxiety was increased following a high dose of THC). As is evident from this review, most studies have been conducted among people with no diagnosis of cannabis use disorder (but they also do not typically exclude people with CUD), and thus these studies primarily inform the theoretical models by Cox and Klinger (1988) and Cooper and colleagues (1995, 2016). No research to date has examined whether affective manipulations lead people to use marijuana. Additionally, marijuana has been proposed as an anxiolytic treatment for mood disorders, though it has been noted that this may be premature based on the existing evidence (Turna et al., 2017).

However, none of these reviewed studies directly examine the notion that marijuana use is preceded by affect in people's everyday life. Despite the robust cross-sectional associations between motives and use, people's intuitions about the reasons for their own behavior are frequently unsupported by evidence (Feil et al., 2020; Mazar & Wood, 2022; Nisbett & Wilson, 1977; Todd et al., 2004). Further, although laboratory experiments may demonstrate that marijuana use *can* influence affect, it is unclear to what extent such effects occur outside of the tightly controlled laboratory setting. Given that affect reinforcement models posit that substance use serves to regulate emotion in daily life, these models require evidence from people's real-time emotional experiences and substance use behaviors. In a review of 19 such ecological momentary assessment (EMA) studies examining associations between affect and marijuana use, Wycoff and colleagues (2018) found mixed evidence for negative and positive affect predicting subsequent same-day marijuana use, especially in non-clinical samples of college students and young adults. Studies among community samples have reported evidence for (e.g., Buckner et al., 2015) and against (e.g., Chakroun et al., 2010) negative affect preceding marijuana use, as well as null results (e.g., Tournier et al., 2003). Since Wycoff and colleagues' review (2018), several additional EMA studies among college students and young adults have been published, in which results have been similarly mixed (e.g., Emery et al., 2020; Sznitman et al., 2022; Testa et al., 2019). Findings in EMA studies among clinical samples are also mixed, with studies finding that negative affect precedes marijuana use (Gruber et al., 2012; Shrier et al., 2014), null results (Bhushan et al., 2012; Tyler et al., 2015), and one study finding that following higher experiences of sadness people were less likely to use marijuana (Swendsen et al., 2011). Taken together, it is difficult to find convincing and robust evidence for affect predicting marijuana use in the published EMA literature.

Evidence supporting the notion that affect is disrupted the day after marijuana use is drawn largely from clinical research. In line with Koob and LeMoal's (2008) theoretical model, which points to negative affect as the hallmark of withdrawal, several clinical and experimental studies with small sample sizes (typical n = 5-30) showed that abstinence from marijuana reliably led to experiences of withdrawal, which were primarily affective in nature (Budney, 2004). One study in which participants smoked-as-usual for five days and then remained abstinent for 45 days showed that regular users experience affective withdrawal symptoms, such as anxiety and irritability (Buckner et al., 2015), as soon as the first day following use and peaking three days following use (Budney et al., 2003).

However, the evidence that marijuana use leads to changes in affect the day following use is less convincing in experience sampling studies from community samples. Some studies have found increased negative affect following alcohol use in samples of college students (Armeli et al., 2014, 2018; Hussong et al., 2001), but the evidence is more mixed among studies of marijuana use. A recent EMA study found that negative affect was increased on the day following simultaneous alcohol and marijuana use compared to non-use days, but only for female participants high in trait anxiety (Linden-Carmichael et al., 2021). Another EMA study found a similarly complicated pattern of results in a relatively small sample (n = 41), with changes in negative and positive affect 12 hours following the use episode differing for participants depending on whether or not they met DSM-IV criteria for marijuana dependence (Ross et al., 2018). Yet another study found affect to be unchanged the morning following use in young adults (Testa et al., 2019). In summary, it is unclear whether we should expect changes in affect the day following marijuana use in non-clinical samples.

Most EMA studies have been conducted on non-clinical samples of adolescents and young adults, in part because this is a period of development during which marijuana use is peaking (SAMHSA, 2013). Additionally, recent epidemiological data suggests that rates of marijuana use disorder range from 9% to 16% among those aged 18-23, although rates of marijuana disorder are substantially higher (26 – 32%) among those who have ever used marijuana (SAMHSA, 2020). This suggests that also studies among young adults that do not have an inclusion criterion relating to cannabis use disorder likely include at least some participants that meet criteria for CUD. However, beyond this degree of similarity, most studies differ on a number of important design characteristics, making it difficult to integrate findings into one coherent narrative. Previous studies have employed a range of *inclusion criteria regarding use frequency and quantity of use.* For example, some studies have included participants with any prior marijuana use (Ansell et al., 2015), use in the past three months (Buckner et al., 2012) or past month (Buckner et al., 2013, 2015), those who report using at least two days per week (Emery et al., 2020; Shrier et al., 2014; Testa et al., 2019), or only those who used at least once *during* the study period (Bhushan et al., 2012; Trull et al., 2016). Authors have chosen to *assess positive and negative affect in different ways*, such as aggregate scores of various affect items (Bhushan et al., 2012; Buckner et al., 2013, 2015; Shrier et al., 2014; Sznitman et al., 2022; Testa et al., 2019), or have reported a range of discrete emotions such as happy, depressed, and anxious (e.g., Buckner et al., 2012; Chakroun et al., 2010; Sagar et al., 2016). Studies have also probed the affect-marijuana use association *at different timescales*, such as the daily level (e.g., Ansell et al., 2015; Buckner et al., 2012; Emery et al., 2020), the momentary level (e.g., Bhushan et al., 2012; Chakroun et al., 2010; Sagar et al., 2016; Shrier et al., 2014; Testa et al., 2019; Trull et al., 2016), and from one day to the next (Linden-Carmichael et al., 2021; Testa et al., 2019). The variety of time intervals is particularly relevant given that previous work has found that the association between affect and marijuana use varied depending on duration of time between assessment of affect and initiation of use (Ross et al., 2018). Finally, studies have adopted a *variety of data-analytic approaches* and reported models with a *wide range of covariates* that may ultimately influence the inferences we make regarding the associations between affect and marijuana use.

