Examining the Interplay Between Physiological Arousal, Stress, and Alcohol Craving During Addiction Treatment: A Longitudinal Study

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Abstract

Objective: Alcohol Use Disorder (AUD) impacts health and well-being. Treatment success is influenced by multiple factors, with alcohol craving playing a critical role. Stress significantly influences craving, but relying solely on self-reports introduces biases, making physiological arousal measurements, such as heart rate, valuable. This study investigates the concurrent relationship between heart rate and self-reported stress levels and the predictive effect of heart rate on stress in individuals undergoing alcohol addiction treatment. Additionally, it explores the direct and predictive effects of stress and heart rate on alcohol cravings using ecological momentary assessment (EMA) to analyse within- and between-person effects. **Method:** Data for this study was obtained by van Lier et al. (2022). Data were collected from 10 individuals diagnosed with AUD during a 100-day treatment period. Participants received questionnaire prompts every three hours, eight times a day. Physiological arousal was measured using the E4 Empatica wristband. Data were analysed using multiple Linear Mixed Models and mediation analysis. **Results:** The findings revealed a significant positive relationship between heart rate and self-reported stress levels at the individual level. Heart rate did not significantly predict future stress levels. Both heart rate and stress were strongly associated with craving, primarily driven by within-person effects. Notably, both immediate and lagged stress levels were found to be a more robust predictor of craving compared to heart rate. Further analysis revealed that stress mediates the relationship between heart rate and craving, with the counterintuitive finding that higher heart rates predicted lower stress levels, predicting lower cravings.
Conclusion: This study emphasises stress's critical role in alcohol addiction. Despite limitations, such as low compliance rates, it underscores the importance of incorporating stress management into treatment and highlights the potential for individualised approaches. Using biofeedback techniques to monitor and manage stress and craving levels is suggested. Further research could yield valuable insights into the underlying mechanisms in more detail.

Keywords: Alcohol Craving, Stress, Heart Rate, Physiological Arousal, EMA

Examining the Interplay Between Physiological Arousal, Stress, and Alcohol Craving During Addiction Treatment: A Longitudinal Study

Alcohol use disorder (AUD) is ranked among the most prevalent mental disorders worldwide (Carvalho et al., 2019; Grant et al., 2015; Witkiewitz et al., 2019). AUD is characterised by a compulsive urge to consume alcohol in large quantities and a loss of control over alcohol intake (Carvalho et al., 2019; Connor et al., 2016). Beyond its direct health implications, AUD is associated with a spectrum of physical and psychological comorbidities, contributing to heightened mortality and widespread morbidity. The disorder extends its impact by diminishing productivity and straining interpersonal relationships, imposing considerable psychological and economic burdens on affected individuals and their families, friends and co-workers (Connor et al., 2016; Grant et al., 2015). Given AUD's prevalence and complex consequences, it is important to explore factors that contribute to its persistence and influence treatment efficacy (Schneekloth et al., 2012).

Among the critical factors studied in alcohol consumption, AUD, and alcohol addiction treatment, alcohol craving stands out (Leggio, 2009). Generally, craving can be defined as the urge or desire to consume substances (Flannery et al., 2001; Kavanagh et al., 2014; Leggio, 2009). Craving symptoms in individuals with AUD can vary widely, including not only obsessive thoughts and physiological arousal but also emotional distress, behavioural changes, such as social withdrawal or risk-taking behaviour, and physical discomfort (Bilevicius et al., 2020; Flannery et al., 2001; Kavanagh et al., 2014; Leggio, 2009). Craving episodes can last from a few minutes to several hours, whereby the duration and intensity are often influenced by the individual's history of alcohol use, such as the severity of their dependence or the length of their abstinence period (Anton, 1999; Serre et al., 2015). Typically, for most individuals, craving episodes tend to decrease over time with sustained abstinence and during progressing treatment (Schneekloth et al., 2012) but may also recur or persist, particularly in response to some environmental cues or stress (Heinz et al., 2009; Sinha et al., 2011b). To gain a better understanding of why cravings persist and the potential difficulties in overcoming them, it is essential to explore the underlying biopsychological mechanisms in craving experiences. Current theories suggest that craving may persist due to a complex interplay of neural adaptations, conditioned responses to alcohol, and subconscious processes (Flannery, 2006). Neural adaptations refer to changes in the brain rewards system, specifically in dopamine pathways, which can cause the brain to rely on alcohol for dopamine release and, therefore, pleasure, leading to persistent cravings even during abstinence (Koob & Volkow, 2010). Furthermore, conditioned responses occur when environmental cues, such as certain emotional states or specific places, become associated with alcohol use, which can then trigger cravings when the individual finds themselves in familiar contexts, sometimes even without conscious awareness, as part of the brain´s automatic processing. These subconscious processes can further complicate the control or prediction of craving episodes, posing another challenge on the path to abstinence (Flannery, 2006; Tiffany, 1999).

Serving both as precursors to and as a result of alcohol use, alcohol cravings represent a crucial challenge in addiction management, especially for those striving to stay abstinent (Lowman et al., 2000; Singleton & Gorelick, 1998). Research underscores the importance of addressing cravings, as higher levels of cravings are associated with increased risk of relapse post-treatment (Schneekloth et al., 2012). Therefore, analysing factors that may influence, announce or even predict its occurrence and persistence is essential for improving treatment outcomes and supporting long-term recovery.

One of the significant factors influencing alcohol cravings is stress. Research has extensively documented the strong connection between stress and alcohol craving, making it an essential area of focus in understanding alcohol use and relapse (Brady & Sonne, 1999; Higley et al., 2011). Stress is typically defined as the body's reaction to specific stimuli or events that an individual interprets as potentially harmful or distressful. Individuals respond differently to stressors, with those having problematic alcohol use often exhibiting heightened emotional reactions to stress and increased sensitivity to it (Brady & Sonne,1999; Chaplin et al., 2010; Sinha et al., 2009). Several explanations exist for this phenomenon. For instance, chronic alcohol consumption can lead to neuroadaptive changes in the brain, particularly in the systems regulating stress (Breese et al., 2011). These changes could increase the sensitivity of the brain´s stress pathways, heightening individuals' vulnerability to stress-induced cravings. Moreover, chronic alcohol use might dysregulate the hypothalamic-pituitary-adrenal (HPA) axis, a key mechanism in stress-response regulation, leading to an increased stress response that further intensifies alcohol cravings (Adinoff et al., 2005; Sinha et al., 2011a). Exemplary, a daily assessment approach used by Wemm et al. (2019), revealed a significant association between stress and alcohol craving, with higher stress levels corresponding to elevated craving levels and an increased risk of alcohol relapse. These findings are consistent with other studies that have reported a positive association between higher stress levels and increased alcohol craving (Sinha, 2008; Sinha et al., 2009; Wemm et al., 2022). The stress-craving relationship also extends beyond the alcohol addiction context, as demonstrated in studies by Fox et al. (2008) and Sinha et al. (1999), independently investigating the relationship between stress and craving in cocaine-dependent individuals. Study results indicate that heightened exposure to stress led to significant increases in cocaine craving.

