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Point process analyses of variations in smoking rate by setting, mood, gender, and dependence

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Abstract

The immediate emotional and situational antecedents of ad libitum smoking are still not well understood. We re-analyzed data from Ecological Momentary Assessment using novel point-process analyses, to assess how craving, mood, and social setting influence smoking rate, as well as assessing the moderating effects of gender and nicotine dependence. 304 smokers recorded craving, mood, and social setting using electronic diaries when smoking and at random nonsmoking times over 16 days of smoking. Point-process analysis, which makes use of the known random sampling scheme for momentary variables, examined main effects of setting and interactions with gender and dependence. Increased craving was associated with higher rates of smoking, particularly among women. Negative affect was not associated with smoking rate, even in interaction with arousal, but restlessness was associated with substantially higher smoking rates. Women's smoking tended to be less affected by negative affect. Nicotine dependence had little moderating effect on situational influences. Smoking rates were higher when smokers were alone or with others smoking, and smoking restrictions reduced smoking rates. However, the presence of others smoking undermined the effects of restrictions. The more sensitive point-process analyses confirmed earlier findings, including the surprising conclusion that negative affect by itself was not related to smoking rates. Contrary to hypothesis, men's and not women's smoking was influenced by negative affect. Both smoking restrictions and the presence of others who are not smoking suppress smoking, but others' smoking undermines the effects of restrictions. Point-process analyses of EMA data can bring out even small influences on smoking rate.

Keywords

Smoking; craving; mood; EMA; smoking restrictions; gender differences; nicotine dependence

Introduction

Smoking is thought to be largely driven by smokers' needs to maintain nicotine levels (Shadel, Shiffman, Niaura, Nichter, & Abrams, 2000). Within this broad motivational

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framework, smoking of particular cigarettes is thought to be cued or suppressed by immediate situational factors. In a previous paper (Shiffman et al., 2002), we analyzed the immediate antecedents of smoking among 304 smokers who were studied for two weeks using ecological momentary assessment (EMA; Shiffman, Stone, & Hufford, 2008; Stone & Shiffman, 1994) data collected in real time via palmtop computers. In this paper, we revisit those situational associations of smoking using a new statistical analysis that produces more accurate results (Rathbun, 2007), and extend the prior main-effects analyses to address how interactions and individual differences – in particular, gender and dependence – moderate situational influences.

Both theory and global reports emphasize the link between smoking and negative affect (Gilbert, Sharpe, Ramanaiah, Detwiler, & Anderson, 2000; M. A. H. Russell, Peto, & Patel, 1974). However, our previous analyses showed no relationship between smoking and mood. Further, though some EMA studies (Shapiro et al., 2002; Todd, 2004, Beckham et al, 2008) found mixed patterns of association between mood and smoking, two other EMA studies replicated the null effect (Shiffman, Paty, et al., 2004; Carter et al, 2008). However, these analyses did not take into account the interaction between negative affect and arousal, which the circumplex model of affect posits is essential in defining emotions (J. Russell, 1980). For example, anger consists of negative mood along with high arousal, whereas sadness consists of negative mood along with low arousal. Thus, we extend our previous analyses to consider not just negative affect but its interactions with arousal.

We also assess whether the association of negative affect with smoking differs by gender or dependence. Women are more likely to report that they smoke when upset, and smoke to relieve emotional distress (Fidler & West, 2009; Zvolensky et al., 2006; though see Todd, 2004). Thus, we hypothesized a stronger association with negative affect among women smokers. We also expected the association to vary with degree of dependence. The link between smoking and mood is thought to be rooted in the experience of withdrawal-related negative affect (Parrott, 1999), and thus should be stronger among more-dependent smokers.

Smoking is also affected by external stimuli. In prior EMA analyses, being around others smoking was related both to both ad lib smoking (Shiffman et al., 2002) and relapse (Shiffman et al., 1996; Ferguson & Shiffman, 2010). However, such effects might be moderated by individual differences. Cues should have greater influence on less-dependent smokers, since their smoking is likely less driven by the ebb and flow of nicotine levels, and more by external cues (Shiffman & Paty, 2006). Cues are also expected to have a greater influence among women, as it has been posited that women's smoking is more driven by cues than by the need for nicotine (Perkins et al., 1995).

External social influences can also suppress smoking. Situational smoking restrictions are pervasive, and we and others have shown that they can suppress smoking (Chandra et al., 2007; Fichtenberg & Glantz, 2002; Gallus et al., 2006; Shiffman et al., 2002; Shiffman, Paty et al., 2004). Here, we consider how the effect of smoking restrictions might be undermined if others are flouting the restrictions and smoking in no-smoking areas. The effect of smoking restrictions was also expected to be diminished among more-dependent smokers, who may be less able to bring their smoking into conformity with such social rules. (Indeed, one item on the Fagerstrom Test of Nicotine Dependence assesses smokers' ability to do so; Heatherton, Kozlowski, Frecker, & Fagerstrom, 1986.) We also considered moderation by gender, as there is some evidence that women are generally more responsive to social rules and contingencies (Reiss & Mitra, 1998).

While it may seem obvious that smoking would be related to craving, this relationship has been controversial (Tiffany, 1990). In previous analyses of EMA data (Shiffman et al., 2002;

Shiffman, Paty et al., 2004), craving was strongly related to smoking, via a curvilinear function. This relationship should be moderated by nicotine dependence: Since craving is often regarded as a central expression of dependence, it might be expected to play a greater role in the smoking of more-dependent smokers. Conversely, though, some analyses (Shiffman, Waters, & Hickcox, 2004) suggest that highly-dependent smokers' craving is more chronically elevated, perhaps weakening its association with smoking. The influence of craving may also be moderated by gender, as it has been proposed that women's smoking is less tied to nicotine dependence (Perkins et al., 1995).