Affect reinforcement theories do not specify over what timescale associations between affect and substance use should occur or whether effects should be consistent across affective subscales. Thus, differences in study designs and analytic choices are not invalid or ill-justified and, in fact, are usually motivated and well-justified. What is unclear, however, is to what extent the inconsistent results reviewed by Wycoff and colleagues (2018) can be attributed to these choices. Any single study typically presents only one or a few of the potential model specifications (e.g., modeling the effect of average negative affect on the subsequent likelihood to use marijuana in weekly-using college students) that could be considered from the universe of reasonable design and analytic choices. The notion of the "garden of forking paths" (Gelman & Loken, 2013) describes how many small, reasonable data-analytic decisions can drive differences in inferences about theory. Several studies have now demonstrated that different expert teams of data analysts will come to different conclusions given the same question and the same data (e.g., Silberzahn et al., 2018). The problematic result is a set of studies with potentially disparate findings, each asserting a singular conclusion, but with no easy way to determine the source of differences. Although positive findings might be taken as evidence in support of affect reinforcement theories, because studies typically vary along many different dimensions, it is difficult to build a coherent understanding of where affect reinforcement theories are best supported. Moreover, it is difficult to use null findings to falsify some aspect of affective reinforcement because alternative tests are always possible. To better characterize the association between affect and marijuana use and more fully assess the robustness of these findings, it is necessary to examine the full array of justified tests in the same data rather than a limited subset.

Thus, one solution to this problem is to identify a large set of analyses that are valid and justified and explore whether they collectively provide evidence for a hypothesis. Specification curve analysis (Simonsohn et al., 2020) is a data-analytic approach which estimates a "multiverse" of many models that are compatible with a single hypothesis test, but which may vary in their specific operationalization. Specification curves have been used to probe the robustness of a number of important psychological hypotheses that have been tested many different ways, such as which individual differences correlate with risk preference (Frey et al., 2021), whether birth order influences personality (Rohrer et al., 2017), and whether dysregulated gaming is associated with reduced well-being (Ballou & van Rooij, 2021). In the current study, specifications varied according to the timescale, the operationalization of affect, the inclusion criteria, the covariates, and the data analytic approach. We derived these specifications from our review of differences between EMA studies summarized above. Mapping the results across all specifications and comparing them to identical hypothesis tests in shuffled versions of the data where we *know* the null hypothesis is true allowed us to test whether there is an association between affect and marijuana use in general, and the degree to which that association is sensitive to the specific model specification.

In summary, although researchers theorize that affect precedes marijuana use and that affect is disrupted on days after marijuana use episodes, a growing body of literature presents inconsistent findings for these hypothesized associations in daily life. The range of study approaches outlined above may inform the discrepancies found in the literature. The present study seeks to examine the temporal relations between daily affect and marijuana use among regularly using college students. To explore whether mixed findings in the existing body of literature come down to the between-study differences outlined above, we employed specification curve analyses (Simonsohn et al., 2020) using EMA data to assess the robustness of our results in a sample of young adults. We explored two basic research questions that lay at the heart of the EMA literature on affect and marijuana use: Is affect associated with subsequent marijuana use on the same day (RQ1)? And is marijuana use associated with subsequent affect on the next day (RQ2)?

Methods

Participants and procedure

We combined data from two ecological momentary assessment (EMA) studies (described as Study 1 and Study 2 below). A total of 287 undergraduate students aged 18 to 22 ($n_{\text{Study 1}} = 160$, $n_{\text{Study 2}} = 127$; 61.0% female; 53% White) completed 7,871 momentary surveys (79.7% overall compliance) and responded to at least one survey on 2,503 days (95.7% daily compliance). Participants who reported using alcohol or marijuana at least weekly in the past month were eligible for both studies. Individuals who participated in Study 1 were excluded from Study 2. At baseline, the majority of participants reported using marijuana at least once in their lifetime ($n = 250$), as well as in the past 30 days ($n = 230$), and in the past 30 days to the point of being high ($n = 212$). Participants reported using marijuana on 7.5 days per month on average ($SD = 7.95$ days).

Both studies had identical measures, identical inclusion criteria, identical recruitment procedures, and only differed in terms of the EMA schedule, making it appropriate to pool the data for analysis. In both studies, participants, who were recruited via the University of Washington's subject pool, first completed a baseline survey, were trained on the EMA protocol, and received course credit in exchange for participation. In Study 1, participants responded to up to three momentary surveys (morning, midday, evening) for ten consecutive days. In Study 2, participants responded to up to five momentary surveys (morning, midday, afternoon, evening, night) for eight days (Thursday, Friday, Saturday, Sunday for two consecutive weeks). Surveys were spaced evenly apart between 9am and 9pm and separated by at least two hours. As most marijuana use occurred late in the day, our study design did not allow us to robustly explore the effect of marijuana use on subsequent same-day affect, which is why we focus exclusively on next-day affect. Participants always received a reminder via text after one hour. Both study protocols were approved by the local ethics review board.

EMA measures

Marijuana use. During EMA morning assessments, participants reported whether they used marijuana on the previous day (0 = did not use marijuana, 1 = used marijuana). They also reported the approximate time of day during which they started using, which we used to set up our specifications (see below). If participants missed the morning assessment, they completed substance use items at the second assessment of the day.

Negative and positive affect. Participants rated the extent to which they currently felt five negative emotions (*angry*, *anxious*, *bored*, *irritable*, *unhappy*) and five positive emotions (*calm, cheerful, engaged, friendly, happy*) since (a) the last assessment window (for afternoon and evening assessments) or (b) since they woke up (for the morning assessment), on a 100-point visual analogue scale (scale anchors: 0 = "not at all" – 100 = "very much") at each EMA assessment. Accounting for the nested structure of the data, the set of negative (RkF = 0.96) and positive (RkF = 0.97) items showed high reliability across items and time (Shrout & Lane, 2012).

Baseline measures

For one of our specification clusters, we tested whether controlling for variables that are commonly associated with substance use in the EMA literature (age, sex, marijuana use motives, impulsivity; Bonar et al., 2017; Dora et al., 2022; Linden-Carmichael et al., 2021; Simons et al., 2010) would impact our results.

Age: Participants reported their age in years.

Sex: Participants reported their biological sex assigned at birth (1 = female, 2 = male).

Marijuana motives: Participants completed the Marijuana Motives Questionnaire (Simons et al., 1998). They indicated how often they use marijuana for a range of reasons, including "To forget your worries", "Because you like the feeling", and "Because it helps you enjoy a party". They answered these items on a 5-point Likert scale ranging from 1 = "Almost never/never" to 5 = "Almost always/always". We computed a mean score for coping motives, enhancement motives, and social motives. Internal consistency of these subscales was high in both studies (αs > .85, ωs > .90).