To accurately study the impact of acute stress on craving, especially considering its transient nature, an Ecological Momentary Assessment (EMA) approach is essential. EMA is a distinctive research method that captures real-time data on individuals' behaviours, experiences, and physiological responses in daily life (Myin-Germeys et al., 2018; Piot et al., 2022; Shiffman et al., 2008). By allowing for real-time data collection, EMA effectively captures the immediacy and context of stress responses as they occur, providing a more reliable and nuanced understanding of stress and craving dynamics (Schiffman et al., 2008; Weber et al., 2022). This approach reduces retrospective bias often associated with self-reported measures and enables the collection of detailed information about specific variables over extended periods, offering insights into dynamic variations in different situations. Moreover, the wealth of collected data allows for flexible organisation and analysis, which can be tailored to the research aims and enable observing unexpected patterns (Schiffman, 2009).

Given the research context of individuals with Alcohol Use Disorder (AUD) during treatment, EMA´s ability to monitor behaviours in natural settings is particularly beneficial. This episodic nature demands a method that can capture immediate situational factors associated with drug/alcohol use, such as craving. Laboratory settings may fail to replicate the complexities of real-life addiction behaviours fully, where participants might feel hesitant to engage in socially unacceptable behaviours. Therefore, EMA addresses this limitation by studying these dynamics in their natural environments, making it a valuable approach for understanding addiction-related behaviours (Schiffman, 2009).

Furthermore, EMA approaches not only have the ability to capture real-time data on subjective experiences but also of physiological responses, making it a valuable tool in studying complex mechanisms such as stress and craving (Weber et al., 2022). This becomes particularly important when investigating stress. Despite promising findings linking heightened stress to increased craving levels in AUD patients, stress itself is a multifaceted construct that requires diverse measurement approaches (Weber et al., 2022). Therefore, physiological measures can provide objective data that can validate and increase the accuracy of self-reported stress levels. By offering direct insights into the body´s concrete stress responses, physiological measures are able to capture changes that might be outside the conscious awareness of the individual (Weber et al., 2022). This could be particularly helpful in cases where individuals are unwilling to acknowledge or are simply unaware of their increased stress levels. Therefore, incorporating subjective as well as objective data on stress allows for a deeper understanding of its potential impact on behaviour and variables such as craving (Beauchaine & Thayer, 2015)

Various physiological markers can be used when investigating stress levels, such as electrodermal activity (EDA) or cardiovascular activity (CVA) (Choi & Gutierrez-Ousan, 2009). Among these different physiological markers, cardiovascular activity, precisely the related heart rate, stands out, with the Autonomic Nervous System (ANS)´s sympathetic and parasympathetic branches playing a pivotal role in stress-induced HR changes (Choi & Gutierrez-Ousan, 2009; Taelman et al., 2009). Specifically, when individuals are experiencing stress, the ANS is triggered, which leads to a suppression of the parasympathetic nervous system (PNS) and activation of the sympathetic nervous system (SNS), causing an increased heart rate of individuals (Taelman et al., 2009). Studies like those of Taelman et al. (2009) and Valentini and Pariti (2009) further highlight heart rate´s predictive potential in identifying stress levels.

While laboratory studies have successfully established a connection between heart rate and stress, these controlled environments often fail to replicate the complexities of real-life stress and craving experiences. This limitation underscores again the need for an EMA approach, which can capture these dynamics in naturalistic settings. By using EMA to study heart rate changes in response to stress, researchers can better understand how these physiological reactions relate to craving and relapse in everyday contexts (Kuerbis et al., 2020; van Lier et al., 2022; Wray et al., 2014).

Building on this methodological foundation and reviewing the existing literature, it becomes clear that stress is a complex construct encompassing both emotional and physiological responses. While self-reported measurements offer insights into an individual’s subjective experience of stress, relying solely on self-reports may overlook important physiological reactions (Brady & Sonne; Schiffman, 2009). Incorporating physiological data, such as heart rate, provides a greater understanding of stress by analysing real-time autonomic nervous system dynamics (Choi & Gutierrez-Osuna, 2009). As we explore the literature about how high-stress levels can elevate craving (Sinha et al., 2009; Wemm et al., 2022), the potential to include heart rate measures as an objective predictor of stress to reveal new insights becomes evident.

Consequently, the present research will utilise the data measured by a study of van Lier et al. (2022), analysing 10 individuals with alcohol use disorder (AUD) over 100 days during their alcohol addiction treatment. Therefore, the study will aim to answer the following research questions:

RQ1: Is physiological arousal, assessed through heart rate measurements, a valid predictor of self-reported stress levels among individuals undergoing 100 days of alcohol addiction treatment, considering both concurrent (simultaneous) and predictive effects, and how do within-person and between-person variations influence this relationship?

It is expected that there is a significant relationship between heart rate and self-reported stress levels, observable both in the concurrent and predictive effects, with higher heart rate being associated with higher self-reported stress at the same time points and at the following time points.

RQ2: To what extent do stress levels and physiological arousal (measured through heart rate) independently and collectively influence alcohol craving in individuals undergoing a 100-day alcohol addiction treatment, considering both concurrent and predictive effects? Additionally, to what extent do stress levels mediate the relationship between heart rate and alcohol craving?

It is expected that there is a significant relationship between stress levels and alcohol craving in individuals during 100 days of alcohol addiction treatment, observable both in concurrent and predictive effects. Specifically, higher stress levels are hypothesised to lead to higher levels of alcohol craving at the same time points and at the following time points. Moreover, it is expected that there is a significant relationship between physiological arousal (heart rate) and alcohol craving. In particular, higher heart rates are hypothesised to affect higher levels of alcohol craving at the same time points and at subsequent time points. Lastly, it is hypothesised that stress mediates the relationship between heart rate and alcohol craving. When both stress and heart rate are included in the model, the effect of heart rate on craving is expected to remain significant, indicating a direct influence. However, stress is also expected to (partially) mediate this relationship, which would result in the direct effect of heart rate on alcohol craving to become smaller in the presence of stress.

Method

Participants

The primary focus of this research was on individuals diagnosed with alcohol use disorder (AUD). Eligibility for the original study, conducted by van Lier et al. (2022), required participants to be over 18 with a diagnosis of moderate or severe AUD, as defined by the DSM-5 criteria. In addition, participants had to be currently enrolled in or willing to enrol in outpatient treatment, either online or in-person. The recruitment, carried out by van

Lier et al. (2022) between September 2016 and March 2017, selected participants from the patient pool of an addiction care facility in the Netherlands and the client base of the online treatment platform alcoholdebaas.nl. Furthermore, given the objective to investigate alcohol craving, which typically emerges in AUD patients during attempts at alcohol abstinence (Leggio, 2009), it was required that participants were committed to the goal of either reducing their alcohol consumption drastically or completely refraining from the use of alcohol. Ten participants participated in the original study, and one participant had to be excluded from the study due to experiencing technical difficulties with the equipment. Moreover, six participants identified as male and four as female, with a mean age of $M = 40$ ($SD = 11$).

Materials

E4 Wristband

To monitor the physiological responses during the study, participants were required to wear Empatica's E4 wristband daily. The E4 is a medically certified wearable biosensor equipped to monitor various psychophysiological responses through four different sensors: a photoplethysmography (PPG) sensor for cardiovascular monitoring, an electrodermal activity sensor for sweat gland activity, a temperature sensor for peripheral skin temperature, and a three-axis accelerometer for physical movement (van Lier et al., 2020). In this specific research, we aim to analyse the cardiovascular activity of the participants. To achieve this, we will exclusively make use of the data from the PPG sensor, which is sampled at 64 Hz and measures the blood volume pulse (BVP) of the participants, allowing for the determination of participants overall heart rates (Chandra et al., 2021; van Lier et al., 2017; van Lier et al., 2020).

