International Journal of Psychophysiology 201 (2024) 112369

Contents lists available at ScienceDirect

International Journal of Psychophysiology

journal homepage: www.elsevier.com/locate/ijpsycho

Registered Report Stage II

The role of interoceptive awareness in shaping the relationship between desire thinking and cigarette consumption

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ARTICLE INFO

Keywords:
Addiction
Tobacco use
Desire thinking
Interoception
Heart rate variability

ABSTRACT

Interoception, the ability to sense and interpret bodily sensations, has recently emerged as a crucial factor in substance use disorders, including smoking. However, the role of interoceptive awareness in tobacco use remains poorly understood. The relationship between interoceptive ability and addictive behavior is complex, and attempting to conceptualize it as a linear association is unlikely to fully capture the complexity of the mechanisms underlying cravings and urges. We hypothesized that the role played by interoceptive awareness in tobacco use is deeply linked to desire thinking, that is, the conscious and voluntary cognitive process orienting to prefigure images, information, and memories about positive target-related experiences. Desire thinking is typically observed in addiction, where it may contribute to interpreting specific bodily sensations, such as the perceived need for a cigarette. From this perspective, the physiological impact and inclination toward desire thinking contribute to a higher daily cigarette consumption, particularly in situations of low interoceptive awareness. To test this hypothesis, we assessed the physiological activation, the tendency toward desire thinking about smoking, cigarette consumption, and the interoceptive abilities of smoking volunteers. Through a moderation analysis, we showed that desire thinking about smoking predicts a higher number of cigarettes per day in individuals with lower interoceptive awareness ($p < .05$). These findings suggest that the relationship between desire thinking and interoceptive awareness is a fundamental component of tobacco use, highlighting the importance of taking into account the bodily feedback deriving from the cognitive representation of smoking in addiction research and therapy.

1. Introduction

Addiction involves significant changes in the neural circuitry related to reward and motivation (Volkow and Morales, 2015). Emotional experiences play a crucial role in substance use (Cheetham et al., 2010), accompanied by physiological changes, such as variations in heart rate, and influencing decision-making (Clore and Huntsinger, 2007). Over time, emotions-related bodily sensations become associated with their past outcomes, impacting future decision-making processes and guiding specific behaviors (Damasio, 1994). The perception of one's heartbeats has been shown to moderate the relationship between decision-making ability and reactivity to affective stimuli (Dunn et al., 2010; Werner et al., 2013). Conversely, false cardiac feedback can also modulate emotional appraisal (Gray et al., 2007) and moral behavior (Gu and Page-Gould, 2013). It is posited that altered processing of bodily signals may be related to substance use. For example, individuals who neglect bodily feedback may rely on non-bodily information (e.g., habits, memories, ideal body state representations) to guide decision-making regarding drug use, potentially leading to a misperception of the body's needs. Conversely, individuals who overestimate body feedback may experience aversive bodily sensations that contribute to withdrawal, amplifying craving and the urge to consume drugs (Verdejo-Garcia et al., 2012).

The process by which the nervous system senses, interprets, and integrates signals originating from within the body, creating a real-time map of the body's internal landscape, is known as interoception (Berntson and Khalsa, 2021). Interoception's main function is to efficiently mobilize crucial resources toward important targets (Quigley

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https://doi.org/10.1016/j.ijpsycho.2024.112369
Received 16 January 2024; Received in revised form 22 April 2024; Accepted 17 May 2024
Available online 18 May 2024

et al., 2021). Historically, interoception has been considered as a perception that follows bodily sensations. However, recent research suggests that the brain continuously predicts the body's energy needs (Sterling, 2012). From this perspective, interoception is achieved by comparing predictions with ascending interoceptive signals. The brain employs prior models to generate interoceptive predictions, which are then tested against sensory data to update the model accordingly (Barrett and Simmons, 2015). In Bayesian terms, our beliefs based on past experience represent the priors, the likelihood is the probability of interoceptive data, and the posterior reflects our updated belief considering the observed sensory evidence (Friston et al., 2012). A healthy interoceptive profile weights priors diversely and adaptively to account for the physiological noise associated with interoceptive ascending information (Ainley et al., 2016). Consequently, it has been proposed that inaccurate priors play a significant role in drug addiction (Friston, 2012).