Impulsivity: Participants completed the UPPS-P Impulsive Behavior scale (Whiteside & Lynam, 2001). They indicated to what extent they agree with several statements about themselves, including "I have trouble controlling my impulses", "I tend to lose control when I am in a great mood", "Unfinished tasks really bother me", "I like to stop and think things over before I do them", and "I'll try anything once". They answered these items on a 4-point Likert scale ranging from 1 = "Disagree strongly" to 4 = "Agree strongly". We computed a mean score for negative urgency, positive urgency, perseverance, premeditation, and sensation seeking. Internal consistency of these subscales was high in both studies (αs > .82, ωs > .88).

We added age, biological sex, coping motives, enhancement motives, social motives, negative urgency, positive urgency, perseverance, premeditation, and sensation seeking as control variables to the model as specifications (described below).

Specification curve analyses

We conducted all analyses in R (version 4.0.5; R Core Team, 2021) with the help of the *lme4* package (version 1.1.27.1; Bates et al., 2015) and the *tidyverse* (version 1.3.1; Wickham et al., 2019). All measures, processed data, data analysis scripts, and modeling results can be found on the Open Science Framework project page of this article (https://osf.io/tds7h/). In total, we fitted four specification curves as described by Simonsohn and colleagues (2020). With the first two curves, we tested whether negative and positive affect respectively precede marijuana use (RQ1). With the second set of curves, we tested whether marijuana use is associated with next-day negative and positive affect respectively (RQ2).

Affect predicting marijuana use (RQ1). Our basic model was a generalized mixed-effects model, which included a random intercept to account for variability in marijuana use frequency between participants, predicting marijuana use from affect: glmer(marijuana use ~ 1 + affect + (1 | subject), family = binomial). Model specifications included the following:

- Different ways to operationalize affect (*individual* negative/positive emotion items, an *average* of negative/positive emotion items, and, in the case of negative affect, an average of negative emotion items *without boredom*)
- Different ways to calculate affect on days in which participants reported marijuana use (*averaging* affect reports prior to use onset, selecting affect report *immediately* prior to use onset)
- Different ways to calculate affect on days in which participants reported no marijuana use (averaging affect over *entire day*, averaging affect prior to *median time of use onset on use days*)
- Different inclusion criterion (self-report of *any lifetime marijuana use*, *marijuana use in the past 30 days*, *marijuana use in the past 30 days to the point of being high*)
- Different control variables in model (age, sex, coping motives, enhancement motives, social motives, negative urgency, positive urgency, perseverance, premeditation, sensation seeking)

This resulted in 924 model specifications for negative affect and 792 model specifications for positive affect. We chose to use both individual emotion items and average negative and positive affect to reflect the variability of affect variables in the literature. We chose to vary the timing of affect reports on use and non-use days to explore the extent to which the associations are robust at multiple time frames. We chose multiple inclusion criteria and control variables to reflect the variability in samples and model specifications in the literature. We acknowledge that we likely did not capture all meaningful differences in previous work with these specifications. We consider that an impossible task, and so we decided to use our best judgment paired with recent work connecting theory to EMA methodology (Hopwood et al., 2021) to test specifications that EMA researchers would expect to have an effect on the inferences we draw.

Marijuana use predicting next-day affect (RQ2). Our basic model was a linear mixed-effects model, which included a random intercept to account for variability in affect between participants, predicting next-day affect from marijuana use controlling for same-day affect, lmer(next-day affect ~ 1 + marijuana use + affect + (1 | subject)). Model specifications included the following:

- Different ways to operationalize affect (*individual* negative/positive emotion items, an *average* of negative/positive emotion items, and, in the case of negative affect, an average of negative emotion items *without boredom*)
- Different ways to calculate next-day affect (*averaging* affect over next day, selecting affect reported *next morning*)
- Different ways to translate the research question into the statistical test (*model described above*, model estimating *change in affect from pre- to post-marijuana use* by pairing two affect scores

(pre/post) in each marijuana use episode: lmer(affect ~ 1 + marijuana use + (1 | subject/episode)). Thus, the first model tests whether affect differs following *use days compared to non-use days*, and the second model tests whether affect differs *following a use episode compared to prior to that same use episode*.

- Different inclusion criterion (self-report of *any lifetime marijuana use*, *marijuana use in the past 30 days*, *marijuana use in the past 30 days to the point of being high*)
- Different control variables in model (age, sex, coping motives, enhancement motives, social motives, negative urgency, positive urgency, perseverance, premeditation, sensation seeking)

As for RQ1, this resulted in 924 model specifications for negative affect and 792 model specifications for positive affect. We chose to vary the timing of next-day affect to explore the extent to which the associations are robust at multiple time frames. For this, we made sure that next-day affect was always reported prior to any further next-day marijuana use to prevent the influence of subsequent uses on affect. We chose to model this research question in two ways to see if the conclusions differ if we compare affect following use to non-use days or alternatively compare affect pre- to post-marijuana use.

We calculated the median effect size across all specifications and the proportion of specifications that resulted in a significant main effect of affect/marijuana use. Then, as described by Simonsohn and colleagues (2020), we performed a permutation test to explore how inconsistent our results were across all specifications under the assumption that the true association is zero. To do so, we created 500 datasets in which we shuffled whether or not marijuana was used across days (but within participants, to account for the nested structure of our data). Thus, we forced population-level null associations between affect and marijuana use in our dataset. This allowed us to explore the distribution of specification curves under a null hypothesis by calculating the proportion of datasets in which we observed more significant specifications than in the original sample. The p-value associated with this permutation test reflects the number of shuffled datasets in which more specifications were significant than in the unshuffled dataset divided by the total number of repetitions (i.e., 500).

Results

Descriptive statistics

Participants reported consuming marijuana on 20.4% of study days. Consistent with prior EMA work (Dora et al., 2022; Trampe et al., 2015; Zelenski & Larsen, 2000), participants reported relatively low levels of momentary negative affect ($M = 17.62$, $SD = 14.92$) and moderate levels of momentary positive affect ($M = 50.00$, $SD = 22.27$) on average.

Specification curves

Table 1 summarizes the findings from our four specification curves. For RQ1, we report odds ratios representing the likelihood to use marijuana following experiences of negative and positive affect. An odds ratio of 1 indicates that marijuana use is equally likely when affect is at its mean and when it increases by 1 standard deviation. An odds ratio of 1.25 indicates that marijuana use is 25% more likely when affect increases by 1 standard deviation compared to when affect is at its mean. For RQ2, we report the predicted in- or decrease in affect on the natural 100-point scale.