Generally, when introducing new physiological measurement devices, verifying their validity is necessary. Therefore, van Lier et al. (2020) introduced a comprehensive validity assessment protocol. To assess its performance, the E4 wristband was compared to a reference device, which was previously assessed as valid in measuring physiological data. According to the findings, the E4 proved effective in capturing average heart rates. However, this was only when looking at bigger stressors over extended periods. The wristband showed no sensitivity for shorter stressors, such as when suddenly being startled by something, making it less applicable for short-term use. Despite this limitation, it has been argued that the wristband is especially useful when being used over a longer period, making it particularly suitable for our study, which extends over 100 days and aims to capture the impact of significant stressors experienced during participants daily lives (van Lier et al., 2020).

Measures

Self-reported Craving

To minimise participant burden and increase compliance, particularly among participants with AUD, the study employed a single-item, 0-10 Likert scale to measure craving levels (Schiffman, 2009; Song et al., 2023; van Lier et al., 2022). Song et al. (2023) argued that single items in EMA studies show concurrent and predictive validity similar to multiple-item questionnaires. Therefore, participants were prompted to answer the question: "How strong is your craving currently?" with responses ranging from 0 = no craving to 10 = high craving (van Lier et al., 2022).

Self-Reported Stress Levels

To measure the self-reported stress levels, a single-item construct with a Likert scale ranging from 0 to 10 was employed (van Lier et al., 2022). Specifically, participants were asked, “How stressed are you in this moment?” with 0 = no stress and 10 = high stress.

Mean HR – CVA

Using the data from the E4 wristband (photoplethysmography (PPG) sensor), the mean heart rate per minute was chosen to represent the participants' physiological arousal. Generally, immediate heart rate was acquired by dividing the average interval between consecutive P-waves (PP-interval) per minute by 60 seconds. Moreover, heart rate was chosen instead of the PP interval because heart rate is a more widely recognised representation of the PP interval. The mean heart rate per minute was then averaged over the three hours before the end of question administration and used as the primary variable (van Lier et al., 2022).

Procedure

In the beginning, all participants had to answer some demographic questions. During the study, the participants received one questionnaire at the start and end of the day, multiple questions during the day, and one questionnaire via their mobile phones at the end of the week. The study made use of a time-contingent design. In time-contingent designs, participants receive the questionnaire prompts at fixed times within a previously defined time frame (de Vries et al., 2021). Considerably, the data of the self-reported questions were collected eight times a day at 7, 10, 13, 16, 19, 22, 1, and 4 o´clock. To respond to the questions, participants were given one hour. Moreover, to increase participation, participants received 1 euro compensation for each finished questionnaire (van Lier et al., 2022).

Data Analysis

Data Preparation

The statistical software "IBM SPSS statistics" will be used for the data analysis. Initial steps will include data cleaning and preparation, particularly addressing missing values. First, compliance rates for all participants will be calculated. Multiple aspects must be considered when calculating compliance rates. First, participants were not expected to answer at all times, considering they follow a normal daily rhythm with approximately 16 hours of wakefulness (Waterhouse et al., 2012). Therefore, realistically, participants were assumed to respond to five administrations daily. Answering five times daily would result in 500 registrations per participant over 100 days (van Lier et al., 2022). In line with the original study by van Lier et al. (2022) and considering the sample of alcohol addicts who tend to have lower compliance rates (Jones et al., 2019), a cutoff of compliance rates below 40% was chosen for exclusion. However, the further analyses will be divided into primary and sensitivity analyses. The findings of the primary analyses will be presented first, including data from all participants regardless of their compliance rates. Additionally, a sensitivity analysis will be conducted in which participants with compliance rates below 40% will be excluded. The dual analyses aim to ensure that the findings are robust and not influenced excessively by participants with low compliance rates (Thabane et al., 2013). The following sections will present the primary analyses, including data from all participants. If there are any significant differences between the primary and sensitivity analyses, these changes will be discussed and detailed in the Appendix.

Besides, descriptive statistics will be generated for self-reported stress levels, craving levels, and heart rate data. To understand these variables' general patterns, overall and person-specific mean scores will be calculated. Moreover, to explore the potential relationships between the variables, Pearson correlation coefficients will be calculated (Field, 2018).

Analyses Research Question 1

The first research question will be explored using a linear mixed model (LMM), which is well-suited for the nested data structure (Schietzelth & Nakagawa, 2013). The immediate effect analysis will consider self-reported stress levels as the dependent variable and heart rate (mean HR over the three-hour time interval) as the independent variable. For lagged effects, a new variable representing the mean heart rate 3 hours prior will be created, serving as the independent variable (IV). These analyses will employ an autoregressive covariance structure (AR (1)), as it indicates that correlations will diminish over time (Barnett et al., 2010). To account for individual variability in heart rate and its potential differential impact on participants, a basic model with a random intercept will be compared to an extended model with random slopes for predictor variables. Model fit will be assessed using the Bayesian Information Criterion (BIC), with preference given to models with lower BIC values (Ryoo, 2011). This general analysis establishes a baseline understanding of the overall relationship between heart rate and stress, serving as an essential preliminary step.

Additionally, to differentiate within-person and between-person effects, person-mean centring (PMC) will be employed (Wang et al., 2019). Therefore, the overall mean heart rate will be split into two components: within-person centred heart rate and between-person mean heart rate. By doing this, it will be possible to examine how the deviations from an individual´s average heart rate (within-person effects, WP) and the differences between the participants´ heart rates (between-person effects, BP) predict self-reported stress levels (Wang et al., 2019). Moreover, lagged variables will be included to expand this analysis. Specifically, lagged variables representing the heart rate 3 hours prior to a stress measurement will be computed. This approach will allow for assessing how deviations from an individual's average heart rate at an earlier time point (within-person lagged effects) impact stress levels later. Both immediate and lagged within-person centred and between-person mean variables will be incorporated in separate mixed models. Even though, conceptually, the between-person effect does not need to be investigated in the lagged analysis, as it represents the mean heart rate for each individual, which is always the same, the between-person effect was still included in the model to control for individual differences in average heart rate.

Analyses Research Question 2

The second research question will be investigated with a series of linear mixed models, where the dependent variable is alcohol craving levels. The analysis will be divided into three main parts. The first LMM will examine the immediate effect of self-predicted stress levels on alcohol craving levels, with stress levels as the IV. The second model will investigate the immediate effect of heart rate on alcohol craving levels, using heart rate as the IV. Lastly, a third LMM will be employed, including stress levels and heart rates as the IVs. Therefore, this model will examine the combined effect of heart rate and stress on alcohol craving levels.

To investigate the delayed effects, similar models will be constructed using lagged variables. One model will assess the effect of stress levels at previous time points (3 hours prior) on alcohol craving levels, with lagged stress as the IV. Another LMM will examine the effect of heart rate at previous time points on current alcohol craving levels, using lagged heart rate as the IV. A third lagged LMM will include both lagged stress and lagged heart rate as IVs to investigate their combined delayed effects on alcohol craving levels.