Accordingly, in this paper, we use EMA data to assess how mood, others smoking, smoking restrictions, and craving are associated with smoking, and how gender and dependence moderate these influences. In our analysis of EMA data, we extend current statistical approaches, which typically use multilevel models and generalized estimating equations (GEE; Walls et al, 2006), to use newly developed applications of point process models (Rathbun, Shiffman, & Gwaltney, 2006; Rathbun et al., 2007). In our previous analyses of these EMA data (Shiffman et al. 2002) we used GEE to fit logistic regression models that contrasted smoking and non-smoking moments. However, this approach did not take into account the specifics of the EMA design, such as the timing and sampling of smoking and non-smoking occasions. The temporal point process models used here take into account the specific design: e.g., the variation in the sampling of smoking occasions, based on the prior day' smoking rate, and the variation in the amount of time that each subject was available for observation, as determined by waking time, and by time outs due to instrument failures or to subjects' use of discretionary features such as suspension of prompting (see Shiffman et al, 2002). Failure to take these factors into account can bias parameter estimates and their standard errors, resulting in both false positive and false negative errors in hypotheses tests (Rathbun et al., 2005; Rathbun et al., 2007). The methods used in prior analyses weigh all assessments equally, despite the variation across days and subjects in the cigarette assessment probabilities and random assessment intervals. In particular, in this design, different cigarette assessments represent different numbers of cigarettes, based on the assigned probability of assessment, which is itself a function of the smoking rate, ans may be related to the covariates (e.g., craving). As a result, traditional methods may yield biased estimates of model parameters. Similar arguments can be made for assessment times. Point process models also improve over prior models by directly modeling smoking rate (expressed as cigarettes per hour - cph) at any given point of time as a function of momentary covariates such as mood and social settings. Thus, the present paper revisits key main effects using a statistically more robust model, and extends prior analyses to consider interactions among situational factors, as well as interactions with gender and dependence.

Methods

Participants

Participants were 304 smokers who enrolled in a smoking cessation research study. These are the same participants and dataset that was reported in Shiffman et al. (2002). Participants were recruited via advertisements for smoking cessation treatment, and paid $50 for participating. To be included in the study, participants had to smoke at least 10 cigarettes per day, to have been smoking for at least 2 years, and to report high motivation and overall efficacy to quit during a screening interview (combined score of 150 on the sum of two 0-100 scales).

By questionnaire, participants reported averaging 27.6±11.9 cigarettes per day, smoking their first cigarette of the day 16.1±25.6 minutes after waking, and having smoked for 23.1±9.8 years. Participants averaged 44.1±10 years and were mostly female (57%) and Caucasian (93%).

Procedure

The methods have been described in detail in Shiffman et al. (2002). After completing informed consent, participants completed questionnaires that included the Nicotine Dependence Syndrome Scale (NDSS; Shiffman, Waters et al., 2004) and the Fagerstrom Tolerance Questionnaire, including an item reporting how soon after smoking the participants smoked their first cigarette of the day. Smoking within 30 minutes of waking has been regarded as one of the best indicators of dependence (Baker et al., 1987).

Participants were then trained to use a hand-held computer designed to support EMA (Shiffman et al., 2008; Stone & Shiffman, 1994); that is, data collection in near real-time. The Electronic Diary (ED; see Shiffman et al., 1996) was used to monitor ad-lib smoking for 16 days prior to a designated quit date, during which time participants were instructed not to change their smoking. The first 3 days of monitoring were designed to allow the participant to become familiar with the ED; data from these days were not used in analysis. We used data from the 13 days after this period, leading up to the quit date (days 4-16).

Participants were instructed to record each cigarette on the ED, immediately before smoking. On most of these occasions, ED simply recorded the smoking event. On about 4-5 smoking occasions per day (M=4.4, SD=2.6), selected at random by ED, ED administered an assessment. To allow for assessment of a constant number of cigarettes, even if a participant's smoking rate drifted, the probability of a cigarette being assessed was adjusted based on the previous day's cigarette consumption to target an expected 5 cigarette assessments.

Participants were also prompted audibly by the ED 4-5 times daily (M=4.8, SD=2.3) to complete a similar assessment while they were *not* smoking (Non-Smoking assessments). The timing of the prompts was random, with the constraint that no prompts were issued for 10 minutes after a cigarette entry. Prompting covered all waking hours. However, subjects put ED to sleep when they slept, and could also suspend promoting for naps, or brief periods when they could not be prompted. Prompts were sometimes absent due to software and hardware failures.

Compliance was very high, with participants responding to random prompts within the 2 minutes allowed 91% of the time. Participants only suspended prompting an average of once every 2.5 days, for an average of 24.2 minutes per day, and used a nap feature once every 5 days, for a daily average duration of 18.4 minutes. ED cigarette entries were correlated with concentrations of cotinine (nicotine's major metabolite) and recent entries were correlated with carbon monoxide concentrations, indicating timely recording of cigarettes (Shiffman, 2009). There was evidence of possible reactivity: daily smoking frequency dropped an average of 0.30 cigarettes per day over the study period ($p<.0001$).

Momentary Assessments

Cigarette and Non-Smoking assessments incorporated identical assessments of situation, activity, and mood. Participants reported whether smoking was permitted (forbidden, discouraged, allowed), whether they were with others (yes/no), and whether others were smoking in view of the participant (yes/no). Participants rated smoking “urge” on a 0-to-10 scale.

Participants reported their emotional state by rating mood adjectives derived from the circumplex model of affect (Larsen & Diener, 1992; J. Russell, 1980) which specifies that affect consists of two bi-polar dimensions: positive-negative affect and arousal. These items were scored on a 4-point scale (“NO!!, no??, yes??, YES!!”; see Meddis, 1972). We also included bipolar affect and arousal items to directly tap these key circumplex dimensions, as

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well as affect items drawn from the DSM-IV (American Psychiatric Association, 1994) criteria for tobacco withdrawal. Factor analyses of the mood data yielded three orthogonal factors (Shiffman et al., 1996): Negative Affect (alpha=.87), a bipolar valence factor, such that high scores indicate affective distress, while low scores indicate positive affect; Arousal (alpha=.79) also bipolar. These two factor comprise the dimensions of emotion according to the circumplex model, which posits that specific feelings represent combinations of these two dimensions. We also assessed Attention Disturbance (alpha=.64), or difficulty concentrating. We scored these as factor scores, which are normal deviates with mean 0 and SD of 1.

Data Reduction and Analysis

Complete data on gender, the Nicotine Dependent Syndrome Scale (NDSS), and Time to First Cigarette (TTFC) were available for 283 of the 304 subjects. EMA data on Others Smoking and Allowed were available for only 239 participants, because a subset of participants had been randomly assigned to a reduced-assessment group that did not rate these variables.