Negative affect predicting marijuana use. 38.0% of the 840 specifications for negative affect motivating marijuana use resulted in statistical significance ($p < .05$). The median effect size was 0.87, which translates to a 14% increased likelihood to use marijuana on days participants reported negative affect one standard deviation *lower* than the participant's own average. In the 500 shuffled datasets in which we forced the null hypothesis to be true, none resulted in more than 38% of significant specifications ($p < .001$). Thus, we could reject the null hypothesis of no daily association between negative affect and marijuana use.

These results are further visualized in Figure 1[1]. The upper graph displays the effect of negative affect on marijuana use for each of the 924 specifications. The lower graph displays the results split by specification. In both graphs, we indicate significant effects in blue. These graphs showcase that significant effects were driven by the way we operationalized affect, with significant specifications found for *average negative affect*, *anxious* and *unhappy*, but not angry, irritable, or bored. Significant effects were equally distributed for the other specifications, and hence do not seem to depend on inclusion criterion, control variables in the model, or temporality.

Positive affect predicting marijuana use. 32.7% of specifications for positive affect motivating marijuana use resulted in p-values lower than .05. The median effect size was 1.12, which translates to a 13% increased likelihood of using marijuana on days when participants reported positive affect to be one standard deviation *higher* than their own average. Only two of the 500 shuffled datasets resulted in more significant specifications, implying that we can reject the null hypothesis of no effect of positive affect on subsequent marijuana use ($p = .004$).

These results are further visualized in Figure 2 (significant effects highlighted in orange). We can see that the sig-

[1] For readability, we removed the control variable specifications from Figures 1 – 4. The full figures including control variable specifications can be found at https://osf.io/tds7h/

nificant effects are once again driven by the operationalization of affect, with significant specifications found for *average positive affect*, *cheerful*, *calm*, and *happy* but not friendly or engaged. Significant specifications did not depend on inclusion criterion, control variables in the model, or temporality.

Marijuana use predicting next-day negative affect. Only 1.4% of specifications resulted in a significant effect of marijuana use on subsequent negative affect, with a median effect size of an increase in negative affect of 0.74 points (on a 100-point scale) following marijuana use. Our permutation test in the shuffled datasets revealed that this effect is not inconsistent with the null hypothesis (p = .566) [2]. These results are further visualized in Figure 3, highlighting that the lack of an association between marijuana use and negative affect did not depend on our operationalization of affect, temporality, statistical modeling, or control variables in the model.

Marijuana use predicting next-day positive affect. 10.1% of specifications for the effect of marijuana use on subsequent positive affect resulted in a p-value lower than .05, with the median effect size indicating a 1.67-point *decrease* in positive affect following marijuana use. This effect across all specifications was not inconsistent with the null hypothesis (permutation p = .174)[3]. Figure 4 shows that the significant effects were mainly found for decreases in self-reported cheerfulness, but they are too infrequent to result in a robust effect. Significant effects were also found mostly for affect averaged over the day following use (compared to affect reported in the morning) and when positive affect following use days is compared to positive affect following non-use days (compared to changes from prior to use to following use). The results do not seem to depend on the other specifications.

[2] As previous research (Budney et al., 2003) indicates that affective withdrawal peaks three days after use, we repeated these analyses predicting negative affect three days post-use. There is also no evidence for use predicting changes in negative affect after three days, median effect size = -1.49, p = .728.

[3] There is also no evidence for use predicting changes in positive affect after three days, median effect size = 1.15, p = .724.

Table 1. Results of specification curve analyses.

	Results of specification curve in original dataset			Permutation test with 500 shuffled datasets
Analysis	*n* of specifi-cations	Median effect size across specifications	*n* of significant [$p < .05$] specifications (%)	*n* of shuffled datasets with more significant specifications than original (*p*)
Does NA predict same-day marijuana use?	924	$OR_{use} = 0.87$	351 (38.0s)	0 (< .001)
Does PA predict same-day marijuana use?	792	$OR_{use} = 1.12$	259 (32.7)	2 (.004)
Does marijuana use predict next-day NA?	924	+ 0.74 points	13 (1.4)	283 (.566)
Does marijuana use predict next-day PA?	792	- 1.67 points	73 (10.1)	87 (.174)