Additionally, the models mentioned above will separate within-person and between-person effects. The within-person effects will be investigated using centred versions of the stress and heart rate variables to explore how deviations from a participant´s average stress and heart rate relate to craving levels. The between-person effects will be calculated by including the mean levels of stress and heart rate for each individual across the period of the study to determine how individual differences in average stress and heart rate affect craving levels (Wang et al., 2019). Moreover, as explained above, the lagged effect of within-person effects will be employed.

Furthermore, each LMM will employ the autoregressive covariance structure (AR (1)) (Barnett et al., 2010). Again, a basic model with random intercepts will be compared to an extended model that includes both random intercepts and random slopes. Model fit will be examined by investigating the Bayesian Information Criterion (BIC), with lower values indicating a better model fit (Ryoo, 2011).

Mediation Analysis for RQ2

To investigate whether the changes in the combined LMM, which includes both heart rate and stress levels and their effect on alcohol craving, can be attributed to a mediation effect, a separate mediation analysis will be performed. This will be done using the PROCESS macro extension for SPSS, developed by Andrew Hayes (Hayes, 2012). Given that PROCESS cannot account for the nested structure of repeated measures data, lagged variables will be used to ensure the correct temporal ordering of the variables. According to Di Maria et al. (2024), the independent variable must precede the mediator, and the mediator must precede the dependent variable in time. Therefore, heart rate lagged by two time points (6 hours) will be used as the independent variable, alcohol craving as the dependent variable, and stress lagged by one time point (3 hours) will be included as the mediator.

Results

Descriptive Statistics and Compliance Rates

To get an overview of the distribution of the variables and our ten participants, descriptive statistics were computed (Table 1). The compliance rates for this study varied from 11.6% to 76.33%, with M = 43.26% and SD = 23.40 (Table 1). As previously outlined in the data analysis section, the sensitivity analyses will exclude participants with compliance rates below 40%. Consequently, participants 1, 2, 5, and 6 were excluded from these analyses.

Table 1

Descriptive Statistics for All Participants and Compliance Rates

Participant	Stress		Craving		Heart Rate		Compliance Rates
	N	*M (SD)*	*N*	*M (SD)*	*N*	*M (SD)*	*%*
Participant 1	141	2.14 (2.50)	140	1.51 (2.49)	163	66.47 (9.66)	29.60*
Participant 2	79	2.48 (2.09)	77	0.51 (1.40)	18	83.74 (8.88)	11.60*
Participant 3	314	1.62 (1.62)	311	1.51 (2.71)	234	68.74 (9.04)	57.27
Participant 4	282	0.21 (1.28)	281	0.37(1.45)	74	87.91 (8.12)	42.47
Participant 5	106	3.73 (1.97)	104	3.89 (2.35)	121	74.56 (10.44)	22.07*
Participant 6	228	3.89 (2.29)	224	2.83 (2.89)	111	66.18 (5.21)	37.53*
Participant 7	435	0.49 (1.36)	435	1.17 (2.81)	275	77.61 (7.63)	76.33
Participant 8	303	0.77 (1.70)	301	0.88 (1.91)	308	76.37 (9.86)	60.80
Participant 9	404	0.69 (1.81)	404	0.47 (1.54)	116	91.23 (5.81)	61.60
Participant 10	327	2.84 (1.44)	327	1.15 (1.84)	329	75.17 (4.93)	65.53
Overall	2619	1.53 (2.11)	2604	1.23 (2.38)	1749	75.17 (10.44)	43.26 (23.40)

Note. *Compliance rate < 40%

Correlations

Correlations were computed to examine the relations between the independent and dependent variables (Table 2).

Table 2

Correlations between all Variables

Variable	1	2	3	4	5
1. Stress	-				
2. Craving	.37**	-			
3. HR	-.06	.11**	-		
4. Lagged Stress	.49**	.19**	-.00	-	
5. Lagged HR	-.12**	.05	.76**	-.06	-

Note. ***p* < .01.

Research Question 1

To answer the first research question concerning the concurrent association of heart rate on self-predicted stress levels of the participants, a linear mixed model was employed. Specifically, the model, including only random intercepts, was employed in all the analyses, as this basic model provided a better fit based on the Bayesian Information Criteria (BIC).

Relation between Heart Rate or Lagged Heart Rate and Self-Reported Stress Levels

The outcome of the linear mixed model (LMM) concerning the concurrent effects of heart rate on stress levels showed a significant positive relationship between heart rate and stress levels (β = .02, *p* = .015) (Table 3). This indicates that higher heart rate levels lead to higher stress levels. However, the results of the LMM for the sensitivity analysis showed no significant effect between heart rate and stress levels (β = .02, *p* = .37), indicating that the relationship does not hold when excluding participants with low compliance rates (Table A1, see Appendix).

A lagged analysis (Table 3) was conducted to further explore the relationship between heart rate and stress. The LMM showed that heart rate three hours prior does not predict stress levels (β = -.002, *p* = .85).

Table 3

Estimates of Fixed Effects with Heart Rate (HR) or Lagged Heart Rate as Independent Variable and Stress as Dependent Variable (N = 10)

						95% Confidence Interval	
Parameter	Estimate	*SE*	*df*	*t*	Sig.	Lower Bound	Upper Bound
Intercept	.42	.74	59.82	.57	.57	-1.05	1.91
Heart Rate (HR)	.02	.01	971.16	2.44	.015	.00	.03
Intercept	1.96	.71	96.32	2.81	.006	.58	3.34
Lagged HR	-.002	.01	829.18	-.19	.85	-.02	.01

Note. df = Degrees of freedom

Within-Person and Between-Person Effects of Heart Rate and Lagged Heart Rate on Stress

The analysis was extended to examine the effects of within-person (WP) and between-person (BP) to investigate further the relationship between heart rate and self-reported stress levels. The primary analysis results using the LMM indicate a significant positive within-person effect (β = .02, *p* = .008), suggesting that changes in an individual´s heart rate from their own mean are positively associated with changes in their stress levels. However, the between-person effects did not yield a significant effect (β = -.09, *p* = 0.08), indicating that differences in mean heart rate between participants are unrelated to stress levels (Table 4). Contrastingly, the results of the sensitivity analysis indicate that neither the within-person effects (β = .01, *p* = .29) nor the between-person effects (β = -.03, *p* = .46) were significant indicators of stress levels (Table A2, see Appendix).

Additionally, another LMM was performed to investigate the lagged within-person effects of heart rate on stress (Table 4). The primary analysis results yielded non-significant lagged within-person effects of heart rate on stress (β = .002, *p* = .82). Moreover, in this model, there was a weak but significant negative between-person effect for the overall mean heart rate on stress levels (β = -.09, *p* = .048) (Table 4). Contrastingly, the results of the sensitivity analysis showed that neither the between-person effects (β = -.05, *p* = .33) nor the lagged within-person effects (β = -.01, *p* = .48) were significant predictors of stress levels (Table A3, see Appendix).

Table 4

Within-Person (WP) and Between-Person (BP) Effects of Heart Rate and Lagged Heart Rate on Stress (N = 10)

						95% Confidence Interval	
Parameter	Estimate	*SE*	*df*	*t*	Sig.	Lower Bound	Upper Bound
Intercept	8.61	3.37	7.95	2.55	.03	.83	16.37
BP HR	-.09	.04	7.97	-2.02	.08	-.19	.01
WP HR	.02	.01	976.37	2.68	.008	.01	.04
Intercept	8.37	2.83	8.08	2.96	.02	1.85	14.88
BP HR	-.09	.04	8.10	-2.32	.048	-.17	-.001
Lagged WP HR	.002	.01	859.04	.23	.82	-.01	.02

Note. df = Degrees of freedom

Research Question 2

Relation between Stress or Lagged Stress and Craving

The outcome of the LMM revealed that stress is a significant covariate of alcohol craving with a strong effect (β = .52, *p* < .001) (Table 5). This indicates that as participants´

stress levels increase, alcohol craving tends to increase substantially. Additionally, the analysis investigating the predictive effect of stress on craving showed that stress levels three hours prior are a significant predictor of alcohol craving (β = .09, p = .009), suggesting that higher stress levels three hours prior are associated with higher craving levels (Table 5).