Interoceptive accuracy and interoceptive sensibility are two distinct concepts related to our perception of internal bodily sensations. Interoceptive accuracy refers to the objective ability to detect these sensations (referred to as the likelihood of interoceptive data), while interoceptive sensibility relates to our self-perceived tendency to be aware of them (referred to as interoceptive priors). Since subjective and objective ratings can differ, we can calculate a level of conscious insight known as interoceptive awareness (IA), which represents the correspondence between objective and self-perceived interoceptive performance or the accuracy of our priors (Garfinkel et al., 2015). IA can be measured by examining the difference between interoceptive sensibility and accuracy, which indicates the degree of over- or undervaluation. In this way, we can determine how well interoceptive priors account for the actual probability of inner perception.

Previous works did not find any significant correlation between smoking habits and interoceptive accuracy or sensibility (Hina and Aspell, 2019). Accordingly, we believe that these measures taken separately may not account for the complexity of tobacco use. While the ability to perceive bodily information is essential to survival behaviors, being aware of the reliability of interoceptive perception makes it possible to adjust properly the representations of our needs. We thus hypothesized that individuals with low IA might misinterpret bodily information as a need for a cigarette, leading to increased tobacco use. This suggests that IA could influence cigarette consumption. However, to comprehensively account for this model, an additional factor must be considered, contributing to the misinterpretation of bodily signals specifically as a need for cigarettes, rather than something else.

Some researchers argue that the escalation and persistence of craving are influenced not only by the context of use but also by the activation of “desire thinking”, a conscious and voluntary cognitive process that involves imagining positive target-related experiences, such as prefiguring images, information, and memories about smoking (Caselli and Spada, 2015). For example, when someone experiences negative sensations due to craving, they might engage in desire thinking to mentally simulate the act of smoking, plan how to obtain a cigarette, and compare the actual sensation with the feelings associated with smoking to regulate their internal state (Caselli et al., 2013). Initially, this activity may have a positive effect by momentarily decreasing the unpleasant sensation of abstinence or withdrawal. However, it can increase the strength of memories associated with the context of smoking (Mattioni et al., 2023), thus making tobacco-related information more accessible and biasing attention toward the smoking context (Spada et al., 2015). Furthermore, desire thinking intensifies levels of craving (Caselli et al., 2013), consequently amplifying the related physiological impact of stress (Sinha, 2009), as evidenced by its influence on heart rate (Kennedy et al., 2015). In particular, the spectral high frequency of heart rate variability (HRV), which is considered a quantitative marker of parasympathetic activity (Malik et al., 1996; Ziemssen and Siepmann, 2019), was shown to be decreased by smoking-related imagery (Erblich et al., 2011) and to predict better smoking outcomes (Libby et al., 2012).

In the present study, we tested if IA could play a role when engaging in desire thinking about smoking. In this view, this cognitive process may increase stress-related physiological activity, thereby reducing parasympathetic control. Thus, during desire thinking, information coming from the body may be interpreted as a need for a cigarette as a result of the tendency to mentally prefigure the smoking context. Individuals lacking proficiency in assessing their ability to perceive bodily sensations may frequently attribute interoceptive signals to the urgent need to smoke for relief, misinterpreting bodily information as linked to that context and, consequently, smoking more. First, we hypothesize an inverse relationship between the extent of increase in high-frequency HRV during desire thinking and smoking habits when accounting for the influence of IA. This would indicate that desire thinking about smoking induces physiological changes that could lead to increased cigarette consumption in individuals with low IA. Second, we expected that the relationship between self-reported predisposition to desire thinking about smoking and cigarette consumption would be negatively moderated by IA. This would indicate that IA might act as a protective factor against the severity of smoking habits induced by the tendency to engage in desire thinking. To test our hypotheses, we assessed heart rate patterns during guided imagery and resting state, the number of cigarettes smoked per day, and interoceptive accuracy, sensibility, and awareness in a group of forty smoker volunteers. Signals originating from the heart represent the most widely accepted interoceptive mechanisms (Nord and Garfinkel, 2022). Among the methods employed to measure cardiac interoceptive accuracy, heartbeat detection (HBD) stands out as one of the most commonly utilized. Therefore, in the current study, HBD was selected as the primary focus.