The outcome of interest is the point pattern comprised of the times at which cigarettes were smoked by the participants. The data were analyzed using point process analysis; see Rathbun et al. (2006) for a review of point process models for repeated behavioral events. The times at which cigarettes are smoked are treated as the realization of a point process model, a random mechanism for generating the time of events (e.g., cigarettes) in a study interval (Diggle, 2003). Point process modeling focuses on estimation of the intensity function $\lambda(t)$, a function of time t that describes the rate at which cigarettes are smoked expressed, for example, in units of numbers of cigarettes smoked per hour. The intensity function gives an instantaneous rate analogous to the current speed of an automobile as indicated on the odometer. The intensity is closely related to the hazard function used in survival analysis. Whereas the hazard is a function of the time since the last smoking event, the intensity is a function of time on a clock or calendar.

To ensure that the fitted intensity is positive, we assume a log-linear model for the intensity $\log\lambda_i(t;\beta)=\beta_0+\beta_1 x_{i1}(t)+\beta_2 x_{i2}(t)+\cdots+\beta_p x_{ip}(t)$, where $x_{i1}(t),x_{i2}(t),\cdots,x_{ip}(t)$ are covariates, and $\beta_0,\beta_1,\beta_2,\cdots,\beta_p$ are model parameters. Both momentary and subject-level covariates may be included in the model. Momentary covariates include measures of emotional state (e.g., negative affect, restlessness, etc.), and environmental variables (e.g., indicators of whether the smoker is alone, with other smokers, etc.). Subject-level covariates included gender, baseline score on the NDSS and reported time to first cigarette (TTFC). Parameters have the same interpretation as the parameters of a Cox-proportional hazards function in survival analysis. Holding all other covariates constant, for every unit increase in the ith covariate, the risk of smoking increases by a factor $\exp\{\beta_i\}$, also called the risk ratio. Model parameters were estimated using the method described in Rathbun et al., (2006); see also Rathbun et al. (2007) for the theoretical justification. Our methods of computing standard errors of parameter estimates do not take into account random variation among smokers in baseline smoking rates. Random effects versions of our models are being developed and preliminary investigations suggests that including random effects does not change parameter estimates, but increase standard errors, suggestion some caution in interpreting p-values from our fixed-effect analyses.

The models estimated the main effects of situational variables (urge, affect, restlessness, arousal, social setting), and posited interactions among them, and also examined the interactions of these situational variables with individual differences by gender and by nicotine dependence (NDSS-T, time to first cigarette [TTFC]). We report hazard ratios, which indicate the estimated change in smoking rate (cph) for each 1-point increase in the predictor, and their 95% confidence intervals, which include 1.0 when the effect is not significant at the α=0.05 level. Because many effects were tested and the analysis has the sensitivity to detect extremely small effects, we interpreted as significant only those effects that reached $p<0.01$, rather than $p<0.05$.

Results

Descriptive Statistics

Table 1 shows the means for subject-level variables. The mean smoking rate was 1.38 cigarettes per hour (cph). The mean NDSS-T score was close to zero, with women having slightly higher means than the men. On average women took slightly longer to smoke their first cigarette, and smoked fewer cph. Table 2 shows the mean values of the momentary variables at the random and cigarette assessments. As expected from these standardized scores, the means for the factors Negative Affect, Arousal, and Attention were close to zero.

Table 3 presents the correlations among the momentary covariates for the random assessments. Since there was a very large number of random assessments (16,231), even the weakest correlations among the momentary variables departed significantly from zero. Correlations (not shown) between the subject-level covariates and the time-averages of the momentary covariates were weak, all below 0.15, with the exception that NDSS-T correlated with craving at $r=0.27$ ($p<0.05$).

Momentary Covariates

Table 4 shows the main effects of situational variables on smoking rate. Urge intensity had the strongest association with smoking rate. For every 1-point increase in rated urge (on a 0-10 scale), the smoking rate increased by 25%. However, the relationship between smoking rate and urge also includes a quadratic component that allows for curvature in the association ($z = 24.66$; $p < 0.001$). As depicted in Figure 1, the smoking rate under the fitted model increases to a peak of 2.54 cigs/hr when urge is 9.55.

Neither NA nor Arousal had main effects on the smoking rate. There was a trend for NA and Arousal to interact, such that smoking rate increased with NA when participants were in low-arousal states, but decreased with NA when participants were more aroused. In contrast to NA, restlessness was associated with increased smoking, such that the smoking rate rose 16% (95 % CI: 13-19%) for every 1-point increase in restlessness (assessed on a 4-point scale). This effect was similar (20%, CI: 17-24%) when restlessness was adjusted for NA. Moreover, there was an interaction between NA and restlessness (Figure 2), such that increased restlessness slightly increased smoking in positive affect states, but more dramatically increased smoking in negative affect states. Smoking rate increased slightly when participants were experiencing difficulty concentrating, as indicated by rising Attention Disturbance scores: each 1-point increase was associated with a 3% increase in smoking rate.

Social setting and regulations had substantial impact on smoking rate. The presence of others smoking increased smoking rates by 84%. Participants smoked an estimated 2.15 cph when others were smoking, but only 1.17 cph when no one was smoking. Smoking rate varied substantially with smoking regulations. When smoking was discouraged (vs allowed) smoking rate decreased by 39%. When smoking was actually forbidden, smoking rate dropped a further 57%. Cigarette smoking rates were estimated to be 0.44, 1.02, and 1.67 cph when smoking was prohibited, discouraged, and allowed, respectively. Thus, smoking rate decreased almost 75% from allowed to forbidden situations. Being alone was associated with a 30% increase in smoking rate (compared to being with others). Participants smoked an estimated 1.44 cph when alone, compared to a rate of 1.11 cph when with others.

A significant interaction was observed between being alone and others smoking (Figure 3a; $z = 4.25$; $p < 0.001$). (Participants could have been alone in the presence of others smoking if, for example, they are dining alone in a restaurant where smoking was occurring.) When others were smoking, being alone had little impact on smoking rate. However, when no one was smoking, smoking rate was 50% lower when participants were with others.

Substantial interactions were also observed between smoking regulations and the social settings factors others smoking ($p = 0.002$) and Alone ($p = 0.004$). Regardless of smoking regulations, smoking rates were higher when others were smoking (Figure 3b). However, the effect of others smoking was weaker when smoking was discouraged than when it was either prohibited or allowed. The effect of being alone also depended on smoking regulations (Figure 3c). When smoking was either allowed or prohibited, being alone had little impact on smoking rate, but when smoking was discouraged, smoking rate was 30% higher when the participant was alone than when with others.