Table 5

Estimates of Fixed Effects with Stress or Lagged Stress as Independent Variable and Craving as Dependent Variable (N = 10)

						95% Confidence Interval	
Parameter	Estimate	*SE*	*df*	*t*	Sig.	Lower Bound	Upper Bound
Intercept	.45	.23	8.86	1.94	.09	-.07	.97
Stress	.52	.02	2444.60	22.60	<.001	.48	.57
Intercept	1.44	.35	8.72	4.09	.003	.64	2.24
Lagged Stress	.09	.03	1504.41	2.63	.009	.02	.16

Note. df = degrees of freedom

Relationship Heart Rate and Craving

The results of the primary analysis using the LMM showed that heart rate is a significant covariate of alcohol craving (β = .05, p < .001), indicating that as participants' heart levels increase, alcohol craving tends to increase as well (Table 6). Furthermore, when examining heart rate levels from three hours prior, the analysis revealed a weak but significant predictive effect on alcohol craving levels (β = .02, p = .046), suggesting that an increased heart rate three hours earlier is associated with a slight increase in craving levels (Table 6). However, the results of the sensitivity analysis yielded non-significant results for the lagged heart rate (β = .02, p = .08), indicating that the exclusion of these participants alters the overall findings (Table A4, see Appendix).

Table 6

Estimates of Fixed Effects with Heart Rate or Lagged Heart Rate (HR) as Independent Variable and Craving as Dependent Variable (N = 10)

						95% Confidence Interval	
Parameter	Estimate	*SE*	*df*	*t*	Sig.	Lower Bound	Upper Bound
Intercept	-2.37	.86	113.54	-2.76	.007	-4.07	-.67
Heart Rate	.05	.01	851.93	5.09	<.001	.03	.07
Intercept	-.01	.87	135.18	-.01	.99	-1.72	1.71
Lagged HR	.02	.01	690.38	2.00	.046	.00	.04

Note. df = degrees of freedom

Combined Concurrent and Predictive Effects of Stress and Heart Rate on Craving

The outcome of the combined LMM showed that both stress (β = .54, p < .001) and heart rate (β = .04, p < .001) are significant covariates of alcohol craving levels (Table 7). When comparing the combined model to the separate analyses, it was observed that the estimate for stress on craving was higher in the combined model (β = .54) than when stress was considered alone (β = .52). Conversely, the estimate for heart rate on craving was slightly lower in the combined model (β = .04) compared to when heart rate was considered alone (β = .05). While these differences were not tested for significance, they suggest potential interactions between stress and heart rate in relation to craving levels.

In the predictive analysis, the combined LMM revealed that when both predictors are included in the model, only lagged stress yields positive significant results (β = .18, p < .001). In contrast, lagged heart rate does not show significant results (β = .01, p = .36) (Table 7). Additionally, it was observed that the estimate for stress was higher in the combined model compared to when stress was a sole predictor, suggesting a potentially stronger effect of stress on craving when accounting for heart rate, though this difference was not tested for significance.

Table 7

Estimates of Fixed Effects with Concurrent or Lagged Stress and Heart Rate as Independent Variables and Craving as Dependent Variable (N = 10)

						95% Confidence Interval	
Parameter	Estimate	*SE*	*df*	*t*	Sig.	Lower Bound	Upper Bound
Intercept	-2.53	.73	169.92	-3.48	<.001	-3.96	-1.09
Stress	.54	.04	956.76	14.83	<.001	.47	.62
Heart Rate	.04	.01	574.14	4.46	<.001	.02	.06
Intercept	.51	.99	150.36	.51	.61	-1.45	2.47
Lagged Stress	.18	.05	632.04	3.59	<.001	.08	.28
Lagged HR	.01	.01	413.83	.92	.36	-.01	.04

Note. df = degrees of freedom

Concurrent and Lagged Within-Person and Between-Person Effects of Stress, Heart Rate on Alcohol Craving

The outcome of the LMM investigating the within-person (WP) and between-person (BP) effects of the relationships between stress, heart rate and alcohol craving revealed significant within-person effects for both stress (β = .54, p < .001) and heart rate (β = .04, p < .001). This suggests that increases in stress and heart rate within participants are strongly related to increases in alcohol cravings. Nevertheless, the between-subject effects for both stress (β = .42, p = .13) and heart rate (β = -.02, p = .54) yielded non-significant results, indicating that the effects in the overall analyses (Tables 7) are mainly attributable to within-person patterns (Table 8).

When examining the predictive relationships between lagged stress and, heart rate and craving, the LMM showed that the relationship is primarily driven by within-person fluctuations (β = .16, p = .002) (Table 8). In contrast, heart rate did not show a significant within-person effect in the predictive model (β = .02, p = .17) (Table 8). These findings suggest that the increase in alcohol craving following heightened stress levels is mainly a within-person phenomenon, whereas heart rate´s influence on craving in a predictive context may be less pronounced.

Table 8

Within-Person and Between-Person Effects of Concurrent and Lagged Stress and Heart Rate (HR) on Craving (N = 10)

						95% Confidence Interval	
Parameter	Estimate	*SE*	*df*	*t*	Sig.	Lower Bound	Upper Bound
Intercept	2.57	3.17	6.31	.81	.45	-5.09	10.22
BP Stress	.42	.24	6.33	1.76	.13	-.16	1.01
WP Stress	.54	.04	1030.29	14.46	<.001	.47	.61
BP HR	-.02	.04	6.38	-.64	.54	-.12	.07
WP HR	.04	.01	934.51	4.76	<.001	.03	.06
Intercept	3.66	3.64	5.85	1.01	.35	-5.31	12.61
BP Stress	.52	.28	6.28	1.84	.11	-.16	1.21
Lag WP Stress	.16	.05	644.84	3.09	.002	.06	.25
BP HR	-.04	.04	5.89	-.88	.41	-.14	.07
Lag WP HR	.02	.01	633.62	1.39	.17	-.01	.04

Note. df = degrees of freedom

Mediation Analysis

A mediation analysis was conducted to investigate whether the changes in the estimators between the different models indicate a mediation effect (Figure 1).

Total Effect. The total effect of lagged heart rate by six hours on craving levels was significant (β = -.02, *SE* = .01, *t* = -2.55, *p* = .01, 95% *CI* [-.04, -.01]). The significant total effect suggests that higher heart rates six hours prior are associated with lower alcohol craving levels overall.