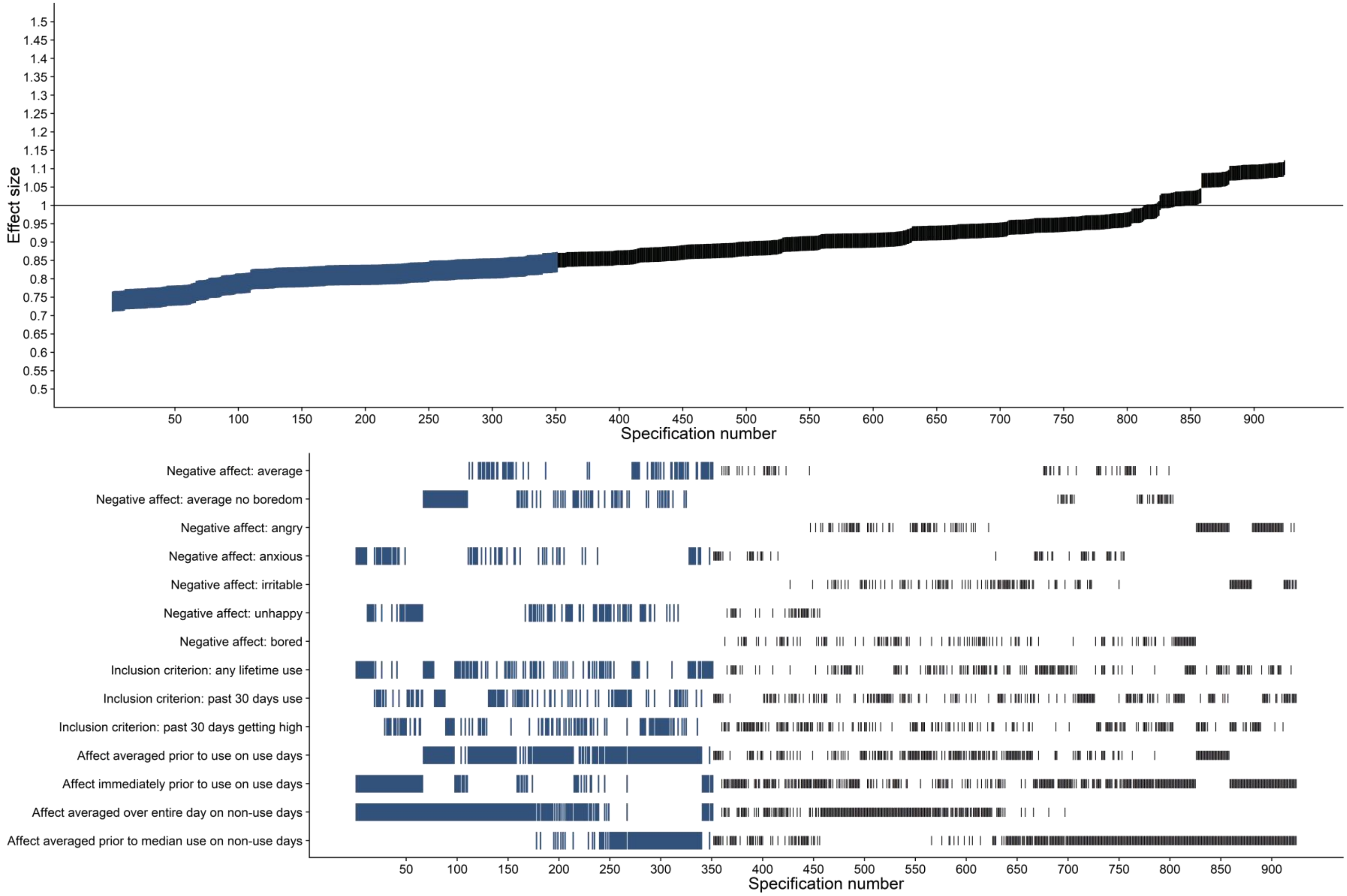

Figure 1. Results of the specification curve analysis for negative affect motivating marijuana use. Each line represents a single of the 924 model specifications. Models that contain a significant effect for affect are highlighted in blue.

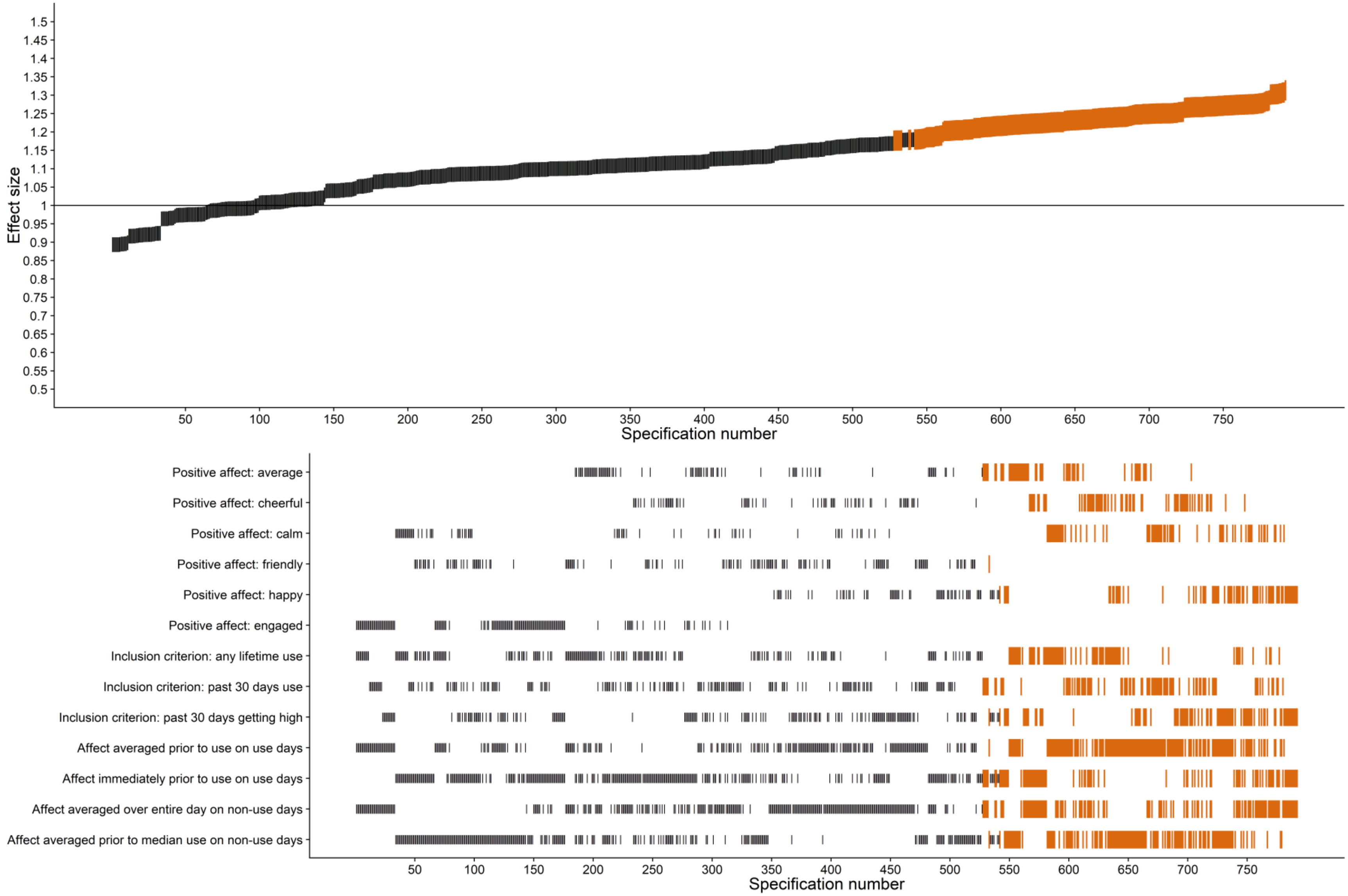

Figure 2. Results of the specification curve analysis for positive affect motivating marijuana use. Each line represents a single of the 792 model specifications. Models that contain a significant effect for affect are highlighted in orange.