Individual differences & moderating effects on momentary covariates

As expected, men smoked at higher rates (1.29 cph, CI: 1.26-1.33) than women (1.21 cph, CI: 1.18-1.24; HR = 0.93, $p < 0.001$). Smokers with TTFC<30 minutes also had higher smoking rates (HR = 1.40; p < 0.001), as did smokers with lower NDSS-T scores. Smoking rates decreased by 6% (CI: 5%-7%) for every ten minutes increase in TTFC, and by 0.3% (CI: 0.2%-0.3%) for every unit increase in NDSS-T. Table 4 gives the estimated hazard for the interactions between these subject-level characteristics and momentary covariates.

Gender—Smoking rate increased with increasing urge for both genders, but more steeply among women (HR = 1.27, CI: 1.25-1.29) than among men (HR = 1.22, CI: 1.20-1.24). However, as with the main effect, the relationship is better described by a quadratic model (Figure 1). Both genders show significant quadratic effects, but the curve for men shows more downward deflection at high levels of urge. As a result, when urge is low, men smoke more cigarettes than women, but when urge is high, women's smoking rate is higher than men's.

There were trends for NA and arousal to more substantially increase smoking among men, rather than women. Gender had no effect on the effects of restlessness, alone or in interaction with NA, or the effects of Attention Disturbance.

The largest moderating effect of gender was on the influence of prohibitions against smoking, which had a stronger effect on women (Figure 4). There was very little difference in smoking rates between genders when smoking was either discouraged or allowed. However, when smoking was prohibited, women's smoking rate dropped to 0.34 cph (CI: 0.31-0.37), whereas men's dropped only to 0.58 cph (CI: 0.53-0.63).

Dependence—The NDSS-T demonstrated several statistically significant interactions, but they were all very small. A 1-SD change in NDSS-T – a substantial variation – only changed the effect of the square of urge intensity on the smoking rate by 0.03%, moderated the effect of arousal by 0.1%, and moderated the influence of social setting (being alone or with others smoking) only by 0.4%.

The interactions involving TTFC were larger, and largely different from the NDSS interactions. TTFC moderated the association of smoking with urges, such that urges had a greater effect when TTFC was shorter (i.e., among more-dependent smokers). This was largely due to the fact that the smoking rate continued to rise with increasing urge intensity among the more dependent smokers, but dropped off among the less dependent, as reflected in an interaction with quadratic curvature. TTFC also moderated the association of smoking with NA, such that NA was associated with increased smoking to a greater degree among less dependent smokers. Similarly, the effect of restlessness (whether or not covaried for NA) on smoking was greatest among less-dependent smokers.

Discussion

In this paper, we used a recently-developed statistical approach to analysis of EMA data to address some of the immediate antecedents of smoking, and how such influences were moderated by individual differences, focusing on gender and dependence as potentially important moderators. The analysis estimates how covariates affect the rate of smoking, which we expressed as cigarettes per hour (cph).

One aim of this paper was to revisit analyses of associations between smoking and situational factors, using a more sophisticated analytic approach. By and large, the results using point process methods confirmed and replicated those obtained using GEE (Shiffman et al, 2000). A key exception was that attention disturbance, a symptom of withdrawal (American Psychological Association, 1994), was now found to be associated with increased smoking rate. The effect was modest in size – smoking rate increased by 3% for every 1-SD increase in attention disturbance – but nevertheless significant, suggesting that variation in sub-clinical withdrawal symptoms may play some role in smoking even during unrestricted ad lib smoking. Otherwise, the point-process results confirmed prior analyses, and extended them by providing interpretable metrics showing how much each situational factor influenced the hourly consumption of cigarettes. The analyses also extended prior work on main effects by examining hypothesized interactions.

Replicating previous analyses of this dataset by different methods (Shiffman et al., 2002), we found that the intensity of the urge to smoke had a powerful influence on smoking. The smoking rate grew from 0.15 cph when urge was rated as 0, to a peak of 2.5 cph at an urge rating of 8.6, increasing by 25% for every 1-point increase in urge intensity on our 0-10 point scale. Whereas a number of authors have questioned the relevance of craving to smoking (e.g., Tiffany, 1990), this reinforces the important relationship between urge intensity and smoking. The relationship between urge and smoking as curvilinear, leveling off once urge levels reached 8 on the 0-10 scale. This may be part of the reason that studies sometimes fail to observe the relationship: if smokers are studied under relatively high craving, further increases will seem to have little relation to smoking.

The point-process analyses confirmed our prior report of no direct link between negative affect and smoking, which had been replicated in other reports (Carter et al., 2008; Piasecki, Smith, & Baker, 1999; Shiffman et al, 2004). We extended those anlayses by examining the interaction between negative affect and arousal, which the circumplex model of affect (J. Russell, 1980) regards as key to characterizing emotions. There were no significant effects, and the estimated parameters suggest that even large changes in mood (1.2 SD on both valence and arousal, representing rare extremes on both dimensions) would change smoking rates by only about $1/10^{th}$ of a cigarette per hour. This further confirms the lack of mood effects during ad libitum smoking, for the average smoker.

Unlike negative affect or arousal, restlessness was related to smoking rate, increasing smoking rates by 20% for every 1-point increase on the 4-point scale, after accounting for NA Furthermore, the effect was enhanced as NA increased, suggesting complex interactions with emotional state that deserve exploration in future studies. Restlessness could reflect activation of appetitive “go” systems (Baker et al., 1987; Robinson & Berridge, 1993; see Shiffman et al., 2002) that may move the smoker towards smoking.

Point process analyses confirmed the large effects of social setting and smoking regulations on smoking (Shiffman et al., 2002; Shiffman, Paty et al., 2004). The presence of others, and the presence of others who were smoking, substantially influenced smoking rates. These variables interacted in complex ways. Being with others who are not smoking did not merely remove the stimulating effect of others' smoking – it suppressed smoking rates even below those observed when smoker were alone, to yield the lowest smoking rate we observed. The presence of others who are not smoking likely creates a local non-smoking norm that suppresses smoking, even if smoking is not explicitly forbidden by regulation. This may be an important way in which smoking prevalence and smoking norms influence smoking.