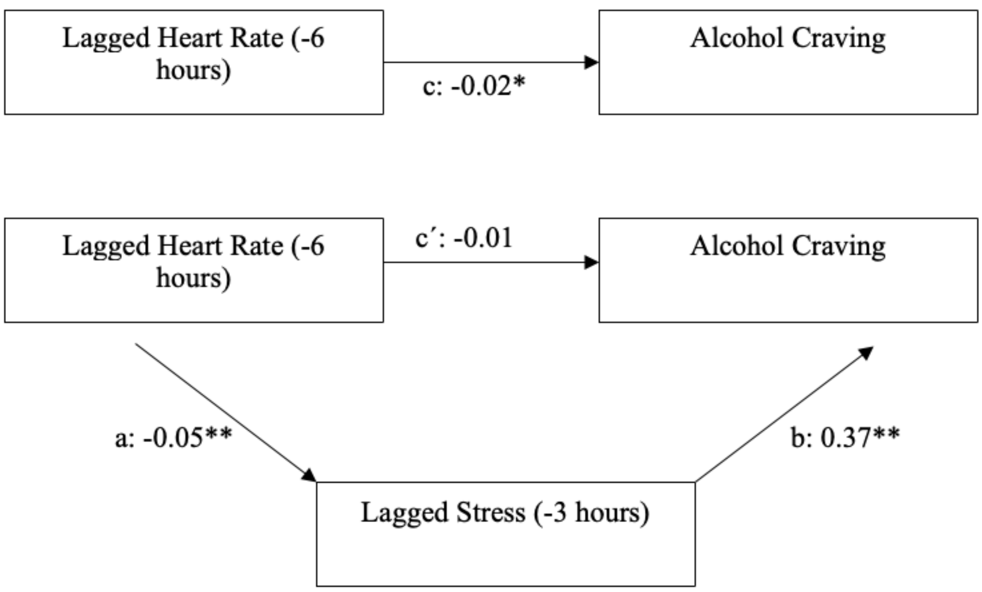
Direct Effect (Path c´). The direct effect of lagged heart rate on craving, controlling for lagged stress, yielded non-significant results (β = -.01, *SE* = .01, *t* = -.99 *p* = .32, 95% *CI* [-.03, .01]). The non-significant direct effect indicates that when the mediating effect of stress is considered, heart rate alone is not a significant predictor of craving.

Indirect Effects (Path a, b and Path ab). Heart rate lagged by six hours significantly predicted stress (lagged by three hours) (β = -.05, *SE* = .01, *t* = -5.08, *p* < .001, 95% *CI* [-.06, -.03]). This indicates that higher heart rate levels predicted lower stress levels three hours later. Moreover, there was a significant positive effect of lagged stress on craving levels (β = .37, *SE* = .05, *t* = 7.17, *p* < .001, 95% *CI* [.27, .47]), meaning that higher stress levels prior significantly predicted higher craving levels. Lastly, the indirect effect of lagged heart rate on craving through lagged stress also yielded significant results (β = -.02, Boot*SE* = 0.004, 95% Boot*CI* [-.02, -.01]), indicating that lagged stress mediates the relationship between heart rate and alcohol craving. This significant indirect effect reveals that higher heart rates six hours prior are associated with lower stress levels three hours later, which are related to lower craving levels. Moreover, as the direct effect (c') becomes non-significant, this hints at a full mediation effect. See Figure 1 for a visualisation of the presented effects.

Sensitivity Analysis. To verify the robustness of these findings, a sensitivity analysis (*N* = 6) was also conducted. The sensitivity analysis showed similar results, except that the total effect of heart rate on craving yielded non-significant results. The rest of the values remained similarly significant.

Figure 1

Mediation between Lagged Heart Rate (-6 Hours) and Alcohol Craving with Lagged Stress (-3 Hours) as the Mediator



Note. * *p* < .05, ** *p* < .001

Discussion

This study aimed to investigate the validity of physiological arousal, assessed through heart rate measurements, as a predictor of self-reported stress levels among individuals undergoing a 100-day alcohol addiction treatment. Specifically, it examined both simultaneous (concurrent) and predictive heart rate effects, considering both within-person and between-person variations. In addition, the study explored how self-reported stress levels and physiological arousal independently and collectively relate to alcohol craving, also considering simultaneous and predictive effects. Moreover, to deepen the understanding of these relationships, the study also investigated a possible mediation effect, examining whether stress mediates the relationship between heart rate and alcohol craving.

Main findings

Associations between Stress, Heart Rate and Craving

The relationship between stress, heart rate, and alcohol craving, particularly the predictive power of stress on craving, was a key focus of this study. The findings revealed a strong within-person relationship between stress and craving, indicating that changes in an individual´s stress levels are closely linked to changes in their craving levels. Notably, higher stress levels not only increased craving at the exact moment but also predicted higher craving levels three hours later, emphasising the significant role of stress in influencing craving over time.

Several interpretations support this relationship. Firstly, research indicates that stress activates the hypothalamic-pituitary-adrenal (HPA) axis, increasing cortisol release, which can enhance the reward value of substances and trigger craving (Adinoff et al., 2005; Blaine et al., 2016; Breese et al., 2011). Moreover, behavioural mechanisms also contribute to this relationship. Individuals often learn to associate stress with alcohol use as a coping mechanism, making stress a trigger for craving due to this conditioned association (Cooper et al., 1992; Drummond, 2000; Weiss, 2005). This conditioned response reinforces the finding that stress significantly influences alcohol craving, both concurrently and predictively. In addition, the significant predictive effect of stress levels on alcohol craving observed in this study aligns with previous research that highlights stress as a critical factor in increasing individuals' susceptibility to alcohol cravings (Breese et al., 2005; Fox et al., 2005; Sinha, 2007). This finding is particularly insightful as it suggests that heightened stress levels can be a precursor to future craving moments. Thus, managing stress is crucial not only for addressing current cravings but also for preventing future increases, emphasising its importance in alcohol addiction treatment.

In addition to stress, the study also examined the impact of physiological arousal, precisely heart rate, on alcohol craving. A significant concurrent effect was found, showing that higher heart rates were associated with higher craving levels within the same individual. This finding reinforces the established link between physiological arousal and craving episodes and further aligns with the previous discussion of stress and craving, as physiological arousal can be seen as a critical component of the body´s response to stress (Choi & Gutierrez-Ousan, 2009). Moreover, consistent with Rosenberg´s (2009) findings, it can be argued that awareness of craving itself can trigger physiological responses, such as an increase in heart rate, possibly explaining the high heart rates and their impact on craving levels.

However, the results were less consistent when examining the predictive effect of heart rate on craving. The predictive effect of heart rate on craving was weak and only significant in the primary analysis (N = 10), suggesting that increased heart rate three hours in advance could predict higher craving levels later. Nevertheless, this effect was not found in the sensitivity analysis, which excluded four participants with low compliance rates. One possible reason for this difference is the reduction in sample size. Reducing the sample from 10 to 6 likely decreased the statistical power, making it harder to detect significant effects, especially given the already weak predictive effect. It is well-documented that larger sample sizes enhance the ability to detect meaningful relationships (Gannon et al., 2019; Lyman, 2019; Makin & Orban de Xivery, 2019). Additionally, Participants 5 and 6, who had the highest craving levels, may have increased variability, making it easier to detect a significant relationship. The inconsistency between the predictive and concurrent effects of heart rate on craving highlights the complexity of physiological responses in addiction contexts, where concurrent effects may not always translate into valid predictions over time. Considering the differences in analyses and the overall weak predictive effect, this finding should be interpreted cautiously and primarily seen as a trend.