2. Methods

2.1. Participants

After obtaining consent, we recruited forty-nine people who smoke (30 females and 19 males) from a list of university students who were willing to take part in behavioral experiments at the D'Annunzio University of Chieti, Italy. Participants were made aware of the current study via advertisement. We randomly divided the sample into two groups, an experimental group engaging in desire thinking and a group engaging in a control imagination task. Participants were Italian native speakers aged between 18 and 30 years (mean age = 22.28; SD = 2.98). Exclusion criteria were the current presence of heart problems and the undergoing of treatment employing psychotropic drugs. Informed consent was obtained from each participant. The research project was approved by the Ethics Committee of the Provinces of Chieti and Pescara (Verbal #22; Oct, 8th, 2020).

2.2. Procedure

Three days before the experiment, participants received and completed the Desire Thinking Questionnaire [DTQ (Caselli and Spada, 2011)], which assesses their tendency to engage in desire thinking about smoking and they were asked to indicate the number of cigarettes smoked per day. The questionnaires were administered using the online survey tool Qualtrics.

Once in the lab, each volunteer performed a guided imagery phase followed by other measures not related to the current study. The following day all participants performed a ten-minute resting state phase, in which they were instructed to watch a cross on the screen for ten minutes allowing their mind to wander, followed by HBD Task (Melloni et al., 2013), a standard procedure designed to measure their interoceptive abilities. The electrocardiogram (ECG) signal was recorded during all experimental phases. Participants were instructed to abstain from smoking or drinking coffee on both days before the experiment, which took place in the morning. In this way, we were able to exclude the acute effects of cigarette smoking (Karakaya et al., 2007) and caffeine (Koenig et al., 2013) on heart rhythm during ECG.

2.2.1. Electrocardiogram

To measure ECG data, three electrodes were used: the ground placed over the right costal margin, the VIN+ placed over the left costal margin, and the VIN- located on the right clavicle. The ECG signal was recorded at a sampling rate of 2 kHz and high pass filtered at 1 Hz to remove baseline fluctuation. Additionally, a 50 Hz comb bandpass and a 35 Hz low pass filter were applied to remove possible artifacts caused by movements. The response collection was conducted using *E*-Prime 3.0 software, while an MP160 BIOPAC system was used to record the ECG signal. Time points of the heartbeats were analyzed and calculated through AcqKnowledge software.

2.2.2. Guided imagery phase

This study utilized two comparable guided imagination conditions, specifically desire thinking and control, each comprising 16 items. In both conditions, participants were instructed to close their eyes and focus their attention on a set of items for approximately 8 min. These items contained suggestions and instructions designed to stimulate cognitive elaboration. Following 3 min of silence, the items were presented to participants via an audio recording, with a 30-s interval between each item. In the desire thinking condition, participants were directed to recall past episodes related to smoking or plan for future opportunities to smoke. For example, they were asked to "Imagine yourself while smoking" or "Plan everything you could do to obtain a cigarette as soon as possible." These items were adapted from the DTQ (Caselli and Spada, 2011). This thinking manipulation had been previously used in a study, demonstrating that it could effectively increase craving by eliciting verbal perseveration (Caselli et al., 2013). In the control task, participants were instructed to recall the route they had taken to reach the laboratory and to plan their return home after the experiment. For instance, they were asked to "Imagine yourself on your way here" or "Plan everything you should do to return home after the experiment." The rationale for selecting these items was to employ a thinking manipulation that engaged participants in cognitive processes similar to those in the desire thinking condition, but without evoking smoking-related content. In this way, even if some participants had begun to think about their desire to smoke during this phase, it is highly improbable that this persisted for an extended duration and surely didn't match the level of reminders given to the experimental group regarding this mental activity. This is especially considering the regularity of the audio prompts presented every 30 s which would have distracted them in case they had engaged in desire thinking. Audio stimuli were delivered through high-performance JBL headphones, and this phase of the study lasted 11 min. During this phase, the ECG signal was recorded to allow the comparison of physiological activation observed in both desire thinking and control conditions with recordings obtained during a 10-min resting-state phase. The ratio between these measurements functions as an indicator of the deviation from rest induced by our guided imagination conditions.

2.2.3. Heartbeat detection task

The HBD task assesses interoceptive accuracy, which refers to individuals' ability to detect their heartbeats (Garfinkel et al., 2015). During the HBD Task, participants were instructed to focus their attention on their heartbeats while keeping their eyes closed and tapping a button in synchrony with each detected heartbeat. Simultaneously, participants' heartbeats were recorded. The HBD task consisted of 2 blocks lasting 2.5 min each.