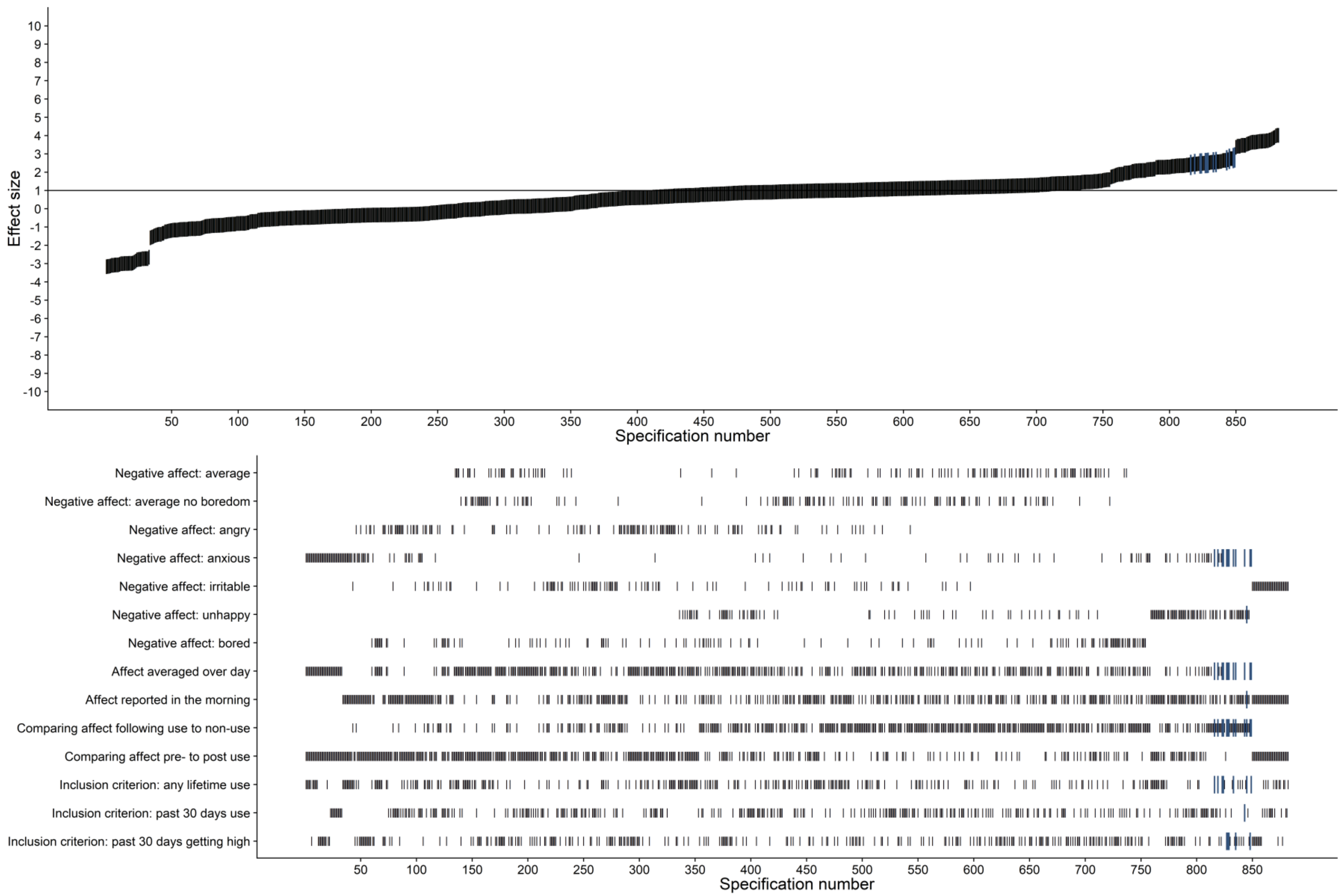

Figure 3. Results of the specification curve analysis for marijuana use predicting next-day negative affect. Each line represents a single of the 924 model specifications. Models that contain a significant effect for affect are highlighted in blue.