Association between Stress and Heart Rate

Given the established relationship between stress, heart rate and craving, it is essential to understand how heart rate, as a physiological marker of stress, interacts with self-reported stress. Therefore, another aim of this study was to analyse whether physiological arousal, assessed through heart rate measurements, can be used as a valid predictor of self-reported stress levels among individuals undergoing 100 days of alcohol addiction treatment. The findings of the primary analysis (N = 10) revealed a significant concurrent effect of heart rate on self-reported stress levels driven by within-person variations, indicating that changes in an individual´s heart rate from their own baseline are closely associated with their perceived stress levels. This finding aligns with the body's physiological "fight-or-flight" response (Chu et al., 2019; McEwen, 2007; Taelman et al., 2009; Yaribeygi et al., 2017; Ziegler, 2012). Furthermore, the findings of multiple studies collectively reinforce heart rate as a responsive indicator of stress (Choi & Gutierrez-Osuna, 2009; Schiffman, 2009; Wray et al., 2014; Taelman et al., 2009; Kaegi et al., 1999; Palatini et al., 2003). This relationship is primarily driven by within-person effects, underscoring the importance of individual physiological baselines in accurately assessing stress responses. Research has shown that individual baseline heart rates vary significantly as they can be influenced by factors such as a person's fitness level, age, and general health status (Nealen, 2016). Moreover, according to Williams et al. (2011), individuals vary greatly in their stress responses, meaning differences occur in the recovery time after a stressor or in their overall vulnerability to experience stress in the first place, underlining the within-person effects.

However, the differences between the primary analyses (N = 10) and the sensitivity analyses (N = 6) are noteworthy. While the primary analyses yielded significant results, the sensitivity analyses, which excluded four participants due to low compliance rates, did not show a significant effect of heart rate on stress. This discrepancy may be due to the reduced sample size, which likely decreased the study's statistical power (Gannon et al., 2019; Lyman, 2019; Makin & Orban de Xivery, 2019). Notably, the four excluded participants (Participants 1, 2, 5, and 6) had some of the highest mean stress levels among all participants. Specifically, Participants 5 and 6 had the highest stress levels, while Participants 1 and 2 had relatively high levels. Including these high-stress participants may have been crucial for accurately capturing the heart rate-stress relationship, as they likely exhibited more pronounced physiological arousals, making significant effects easier to observe. Excluding them might have reduced the range of stress and physiological responses, leading to less robust findings. Furthermore, participants with higher compliance rates may have better coping mechanisms, while low compliance rates could be linked to high stress levels. Those who reported high-stress levels throughout the study likely struggled more, leading to lower compliance rates. This hypothesis is supported by Rinatala et al. (2020), who found that participants with more stressful activities or higher levels of unpleasantness were more likely to be non-compliant.

Considering the pronounced differences between the two analyses, the robustness and validity of the effect found in the primary analysis must be critically examined. The exclusion of participants, leading to non-significant results, raises doubts about the findings' validity. Furthermore, the discrepancy between analyses could point to between-subject factors, indicating that a subgroup of people in treatment may show high stress due to shared but unknown characteristics. Identifying such factors could be valuable in targeting treatment more effectively towards stress-relieving support systems. Therefore, the discussed findings should be examined with caution.

While the concurrent relationship between heart rate and self-reported stress levels offers valuable insights into the immediate physiological responses to stress, the predictive power of heart rate in anticipating future stress levels presents a more complex challenge. Despite this significant concurrent relationship, heart rate was not found to be a valid predictor of stress moments. Several factors could explain this discrepancy. Firstly, numerous other influences on heart rate are independent of stress, such as daily routines, physical health, and lifestyle factors, including circadian rhythms, posture, physical activity, and smoking habits (Kim et al., 2018; Felber Dietrich et al., 2008). Predisposed factors, such as sex, age, and genetics, also contribute to variations in heart rate (Kim et al., 2018). Secondly, the transient nature of heart rate responses to stress must be considered. Acute stressors often lead to immediate but short-lived increases in heart rate, which return to baseline shortly after the stressor is removed (Allen et al., 2014; Weber et al., 2022). This rapid normalisation may indicate that a high heart rate observed three hours prior may not persist long enough to predict stress levels at later time points. Additionally, using average heart rate might not be the best indicator of stress. Many other parameters, such as heart rate variability (HRV), may provide more detailed insights into stress when obtained from continuous heart rate measurements (Schubert et al., 2009). Thirdly, the choice of a three-hour lag is also debatable. The variability in stressors' type, context, and intensity throughout the day can complicate establishing a consistent predictive effect. Acute stressors cause short-term increases in heart rate, whereas chronic stressors, such as ongoing relationship problems or work pressures, may lead to different physiological patterns (Almeida, 2005; McEwan, 2017). Fourthly, environmental and situational factors could also be essential in understanding the relationship between heart rate and stress. The context in which a stressor occurs, including the time of day, presence of social support, and individual differences in coping abilities, can further influence how stress affects physiological responses (Cohen & Wills, 1985; McEwan, 1998; Uchino et al., 1996).

Considering that this study did not observe a predictive effect of heart rate on stress levels, it was expected that no predictive within-person or between-person effects would be found. However, the primary analysis (N = 10) yielded a weak negative significant between-person effect, which was not observable in the sensitivity analysis. This would indicate that individuals with higher mean heart rates tend to report slightly lower stress levels. Nevertheless, these unexpected results warrant further investigation into the underlying factors contributing to this relationship.

Stress as a Mediator

Interestingly, the weak negative predictive relationship between heart rate and stress observed in the previously discussed analysis shows some similarities to the findings in the mediation analysis, even though it is crucial to note that these analyses used different time lags. Notably, the mediation analysis applied a six-hour lag for heart rate and a three-hour lag for stress. The findings indicate that stress levels mediate the relationship between heart rate and craving, with higher heart rates predicting lower stress levels, predicting lower craving levels. This suggests that stress is a crucial intermediary between physiological arousal and craving. It highlights the significant role that stress plays for individuals trying to maintain abstinence from alcohol. This finding is crucial as it underscores the importance of addressing stress in treatment interventions for alcohol addiction. The counterintuitive result that higher heart rates predict lower stress levels, a trend that has already been observed earlier, suggests complex physiological interactions. One possible explanation is that awareness of physiological arousal could trigger psychological coping mechanisms, thereby reducing perceived stress. For example, cognitive reappraisal or other stress management techniques might be activated when individuals become aware of their increased heart rate, reducing stress levels (Gross, 2002). Despite interesting findings, the mediation analysis did not differentiate between within-person and between-person effects. Thus, although results provide valuable insights, whether the observed effects are driven by individual variability over time or differences between individuals remains to be investigated. Consequently, future research should aim to distinguish these effects to gain a clearer understanding of the mechanisms at play.

Moreover, to further underline the significance of the mediation effect, the findings of the combined analyses, which investigated the combined effect of heart rate and stress on craving, can be examined. The concurrent analysis revealed that the effect of stress on craving increased when heart rate was also considered in the model, while the effect of heart rate decreased slightly. Similarly, in the predictive analysis, stress maintained its significant impact on craving, overshadowing the predictive power of heart rate, which became non-significant. These findings support the mediation effect observed in the mediation analysis, where stress was shown to mediate the relationship between heart rate and craving. Although we cannot determine if these changes in estimators between analyses are statistically significant, they do underscore the complex interplay between physiological arousal and stress in influencing craving levels.