2.3. Measures

2.3.1. Spectral heart rate variability

Spectral HRV is a valuable physiological measurement that assesses the variability in the time intervals between successive heartbeats, or RR intervals, as analyzed in the frequency domain (Malik et al., 1996; Ziemssen and Siepmann, 2019). It quantifies the complex interplay between the sympathetic and parasympathetic branches of the autonomic nervous system that regulate heart rate. Spectral HRV analysis involves computing a fast Fourier transform of the RR interval sequences, breaking down HRV into different frequency components. High-frequency cyclical changes in heart rate (0.15–0.40 Hz) occur in association with respiration and it is primarily associated with vagal activity, reflecting the body's capacity for rest and recovery (Grossman and Taylor, 2007). This vagal pathway influences emotional experience, regulation, and communication functioning as a brake to the sympathetic nervous system (Porges, 2011). We calculated the high-frequency power spectral density of RR intervals during the imagery and resting state phase of the subsequent day. The ratio between these values indicates the extent to which our guided imagination conditions deviate from the resting state in influencing cardiac vagal control (CVC).

2.3.2. Interoceptive accuracy

We initially time-locked each tapped response to the R-peaks of the participants' ECG. Subsequently, we calculated a window of accurate response following each R-peak (Fig. 1). The length of these time windows varied depending on the participant's heart rate. To account for differences in heart rate between participants, we utilized their instantaneous HR values (Zaccaro et al., 2022). For each R-peak, we determined the time from the current R-peak of the heart wave to the R-peak point of the next wave. Accordingly, we considered 750 ms after the R-peak for an instantaneous HR less than 69.76 bpm; 600 ms after the R-peak for an instantaneous HR between 69.75 bpm and 94.25 bpm; and 400 ms after the R-peak for an instantaneous HR higher than 94.25 bpm. The number of correct responses during these specific time intervals was then averaged between the two blocks to obtain a measure of interoceptive accuracy. This measure represents the objective ability to detect interoceptive sensations, i.e. the likelihood of interoceptive data.

2.3.3. Interoceptive sensibility

After each block, participants were requested to verbally rate their performance on a scale ranging from 1 (indicating their performance was as good as random) to 10 (indicating their performance was perfect This rating served as an indication of their self-perceived dispositional tendency to be interoceptively cognizant, which is defined as interoceptive sensibility (Garfinkel et al., 2015). The scores obtained from each block were subsequently averaged together to assess interoceptive sensibility. This measure represents the level of certainty about one's ability to detect bodily sensations, i.e. the interoceptive priors.

2.3.4. Interoceptive awareness

IA was calculated through the absolute difference between the rescaled (min-max normalization) measures of interoceptive accuracy and sensibility (Eq. 1), accounting for the relationship between the objective and the self-perceived performance (Garfinkel et al., 2015). The scores related to each block were then averaged together to assess IA. This measure represents the reliability of interoceptive sensibility, or the reliability of interoceptive priors.

The formula used to calculate IA. InAw = Interoceptive Awareness; InAc = Interoceptive Accuracy; InSe = Interoceptive Sensibility:

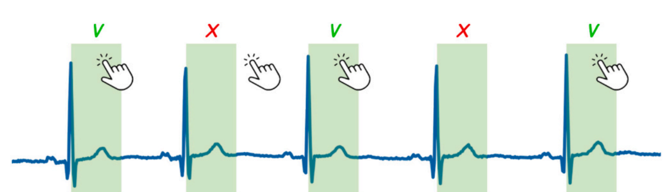

Fig. 1. Schematic representation of the heartbeat detection task.

$$InAw = 1 - abs\left(\left(\frac{InAc - min(InAc)}{max(InAc) - min(InAc)}\right) - \left(\frac{InSe - min(InSe)}{max(InSe) - min(InSe)}\right)\right) \quad (1)$$

2.3.5. Desire thinking questionnaire

The DTQ is a 14-item self-report measure, validated in Italian, where participants rate their agreement with a series of statements on a 4-point Likert-type scale (Almost never, Sometimes, Often, Almost always). This measure aims to assess the tendency to engage in a voluntary cognitive process that involves the verbal and imaginal elaboration of smoking-related thoughts. It can be divided into two factors: Verbal Perseveration, which focuses on the perseveration of verbal thoughts about desire-related content and experience (e.g., "I repeat mentally to myself that I need to smoke" and "When I begin to think about smoking I find it difficult to stop"), and Imaginal Prefiguration, which concerns the tendency to prefigure images related to desire and smoking experience (e.g., "I imagine myself smoking" and "I anticipate the sensations I would feel smoking").