Formal and informal rules and regulations had large effects on smoking rates, but these, too, were subject to complex interactions. Smoking rates increasing almost 4-fold between smoking-prohibited and smoking-permitted contexts. When no one else was smoking, the influence of restrictions was very orderly, decreasing smoking rates from 1.6 cph when smoking was permitted to 1.0 cph when smoking was discouraged, and further to 0.4 cph when smoking was prohibited. However, when others were smoking, this not only increased smoking rates under each level of restriction, but particularly undermined the effect of strict prohibition, making it only equivalent to mere discouragement of smoking. When others smoke in a no-smoking area, its effect is softened to that of mere discouragement of smoking. This suggests that the influence of regulations is moderated by noncompliance with the regulations, which can create a less-prohibitive local norm, as well as the formal regulations themselves.

In addition to examining interactions among situational variables, we examined how such influences interacted with gender and dependence. Regulations had a greater effect on women's smoking than on men's; specifically, women were more responsive to prohibitions. Women may simply be more law-abiding or more sensitive to social norms (Bennett, Farrington, & Huesmann, 2005). Other interactions between momentary covariates and gender suggested that smoking dynamics were substantially different for men and women. Both men and women showed an overall relationship between urge and smoking rate over the low to moderate range of urge intensity. However, as urge intensity rose to peak levels ($\geq$8 on the 0-10 scale) women's smoking rate continued to rise, whereas men's smoking rates leveled off. Women appear to be more sensitive to high intensity urges. It is not clear why this should be so.

Based on smokers' self-reports, where women are more likely to report smoking under stress (Fidler & West, 2009; McEwen, West, & McRobbie, 2008), we expected negative affect and/or arousal to have a greater effect on women. However, although the effect was not quite significant, the trends were consistently in the opposite direction, with men tending to show greater mood effects. These findings are consistent with other EMA data reported by Todd (2004) and Delfino et al. (2001). Thus, the data contradict the impression from smokers' questionnaire reports, emphasizing that smokers' global reports of smoking patterns may be unreliable and invalid (Shiffman, 1993).

Variations in nicotine dependence are often used to explain smoking and smoking patterns, and dependence was expected to moderate the effect of situational influences on smoking. However, the observed effects of dependence were very, very modest. NDSS showed only a few reliable interactions, and these were very small in magnitude. TTFC, which is regarded as a powerful indicator of dependence (Baker et al., 2007), showed more influence in moderating the effect of situational variables, but its effects were still small (changing the effect of situational variables by 1-3% for every 10-minute change in TTFC). Nevertheless, some of the findings on TTFC shed light on the workings of dependence in everyday smoking, cigarette-by-cigarette and hour-by-hour. More-dependent smokers' smoking rates were more influenced by urge levels, consistent with the role that craving is expected to play in dependent smoking. However, other influences of dependence were contrary to the expected effects of dependence. For example, one would expect that more-dependent smokers' smoking rates should be more influenced by negative affect and restlessness, as the dependent smoker experiences sub-clinical variations in nicotine withdrawal that may cue the lighting of the next cigarette (Shadel et al., 2000; Parrott, 1999). However, the opposite was true: more dependent smokers' smoking rates were slightly *less* influenced by negative affect and restlessness. TTFC seems to be a measure of smokers' urgency to smoke when deprived, but the role of affect and withdrawal symptoms in driving ad lib smoking has yet to be established.

Other hypotheses about how the influence of situational factors would differ by level of dependence were also not supported. We hypothesized that dependence would moderate the effect of smoking regulations, because highly dependent smokers would be more likely to violate restrictions, due to their more compelling need to smoke (Heatherton, Kozlowski, Frecker, & Fagerstrom, 1986). This was not observed: regulations had similar effects across the range of dependence in this sample. This is important for policy, as it implies that smoking restrictions influence the most dependent smokers, not just the less dependent smokers. We also expected the smoking rate of more dependent smokers to be less influenced by the presence of others, since their smoking was expected to be driven by internal pharmacological needs. In fact, although the effects were small, smokers with higher NDSS-T scores were slightly <u>more</u> influenced by being alone or being where others were smoking. Whereas one model of dependence holds that dependence makes smoking more independent of setting factors (Shiffman & Paty, 2006), others have suggested that sensitivity to setting and cues can be considered part of a dependence syndrome (Piper et al., 2004). These analyses do not support the concept that dependence is associated with an independence from situational influences on use.

Some of the effects reported here, especially the interaction effects, though statistically significant (i.e., certain) were very, very small. For example, a 1 SD increase in attention disturbance increased smoking rate by 3% (at the mean smoking rate, an increment of 0.04 cph, from 1.37 cph to 1.41 cph). It seems questionable whether these effects would be practically meaningful or discernable to the smoker, though it is possible that such small effects, playing out over a long period (e.g., there are >5,800 waking hours in a year, and smokers like those in this sample smoke over 8,000 cigarettes in a year) might have some effects, even if not consciously discernable. In any case, the ability of the analysis to detect even such miniscule effects speaks to the power of the analysis, given the very large sample of observations (16,231 random and 14,305 cigarette assessments) and the sensitive design and analytic methods.

This study had certain limitations. In our analysis, subjects were treated as fixed effects, i.e., assuming that the relationships assessed were similar across subjects. Random-effects models for point-process analyses are being developed that may better shed light on individual differences. Whereas the fixed effects reported here assume that all smokers behave similarly, and analyze mean relationships, random effect analyses recognize that situational factors may influence different smokers differently, and may be better suited to understanding variations among smokers. The sample consisted of heavy smokers seeking behavioral treatment, and is thus not representative of all smokers. Reports of the situations and moods associated with smoking were made at the time a cigarette was smoked, and are thus not truly prospective, and could have been affected by the subjects' awareness that they were starting to smoke.

Conversely, the study had a number of strengths, notably the large sample of assessments that were collected in real time in real-world settings, using palmtop computers and EMA methodology. Furthermore, the a priori sampling design for both random assessments and for cigarettes to be assessed allowed the point-process analysis to take these factors into account to yield efficient and unbiased estimates of the effects. The point-process analysis also yielded estimates that were substantively interpretable as an hourly smoking rate under conditions specified by the covariates. The analysis also considered – and was powerful enough to identify – subtle interactions among situational parameters, and between situational parameters and subject characteristics.