Strengths, Limitations and Future Research

This study provided valuable insights into the dynamics between physiological arousal, stress levels, and alcohol cravings in individuals undergoing a 100-day alcohol addiction treatment, and it is subject to several strengths and limitations. Using an ecological momentary assessment (EMA) design offered significant advantages over retrospective methods and standard laboratory studies. By measuring participants multiple times daily, EMA helped to avoid retrospective bias, where differences between memory and real-life experience can lead to biased responses (Wray et al., 2014; van den Bergh et al., 2016). This real-time data collection captured authentic experiences, enhancing the reliability of the findings. Additionally, the EMA approach allowed for daily physiological data assessment, providing a more accurate representation of real-life conditions compared to controlled laboratory settings. This approach enabled the study to investigate within-person effects, analysing how changes in heart rate relate to changes in stress and craving within the same individual, offering more precise insights into each participant's unique physiological and psychological responses (Scollon, 2003).

Despite pointing out this study´s strengths, several limitations must be acknowledged. A notable limitation was the overall low compliance rates, which were anticipated due to the extended study duration and the sample of individuals with alcohol addiction, who generally exhibit lower compliance rates (Wray et al., 2019). When non-responses exceed 20%, the sample's representativeness can be compromised, notably if data are missing due to non-random effects (Stone & Schiffman, 2002). This low compliance might introduce bias, as non-compliant participants may differ systematically from compliant ones, affecting the generalisability of the findings. Therefore, future studies should investigate the link between high-stress levels and non-compliance to understand better why participants chose not to comply and enhance participant engagement. Although the 100-day study period offers valuable insights, shorter assessment periods might reduce participant burden. Introducing micro-incentives, a strategy shown to enhance engagement (Musthag et al., 2011), could also be beneficial. While van Lier et al. (2022) included a micro-incentive of up to 1 euro per day for each finished questionnaire, increasing this incentive might further improve compliance.

Another limitation of this study is using heart rate to measure physiological arousal. While simple heart rate measurements provided valuable insights and were the most usable data from the E4 wristband, heart rate encompasses a broad range of information. Different heart rate measurements can reveal unique aspects of this information (Schubert et al., 2009). Moreover, extensive research includes heart rate variability (HRV) when investigating cardiovascular activity related to stress or craving (Alayan et al., 2018; Kim et al., 2018;

Taelman et al., 2009; Quintana et al., 2013; Schubert et al., 2009). HRV analysis offers a more detailed understanding of the autonomic nervous system's activity by differentiating between sympathetic and parasympathetic influences. By interpreting fluctuations in the intervals between heartbeats, HRV provides more detailed insights than heart rate alone (Choi & Gutierrez-Osuna, 2009). Unfortunately, the wristband used in this study did not reliably support HRV data collection (van Lier et al., 2022). Relying solely on heart rate measurements might have limited the study's ability to fully understand the autonomic nervous system's role in stress and craving levels. Consequently, future research should consider incorporating HRV as physiological arousal to understand the studied dynamics better.

Another limitation worth considering is the alignment of heart rate measurements with self-reported stress and craving levels. The heart rate data used was averaged over three hours before the end of question administration, while stress and craving were measured momentarily. This mismatch in timing raises questions about whether the heart rate data accurately reflects the physiological arousal at the time of the self-report. While this timeframe was chosen based on the data provided and aligned with the approach of van Lier et al. (2022), different temporal alignments between physiological measures and self-reports could yield new insights, particularly given that stress responses vary greatly over time and normalise quickly after the stressor is removed (Allen et al., 2014; Weber et al., 2022). Therefore, future research should consider using different time intervals or comparing different time lags to determine the most appropriate alignment between physiological data and momentary self-reported experiences.

Implications

The current research findings have significant implications for understanding the dynamics of stress, physiological arousal, and alcohol craving in individuals undergoing alcohol addiction treatment. These insights can also inform the development of more effective, personalised interventions to support recovery. First, the results highlight the crucial role of stress in alcohol addiction through its impact on alcohol craving. Given the pivotal role of craving in treatment success (Lowman et al., 2000; Singleton & Gorelick, 1998), future interventions should focus on stress reduction techniques to manage alcohol cravings and support abstinence. Additionally, the effects of physiological arousal on stress, stress on craving, and physiological arousal on craving were primarily driven by within-person effects, suggesting the need for individualised treatment interventions. Tailoring strategies to address each individual's unique variations could enhance the effectiveness of addiction treatments. Lastly, the study provides valuable insights into the effects of physiological arousal (heart rate) on key constructs in alcohol addiction. The findings suggest that biofeedback techniques, which monitor physiological arousal such as heart rate, could help individuals recognise and manage their stress and alcohol cravings more effectively. By providing real-time feedback, individuals could be empowered to use stress reduction techniques proactively, potentially reducing alcohol cravings and supporting abstinence.

Conclusion

This study showed a significant positive relationship between heart rate and self-reported stress levels. Stress was identified as a critical factor in both directly and predictively influencing alcohol craving and through its mediating effect on the relationship between physiological arousal and craving. These results, however, should be interpreted with caution due to low compliance rates, which may have influenced the findings. Nonetheless, they highlight the importance of stress management in addiction treatment and suggest the need for individualised treatment strategies. Furthermore, the study suggests potential applications for biofeedback techniques to help individuals monitor and manage stress and craving levels. Overall, this research contributes valuable insights for future studies and positively adds to the existing knowledge on stress, physiological arousal, and alcohol craving.

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Appendix A

Table A1

Estimates of Fixed Effects with Heart Rate (HR) as Independent Variable and Stress as Dependent Variable (Sensitivity Analysis with N = 6)

						95% Confidence Interval	
Parameter	Estimate	*SE*	*df*	*t*	Sig.	Lower Bound	Upper Bound
Intercept	.51	.67	91.12	.74	.46	-.83	1.82
Heart Rate (HR)	.01	.01	738.27	.91	.37	-.01	.02

Note. df = degrees of freedom

Table A2

Within-Person and Between-Person Effects on Stress (Sensitivity Analysis with N = 6)

						95% Confidence Interval	
Parameter	Estimate	*SE*	*df*	*t*	Sig.	Lower Bound	Upper Bound
Intercept	3.54	3.11	4.17	1.14	.32	-4.96	12.04
BP HR	-.03	.04	4.18	-.81	.46	-.14	.08
WP HR	.01	.01	797.06	1.06	.29	-.01	.02

Note. df = degrees of freedom

Table A3

Lagged Within-Person and Between-Person Effects on Stress (Sensitivity Analysis with N = 6)

						95% Confidence Interval	
Parameter	Estimate	*SE*	*df*	*t*	Sig.	Lower Bound	Upper Bound
Intercept	4.73	3.22	4.19	1.47	.21	-4.06	13.51
BP HR	-.05	.04	4.21	-1.11	.33	-.16	.07
Lag WP HR	-.01	.01	716.96	-.70	.48	-.02	.01

Note. df = degrees of freedom

Table A4

Estimates of Fixed Effects with Lagged Heart Rate as Independent Variable and Craving as Dependent Variable (Sensitivity Analysis N = 6)

						95% Confidence Interval	
Parameter	Estimate	*SE*	*df*	*t*	Sig.	Lower Bound	Upper Bound
Intercept	-.29	.83	90.17	-.35	.72	-1.94	1.36
Lagged HR	.02	.01	147.55	1.77	.08	-.00	.04

Note. df = degrees of freedom