2.4. Statistical analysis

As a control analysis, we conducted a series of Mann-Whitney tests to compare the experimental and control groups across all study measures. This initial step was essential to rule out any potential sampling bias, and we expected that no significant between-subject differences would emerge.

Following this, we employed a Spearman correlation analysis, focusing on the CVC change between imagery and resting state, in relation to cigarette consumption and DTQ scores. Our goal here was to explore whether the autonomic influence resulting from our critical manipulation could be associated with participants' smoking habits. We hypothesized that a statistically significant negative relationship between the CVC change and all smoking habit variables would emerge, but only within the experimental group. This result would indicate that the amount of reduced vagal control over the heart during desire thinking may be an index of the severity of tobacco use.

We subsequently conducted a moderation analysis to investigate whether IA plays a significant role in influencing the connection between CVC change and cigarette consumption. This analysis enabled us to examine whether the awareness of the reliability of interoceptive sensibility can mitigate the relationship between a decrease in vagal control during desire thinking and the severity of tobacco use. We hypothesized that IA would serve as a significant positive moderator in the experimental group exclusively, influencing the proposed relationship. Additionally, we performed a secondary moderation analysis using the entire sample to examine whether IA might serve as a negative moderator in the association between DTQ scores and cigarette consumption. A significant finding would indicate that IA lessens the relationship between the tendency to engage in desire thinking and tobacco use. In order to control for heterogeneity of variance in these interactions we use a robust standard errors method, or HC3, which works well for sample sizes as small as 25 (Long and Ervin, 2000).

Correlations were implemented using the software SPSS Statistics 25 (IBMcorp., 2021), and moderation analyses were carried out through PROCESS macro model 1 (Hayes, 2017).

3. Results

Averages of measures used in the study are reported in Table 1. In control analyses, Mann-Whitney tests revealed no statistically significant differences (all $p > .05$) between the experimental and control groups in terms of age, cigarette consumption, DTQ scores, interoceptive measures, and their respective CVC changes.

Within the experimental group, after Bonferroni correction for multiple comparisons ($\alpha = 0.05/2 = 0.025$) significant Spearman correlations were observed between the change in CVC and DTQ score (Rho = −0.476; $p = .014$; Fig. 2A) but not with cigarette consumption (Rho = −0.362; $p = .069$; Fig. 2B). Within the control group, both relationships were not statistically significant [DTQ (Rho = −0.144; $p = .534$; Fig. 2C); cigarette consumption (Rho = −0.272; $p = .210$; Fig. 2D). These findings confirm that changes in CVC due to our crucial thinking manipulation could indeed account for the tendency to engage in desire thinking. However, a simple linear correlation between the reduction in parasympathetic control during engagement in desire thinking and the severity of smoking habits was not statistically significant.

Table 2 presents the results of the moderation analysis, examining the relationship between changes in CVC and cigarette consumption within the experimental group (Fig. 3). As anticipated, IA emerged as a significant positive moderator in the relationship between alterations in CVC during desire thinking and cigarette consumption ($F = 4.354$; $p = .049$). This finding underscores that a heightened awareness of interoceptive sensibility is associated with a reduced impact of decreased parasympathetic control during desire thinking on the severity of tobacco use. In contrast, within the control group, the moderating effect of IA did not reach statistical significance ($F = 2.431$; $p = .135$).

The results of the second moderation analysis (Fig. 4), considering the relationship between DTQ score and cigarette consumption in the entire sample, are presented in Table 3. The negative moderating effect of IA was statistically significant ($F = 4.494$; $p = .040$). This suggests that greater awareness of the reliability of interoceptive sensibility could reduce the impact of the tendency to engage in desire thinking on tobacco use.

4. Discussion

The primary objective of this study was to shed light on the role of IA in desire thinking and tobacco use. Our hypotheses posited that a diminished capacity to accurately assess one's interoceptive information would lead to misinterpretation of bodily signals as cues for cigarette craving when engaging in desire thinking. The results support our hypothesis, showing that IA acted as a moderator within the relationship between the CVC change induced by desire thinking and cigarette consumption. This finding indicates that the physiological activity due to desire thinking about smoking could lead to higher cigarette consumption in people with low IA. Furthermore, we showed that IA was a significant moderator within the relationship between the self-reported tendency to engage in desire thinking and tobacco use, further supporting our hypothesis. Taken together these results suggest that IA could protect against misinterpretation of bodily feedback as a need for a cigarette considering both the physiological effect and the propensity toward desire thinking.