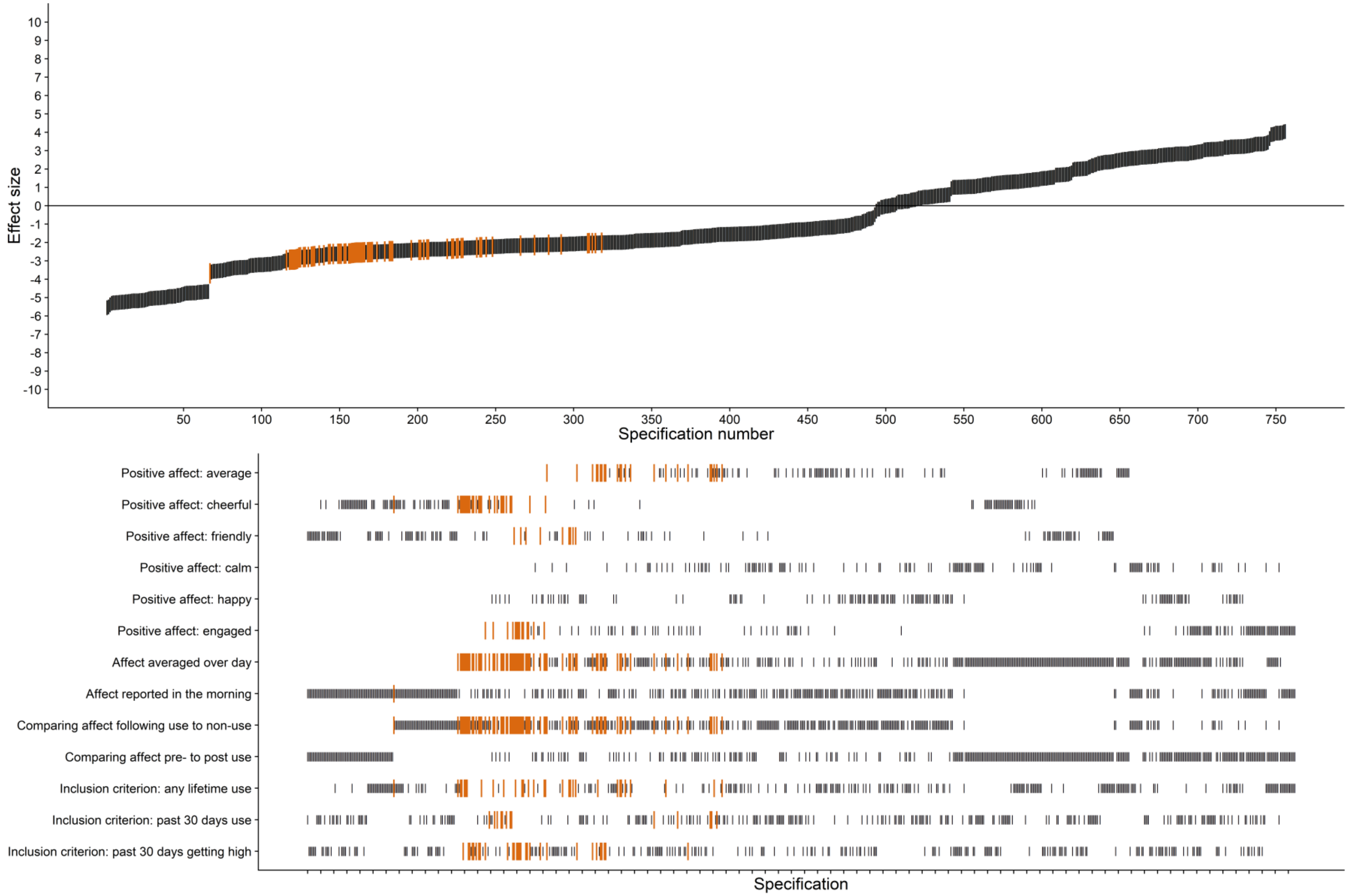

Figure 4. Results of the specification curve analysis for marijuana use predicting next-day positive affect. Each line represents a single of the 792 model specifications. Models that contain a significant effect for affect are highlighted in orange.

Discussion

Despite theories of affect reinforcement that hypothesize that disruptions in affect both precede and follow marijuana use episodes (e.g., Baker et al., 2004), evidence for associations between affect and marijuana use in people's everyday life has been ambiguous. Here, we explored whether such mixed findings might be explained by differences in study design and analytic choices. Applying specification curves to data from two EMA college student samples, our findings suggest that differences in results from prior studies are, out of all specifications we examined, most likely a function of the specific emotion items used to represent affect rather than differences in inclusion criteria, the temporal assessment and modeling of affect, or the covariates added to the model. Moreover, our findings suggest that the weight of the evidence in support of affect reinforcement suggests that marijuana use is most likely to occur on days characterized by *higher positive affect* and *lower negative affect*, both of which are either not predicted by or are inconsistent with affect reinforcement theories (Cox & Klinger, 1988). On the other hand, we found little evidence that marijuana use is associated with *next-day* affect in college students.

Affect predicting same-day marijuana use

In our data, contrary to affect reinforcement models of substance use (Cooper et al., 1995; Cox & Klinger, 1988), people were *less* likely to use marijuana following experiences of higher negative affect (specifically feelings of anxiety and unhappiness). This might seem surprising in light of some previous studies in non-clinical samples which suggested that people may be more likely to use marijuana when their experiences of general negative affect and anxiety are elevated (Buckner et al., 2012, 2013, 2015; Sznitman et al., 2022). It is important to note, however, that these studies employed somewhat small sample sizes (< 100 participants). Thus, these studies might suffer from low statistical power, which would have overestimated the true effect size to the degree that only significant findings were reported either within or across studies (Vasishth et al., 2018). Our results are more consistent with larger EMA studies among young adults. Neither Chakroun and colleagues (N = 212; 2010) nor Testa and colleagues (N = 366; 2019) found an association between feelings of anxiety and subsequent marijuana use, but in both studies the (non-significant) effect was negative. Chakroun and colleagues additionally found that feelings of unhappiness were associated with a decreased likelihood of use (2010). In combination with the findings from the current study, the current evidence suggests that college students are *less* likely to use marijuana following higher-than-average negative affect.

Based on our specification curves, the mixture of negative and null effects is unlikely to be a consequence of sample differences in marijuana use frequency, the timing of affect assessment, or the control variables included in the models. The lack of evidence for the notion that the timing of affect matters is particularly important, because traditional reinforcement theories suggest that a stimulus-response association is more likely to form when the stimulus (negative affect) occurs closer in time to the response (marijuana use). Thus, some critiques of daily-level studies have been that day-level negative affect does not have sufficiently fine temporal resolution to capture negative reinforcement processes. Our findings do not find support for this critique; in our data, the association between negative affect and marijuana use was roughly equally likely to be observed regardless of whether negative affect was averaged across the day or measured immediately prior to use. Results of our models mainly differed according to which discrete negative emotion items were considered. This tells us that the model of general negative and positive affect (Russell, 2003; Watson et al., 1988) might not be the optimal theory of emotion to study associations with substance use. Our analyses indicate that some discrete emotions are associated with marijuana use, while others are not. These effects do not become apparent if we continue to average over varying sets of discrete emotion items in our work predicting marijuana use from basic states of affect. This may be especially problematic when such measures are designed to primarily capture high arousal affect items, such as in the PANAS (Watson et al., 1988). A recent study of affective models of alcohol use in EMA data (Dora et al., 2022) reported that the vast majority of studies relied on PANAS or PANAS-like measures, meaning that there is substantially less information about how low arousal emotions, such as sadness or serenity, are related to substance use. Instead, future work should examine associations across a variety of discrete emotions or at least across more specific affective states as proposed in the PANAS-X (Watson & Clark, 1994). While at this point this work would have to be as exploratory as this study, eventually theoretical predictions could be made regarding which specific emotional states should be associated with substance use, and which should not.

In sum, not only do our findings suggest that people may be *less* likely to use marijuana in the face of negative affect, but also that this association may be specific to discrete negative emotions. This implies that future EMA research should differentiate between the different dimensions of negative affect (e.g., fear, hostility, guilt, sadness, fatigue; Watson & Clark, 1994) and their associations with subsequent marijuana use. It also implies that theoretical models that predict general negative affect to motivate substance use (Cooper et al., 1995; Cox & Klinger, 1988; Wills & Filer, 1996) might need to be updated, at least for populations of young adults who regularly use marijuana, not only with regards to the direction of the hypothesized effect, but also with regards to the nuance with which specific negative emotional experiences relate to substance use. It may be that the association of affect with substance use is not the same across different substances. While we have also recently found that negative affect is not associated with alcohol use in everyday life (Dora, Piccirillo, et al., 2022), another meta-analysis found robust associations between negative affect and tobacco smoking in EMA data (Akbari et al., 2020).