In summary, these analyses confirmed that negative affect by itself is not associated with smoking occasions, though restlessness was associated with smoking. Surprisingly, the analysis contradicted the expectation that women's smoking was more influenced by mood than men's. Conversely, though, women's smoking was more sharply influenced by craving. The analyses also showed gender interactions with smoking regulations, in which women were more sensitive to these setting variables. Dependence had little influence on the effect of situational factors. The analyses revealed important situational interactions between smoking regulations, social setting, and others’ smoking behavior, suggesting that all three factors must be considered jointly to understand their effects on smoking rate. Although the effects were small, they illustrate the ways in which smoking may be influenced by complex interactions among situational variables and smoker characteristics. This suggests that more complex models encompassing a variety of factors and their interactions may be needed to explain smoking behavior.

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Saul Shiffman is a co-founder and Chief Science Officer of invivodata, inc, which provides electronic diary services for clinical trials. Saul Shiffman also consults to GlaxoSmithKline exclusively regarding smoking cessation, and is a partner in a company developing a smoking cessation medication.

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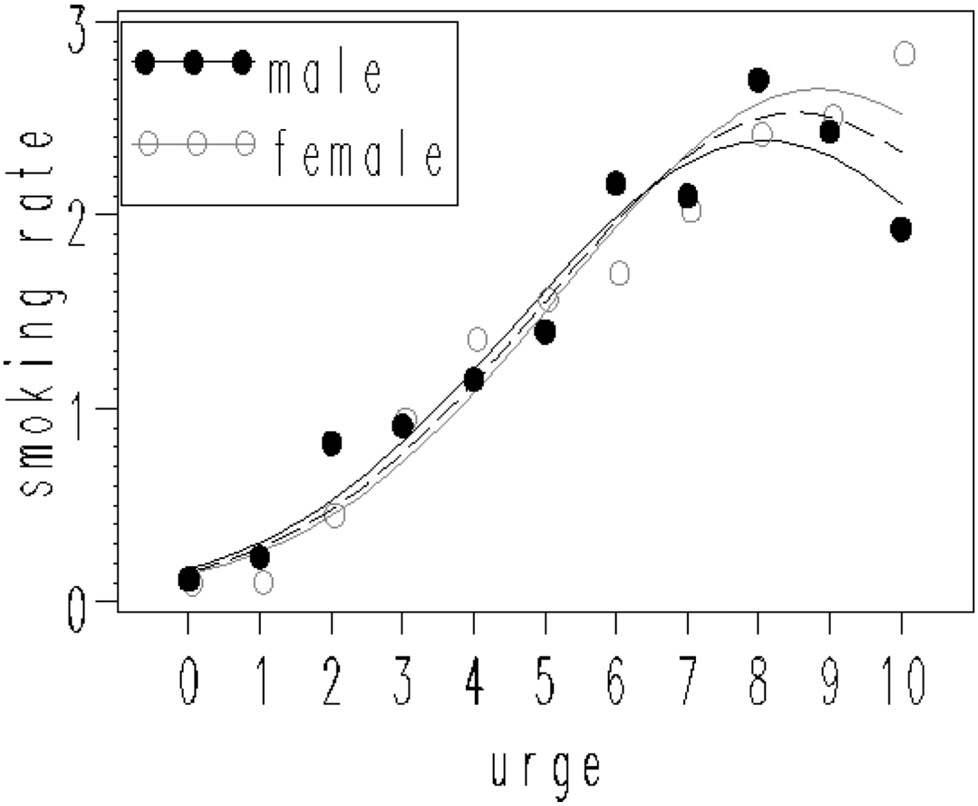

Figure 1.
Estimated smoking rate as a function of Urge to Smoke and Gender. The dashed line gives the average curve over all smokers.

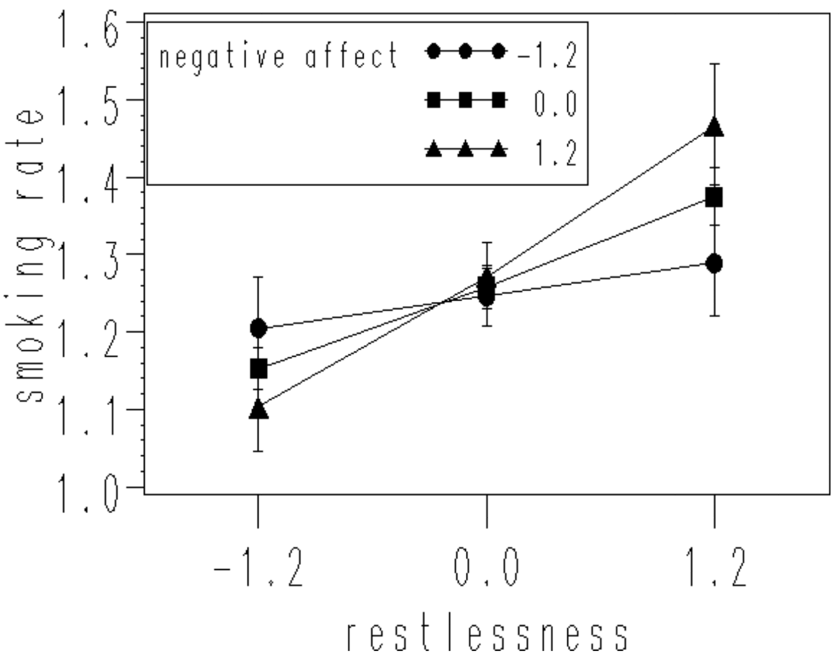

Figure 2.
Interaction between Negative Affect and Restlessness affecting smoking rate.