These results lend strong support to the perspective that addiction represents a maladaptive utilization of neurophysiological mechanisms,

Table 1
Averages of the participants' age, years of smoking, number of cigarettes smoked per day, DTQ score, IA level, and CVC change are reported (standard deviations in brackets).

Group	N	Age	Years	Cigarettes	DTQ	IA	CVC change
Experimental	26	22.8(3.1)	6.4(2.9)	7.4(5.0)	19.0(4.9)	0.76(0.14)	1.2(0.5)
Control	23	22.0(2.9)	5.8(2.8)	8.8(4.6)	19.7(6.5)	0.80(0.14)	1.1(0.4)
Total	49	22.4(3.0)	6.1(2.8)	8.0(4.8)	19.3(5.6)	0.78(0.14)	–

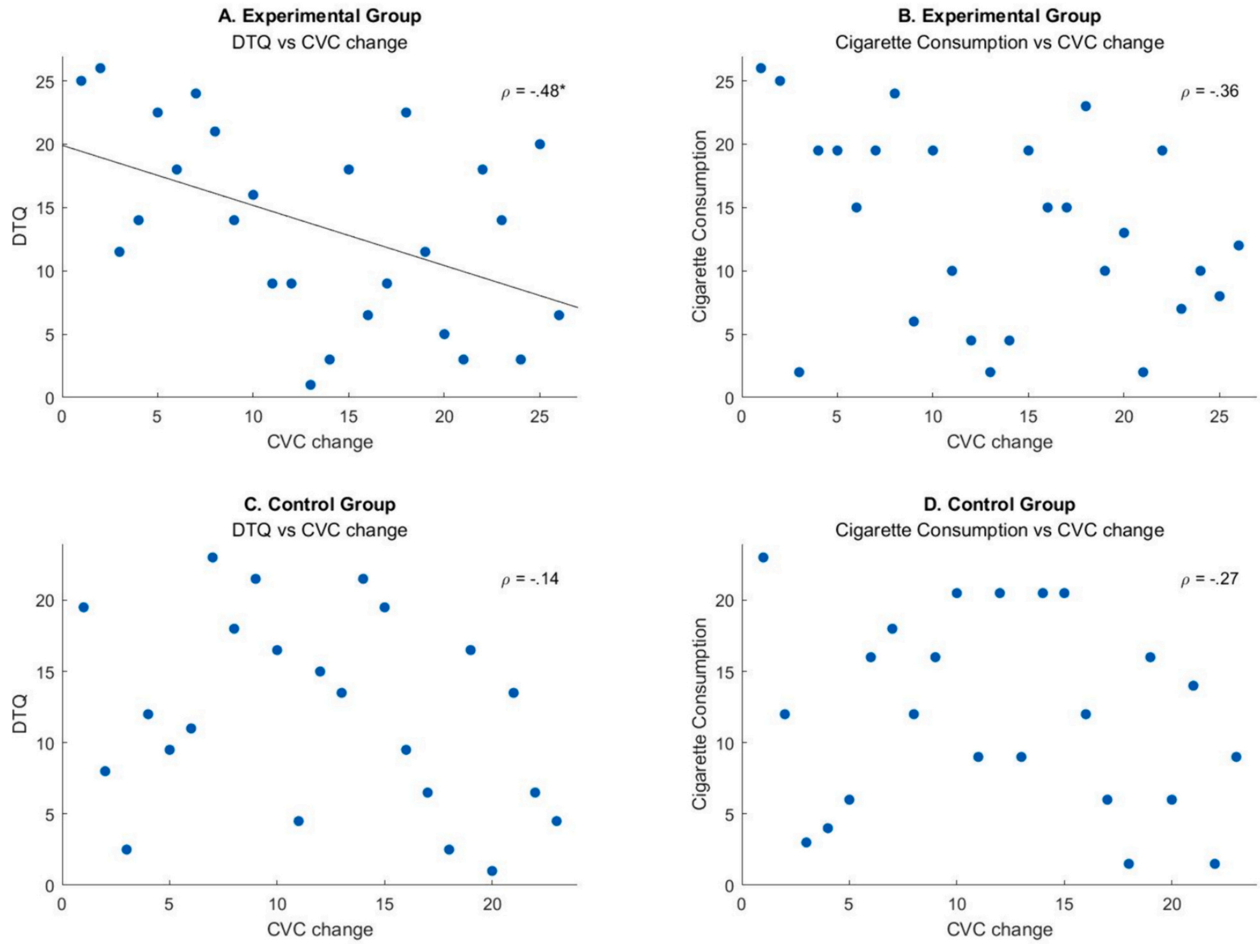

Fig. 2. Results of the Spearman correlations between CVC change, DTQ, and cigarette consumption in both experimental and control groups. * = $p < .025$.