It is notable that the range of negative affect was limited within our sample. Although this is consistent with distributions of negative affect in large-scale community *and* clinical samples (Cho et al., 2017; Dora, Piccirillo, et al., 2022; Trampe et al., 2015; Zelenski & Larsen, 2000), we may not capture behavior that occurs at very high levels of negative emotion, which might be rare but still influential. For example, Wycoff and colleagues (2018) found that the association between heightened negative affect and subsequent marijuana use was most consistently found among clinical populations. Thus, it is possible that marijuana use is more likely at higher levels or more persistent negative affect than reported in this sample. However, previous research has found that clinical profiles characterized by high levels of negative affect like mood and anxiety disorders are not consistently related to marijuana use but may instead be associated with marijuana use problems in young adults (Buckner et al., 2007, 2008). The mechanisms by which daily or momentary affect might predict marijuana problems, but not use, are unclear. It is also noteworthy that relatively few studies of affective reinforcement have been conducted in clinical samples of individuals with cannabis use disorder, despite the centrality of substance use disorders to these models (e.g., Baker et al., 2004; Koob & Le Moal, 2008). Thus, it is an open question whether experiences of heightened negative affect more reliably lead to marijuana use in samples that experience severe withdrawal symptoms and whose use patterns may differ from that of college students and young adults (Sher et al., 2005).

Although motivational models do not explicitly predict positive affect to be elevated prior to substance use, we found robust evidence that experiencing higher levels positive affect was associated with marijuana use later that day. Some previous research suggests that positive affect might be a particularly strong motivator for marijuana use in college students, as odds of using marijuana were elevated on days characterized by higher positive affect in a recent college sample (Sznitman et al., 2022) but not in other samples of adolescents and young adults (Patrick et al., 2016; Shrier et al., 2014; Testa et al., 2019). These results also mirror those found in the literature on alcohol use in everyday life. A recent large-scale meta-analysis (Dora et al., 2022) of this literature, which included a large number of college student samples, found that people were more likely to drink on days that they reported higher positive affect (the daily association between negative affect and alcohol use, on the other hand, was estimated to be close to zero). As such, we are inclined to interpret this result as another piece of evidence that, specifically in college student samples (Dora et al., 2022; Wycoff et al., 2018), people's substance use (alcohol and marijuana) tends to be preceded by positive (rather than negative) emotional experiences. Our specification curve analysis shows further that the discrete emotions one assesses might matter also when it comes to positive affect (we found no effects for *friendly* and *engaged*). However, exactly why this is the case is yet unknown. It could be that positive affect itself causes people to decide to use or put themselves in situations where they are more likely to use marijuana. It could also be that positive affect actually rises in *anticipation* of marijuana use, once the decision to use has been made. One way to get at this question in future work is to model the intention and willingness to use throughout the day in parallel to reports of positive affect and marijuana use (Gerrard et al., 2008). Given the relative consistency of findings for positive affect, coupled with a general recognition that positive affect is an important motivator of substance use, it is somewhat surprising that existing affect regulation models have not explicated the role of positive affect prior to use. Models of substance use, especially those focused on understanding use in young adults and individuals not experiencing significant use-related problems, should more clearly incorporate positive affect prior to use. Thus, future research should also more comprehensively assesses dimensions of positive affect to elucidate which specific emotional experiences may and may not motivate people to consume marijuana, and to understand the contextual and cognitive factors that may help explain this association further.

Marijuana use predicting next-day affect

Across our entire range of model specifications, our analyses revealed that on mornings and days following marijuana use, people reported neither increased nor decreased positive and negative emotions. From this we learn two things. First, that we should not expect to find affective withdrawal effects in college student samples without any inclusion criteria that relate to heavy use or physiological dependence. This stands in contrast with findings on next-day negative affect following alcohol use (Armeli et al., 2014; Hussong et al., 2001). Given that theoretical models surrounding affect and substance use do not make differential predictions for alcohol and marijuana use, we would like to see a similarly exhaustive analysis as presented here to understand the robustness of alcohol use being associated with increased next-day sadness and anxiety. Our specification curves showed that this null result for marijuana was robust across a range of design choices and modeling decisions. Second, these robust null results suggest that clinical models of withdrawal, which specify increased negative affect as a core component, may be less applicable to community/college samples, even among those who regularly use marijuana. This is in line with the results of one recent high-powered study (Testa et al., 2019). Future research should seek to model the development of withdrawal as consequence of and motivation for marijuana use episodes, and to identify at which stage of the transition from regular use to dependence this association (may) appear. It is also important to note that our findings cannot speak to whether marijuana use has short-term effects on negative and positive affect, because the vast majority of marijuana use episodes occurred in the evening, which was also the last assessment of the day. The evidence for this association is similarly mixed (Ansell et al., 2015; Buckner et al., 2013, 2015; Testa et al., 2019; Trull et al., 2016), and future research should test the robustness of momentary associations between marijuana use and subsequent affect within hours using a similar approach as demonstrated here.

Limitations and conclusion

It is important to point out that our analyses are limited to the specifications inherent to this study. While we found no differences in the conclusions we draw from our study as we change the inclusion criterion relating to use frequency (and the inclusion criteria we were able to specify were limited to the available data), it is possible that other inclusion criteria might make a difference. For example, college students who use marijuana (almost) daily might share characteristics with clinical populations, for whom the evidence for affective reinforcement of marijuana is slightly stronger (Wycoff et al., 2018). Indeed, epidemiological evidence suggests that 46 - 52% of young adults (ages 18 – 23) who used marijuana at least 6 times in the past year (less stringent than our inclusion criteria) met criteria for past year marijuana use disorder (SAMSHA 2020). We also cannot generalize from this sample of college students to community and clinical populations. This means that our analyses do not inform theoretical models which predict negative affect to motivate substance use only in people with severe symptoms of dependence (e.g., Baker et al., 2004; Koob & Le Moal, 2008). Similarly, results for general negative and positive affect might have differed had we assessed different or additional emotion items. We also were not able to assess subtypes of negative and positive affect with multi-item scales. We assessed marijuana used retrospectively, with participants reporting whether, and when, they had used the day before. Findings may also have differed with a larger number of assessments per day. Thus, participants may have had reduced accuracy, especially for the time they started use. Perhaps most importantly, we explored the effect of different specifications in the same sample, which limits the generalizability of our specification curve results. Ideally, a future study would perform an analysis similar to ours in a meta-analytic dataset, so that sampling variability can be accounted for. As such, we consider our results fully exploratory and in need of (extended) replication. Despite these limitations, we believe this study advances the EMA literature on affect and marijuana use by highlighting to what extent associations between affect and marijuana use are robust to some, but not all, choices that EMA researchers make when they design and analyze their studies. Given the mixed effects reported in the literature, our study also convincingly shows that college students' marijuana use may be motivated by positive rather than negative affect.

Data Availability

The de-identified data, analysis code, and supplemental material for this paper are available online as at https://osf.io/tds7h/.

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