2.5
2.0
1.5
1.0
0.5
0.0
smoking_rate
no others smoking
others smoking
with others
alone

A

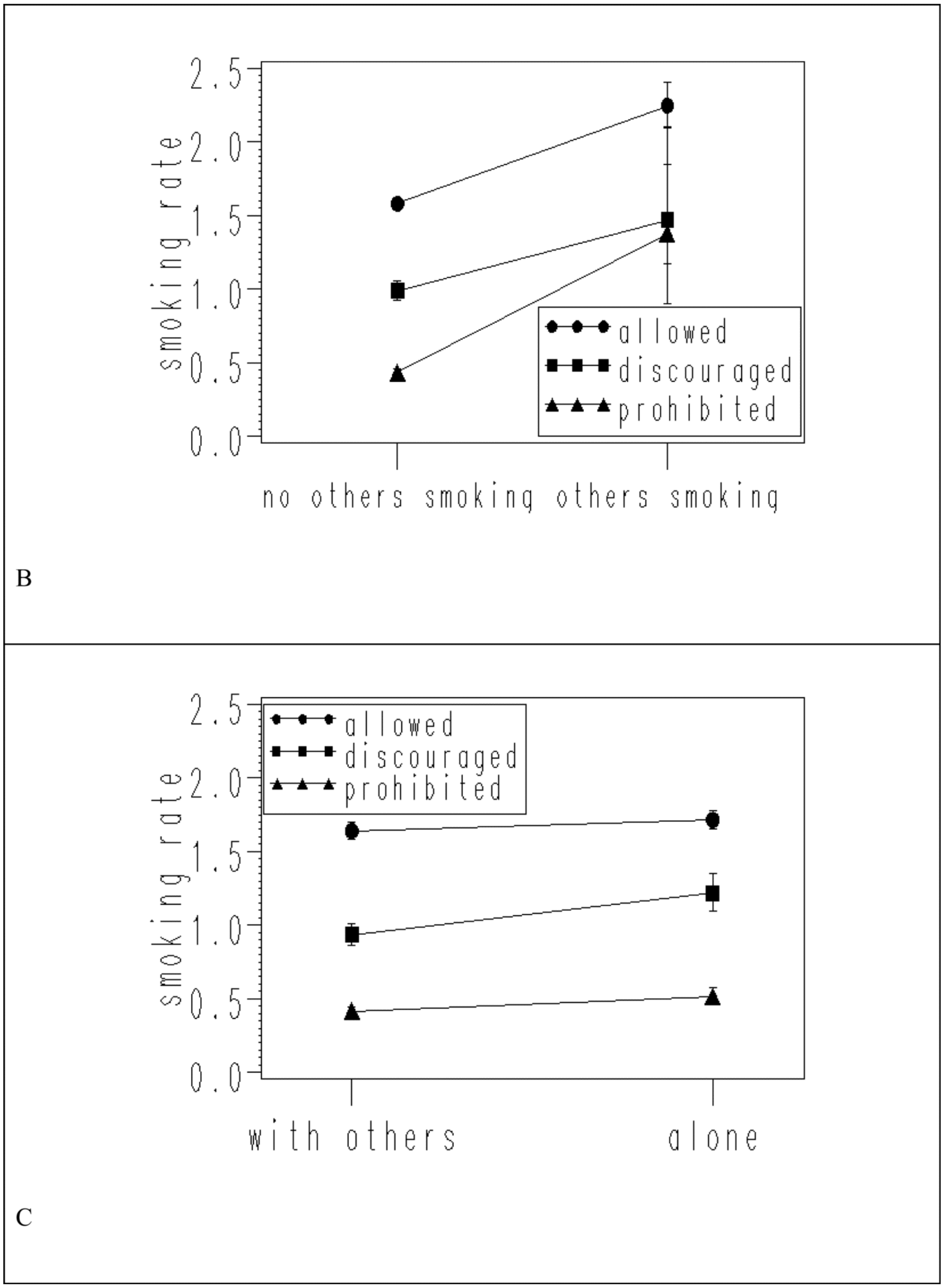

Figure 3.

Estimated smoking rate as a function of social settings. Panel A shows the interaction of Alone and Others Smoking. The standard errors for others smoking while alone is large because very few cases (n=270, less than 1%) reported this combination of factors. Panel B shows the interaction of Others Smoking and smoking Regulations. The standard errors for cases where others are smoking where smoking is either discouraged or prohibited are large because very few cases (n=135 and 48, respectively out of 12,936 assessed cigarettes) fell into these cells. Panel C shows the estimated smoking rate as a function of being Alone and Smoking Regulations. All three panels are scaled to represent a range of 2.0 cph on the Y axis.

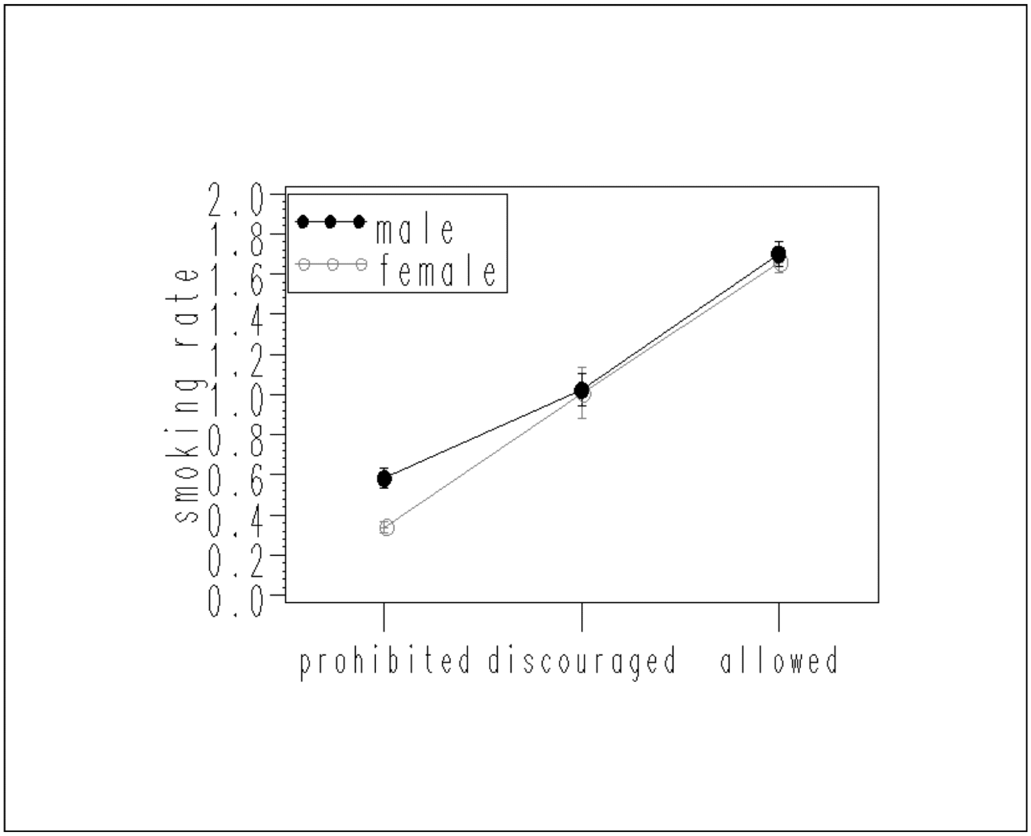

Figure 4.
Estimated smoking rate as a function of gender and Smoking Regulations. The graph is scaled to represent a range of 2.0 cph on the Y axis.