Table 2
Moderation analysis considering the effect of IA on the relationship between CVC changes and cigarette consumption within the experimental group.

Model	coeff	se	t	p	95 % Confidence Interval	
					Lower bound	Upper bound
Constant	34.87	13.16	2.65	0.014	7.59	62.16
CVC	−25.53	11.24	2.27-	0.033	−48.84	−2.23
IA	−29.66	16.30	−1.82	0.082	−63.47	4.16
CVC * IA	27.47	13.17	2.09	0.049	0.17	54.78

which, in regular circumstances, play a role in shaping survival-oriented behaviors linked to the pursuit of rewards and the recognition of cues that herald them (Hyman, 2005). The perceived body is in constant flux, shaped by a continuous interplay between incoming sensory signals and predictions derived from previous instances. This dynamic process efficiently meets the body's need. Should a mismatch between anticipated and actual somatic signals occurs, individuals instinctively enact corrective regulatory measures to alleviate the discordance. One strategy for such self-regulation involves adjusting the reliability of sensory signals, thereby adaptively biasing attention toward bodily signals in accordance with the contextual demands (Barrett and Simmons, 2015). These adaptive corrective actions guide optimal decision-making, promoting homeostatic balance. Conversely, persistent failure to rectify prediction errors culminates in choices that hinder the establishment of optimal conditions for internal bodily functioning optimization (Khalsa and Feinstein, 2018). Repetitive attempts at such corrective measures lead to maladaptive thoughts and behaviors, contributing to ongoing discrepancies between predicted and observed body states (Paulus et al., 2019). Consistent with this, individuals grappling with addiction exhibit deficits in modulating the reliability of afferent interoceptive signals during instances of somatic perturbation (Smith et al., 2020). Furthermore, desire thinking intensifies levels of craving (Caselli et al., 2013), consequently amplifying the physiological impact of stress triggered by cravings (Sinha, 2009), as evidenced by increased heart rate (Kennedy et al., 2015). This, in turn, further reinforces the influence of the proposed interoceptive bias.

Viewing cigarette consumption merely as a byproduct of the connection between tobacco use and its impact on bodily sensations falls short in elucidating the reasons behind individuals' relapses after extended periods of abstinence, a circumstance where this association should theoretically diminish over time. Despite this, it is well known that craving persists even amidst efforts of smoking cessation (Waters et al., 2004), and can precipitate relapse (Shiffman, 2005) even years following abstention (Caraballo et al., 2014). Instead, considering the interplay between IA and desire thinking, which involves the sustained mental representation of the smoking context, may offer insight into these empirical observations. This perspective underscores that the cognitive representation of drug use can trigger a response akin to the actual consumption of the drug itself (Skinner and Aubin, 2010). Accordingly, this viewpoint suggests that the interpretation of bodily feedback, influenced by desire thinking about smoking, might hold greater significance than the actual interoceptive sensations experienced while smoking.

Likewise, our findings offer potential insights into deciphering prior discoveries concerning the neural circuits implicated in tobacco use. Naqvi et al. (2007) discovered that most individuals who sustained