Table 1

Subject-level characteristics

	Gender		
Characteristic	**Male n = 119**	**Female n = 164**	**Total n = 283**
NDSS-T (z-score)	-0.010 (0.97) [-2.18, 2.11)	0.03 (1.00) [-2.36, 2.23]	-0.02 (1.00) [-2.36, .223]
Time to first cigarette (mins.)	16.20 (26.1) [1, 240]	17.0 (26.2) [1, 180]	16.6 (26.1) [1,240]
Hours monitored	188 (24) [105, 236]	186 (22) [102, 226]	187 (23) [102, 236]
Cigarettes per hour (cph)	1.44 (0.56) [0.32, 2.92]	1.33 (0.54) [0.44, 3.61]	1.38 (0.55) [0.32, 3.61]

Note. Mean (SD) [range]

Table 2

Momentary characteristics at random assessments and when cigarettes were being smoked

	Assessment type	
Covariate	**Random n = 16,231**	**Cigarettes n = 14,305**
Negative affect (z)	-0.088 (0.944) [-2.72, 4.45]	-0.082 (0.948) [-2.79, 4.28]
Arousal (z)	0.040 (0.980) [-2.96, 2.77]	0.030 (0.977) [-2.87, 2.97]
Attention (z)	-0.091 (0.878) [-2.22, 4.74]	-0.078 (0.891) [-2.22, 4.76]
Urge (0-10)	4.113 (3.113) [0, 10]	6.173 (2.439) [1, 10]
Restlessness (1-4)	1.502 (0.787) [1, 4]	1.595 (0.847) [1, 4]
Alone (Y/N)	38.7%	45.6%
Others smoking (Y/N)†	9.5%	16.2%
Smoking allowed (Y/N)†	59.20%	76.60%
Smoking discouraged (Y/N)†	13.6%	12.0%
Smoking prohibited (Y/N)†	27.2%	11.4%

Note. * Mean (SD) [range].

†14,707 random and 12,936 cigarette assessments were available for Others Smoking and smoking regulations.

Table 3

Correlations among the momentary covariates

	Arousal	**Attention**	**Restlessness**	**Urge**
Negative affect	0.05*	-0.07*	0.43*	0.13*
Arousal		-0.03*	-0.02*	0.04*
Attention			0.26*	0.09*
Restlessness				0.19*

Table 4

Effects of Individual Difference and Momentary Covariates on Smoking Rate

		Individual difference characteristics		
		Female gender	**NDSS-T (1 SD)**	**TTFC (10 mins)**
	Main effects of individual differences	0.934 (0.901, 0.969)***	0.997 (0.997, 0.998)***	0.940 (0.932, 0.948)***
Momentary variables	Main effects of momentary variables	Interactions of individual differences and momentary variables		
Urge (1 point, 0-10)	1.248 (1.235, 1.261)***	1.042 (1.020, 1.063)***	1.000 (1.000, 1.001)	0.992 (0.986, 0.996)**
Urge (quadratic effect)	0.962 (0.959, 0.965)***	1.003 (0.997, 1.009)	1.000 (1.000, 1.000)***	0.995 (0.993, 0.997)***
Negative affect (1 SD)	1.005 (0.983, 1.028)	0.950 (0.909, 0.994)’	1.001 (1.000 1.002)	1.012 (1.003, 1.021)*
Arousal (1 SD)	0.995 (0.973, 1.017)	0.945 (0.903, 0.989)’	0.999 (0.998, 1.000)*	0.998 (0.988, 1.007)
NA * arousal (1 SD)	0.977 (0.955, 0.999)’	1.052 (1.005, 1.102)’	1.001 (1.000, 1.002)	1.011 (1.001, 1.022)’
Restlessness (1 point, 1-4)	1.165 (1.135, 1.196)***	1.029 (0.976, 1.084)	1001 (0.999, 1.002)	1.029 (1.016, 1.043)***
Restlessness | NA (residual) (1 SD)	1.203 (1.168, 1.240)***	1.031 (0.978, 1.087)	1.001 (0.999, 1.002)	1.029 (1.016, 1.042)***
NA * restlessness | NA (residual) (1 SD)	1.038 (1.011, 1.067)*	1.003 (0.954, 1.054)	1.001 (0.999, 1.002)	0.986 (0.974, 0.999)’
Attention (1 SD)	1.032 (1.008, 1.056)’	0.994 (0.948, 1.042)	1.000 (0.999, 1.001)	0.997 (0.987, 1.007)
Alone (yes/no)	1.296 (1.238, 1.357)***	1.098 (1.001, 1.204)’	1.004 (1.002, 1.006)***	1.021 (1.001, 1.041)’
Others smoking (yes/no)	1.836 (1.713, 1.967)***	1.137 (0.990, 1.307)	1.004 (1.002, 1.007)**	1.010 (0.971, 1.050)
Prohibited vs. discouraged	0.431 (0.395, 0.471)***	0.578 (0.484, 0.691)***	1.077 (1.000, 1.014)	1.031 (0.991, 1.072)
Discouraged vs. allowed	0.611 (0.571, 0.654)***	1.029 (0.896, 1.181)	1.001 (0.996, 1.005)	1.001 (0.969, 1.035)

Note.

Entries are rate ratios and their 95% confidence intervals (when the confidence interval includes 1.0, the effect is not significant at the p<0.05 level). For main effects, the rate ratio is the ratio by which the hourly consumption of cigarettes is increased for every indicated change in the predictor. For interactions, it represents the ratio by which an increment in the individual difference variable (gender difference, 1 SD in NDSS, or 10 minutes in TTFC) moderates the effect of the momentary variable.

’ $p < 0.05$

* $p < 0.01$

** $p < 0.005$

*** $p < 0.001$