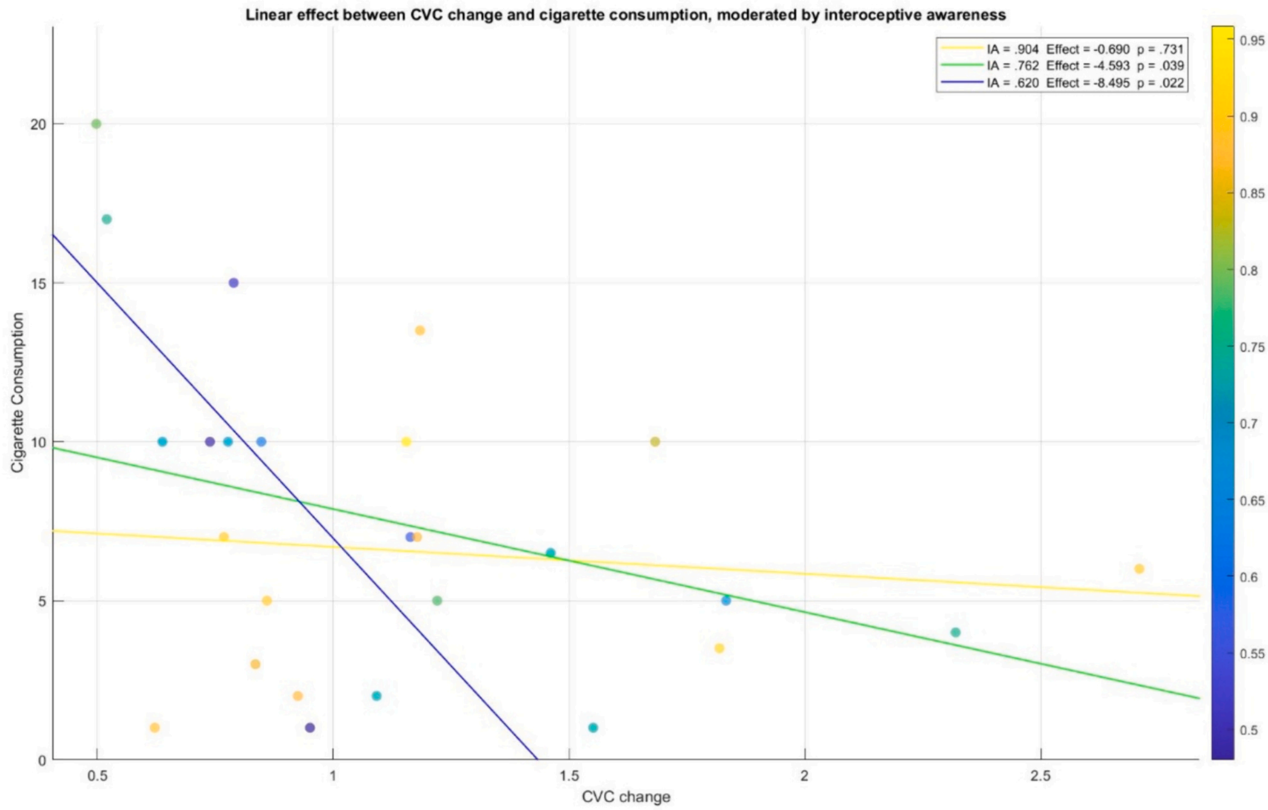

Fig. 3. Results of the moderation analysis showing the influence of IA on the relationship between CVC change and cigarette consumption within the experimental group. The color of the dots corresponds to the level of IA for each subject, as indicated by the bar on the right. For visualization purposes, the regression estimates are presented at discrete values of the moderator: high IA (1 SD above mean, yellow line), medium IA (mean level, green line), and low IA (1 SD below mean, blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

damage to the insula, a brain region that plays a crucial role in integrating top-down and bottom-up interoceptive information (Kleckner et al., 2017), showed an immediate cessation of smoking devoid of conscious urges to smoke. These findings may imply that insula impairment results in diminished smoking pleasure (Naqvi and Bechara, 2010). However, it should be noted that insula activity is primarily related to the conscious urge to indulge in drug use rather than the actual drug-taking act (Tiffany, 1990). Given the complex interplay between desire thinking and IA, it is possible to suggest that the reason smoking cessation occurs after insula damage may be due to the compromised influence of desire-based thinking on bodily information. In essence, the inability of desire thinking to impact interoception may underlie the decline in the perpetuation of tobacco use. Furthermore, this brain region is uniquely engaged in contrasting current and envisioned feelings (Preuschoff et al., 2008) and in marking significant triggers of self-regulatory mechanisms (Menon and Uddin, 2010), both integral facets of desire thinking.

In our view, when interoception lacks reliability, desire thinking leads the brain to continuously translate physiological activity into information regarding the need for cigarettes for body state regulation, even during periods of abstinence. We, thus, suggest that desire thinking emerges as a pivotal target in the conceptualization and treatment of cigarette use. This underscores the importance of therapeutic interventions encompassing awareness training for cognitive style and interoception alike.

4.1. Limitations

One limitation inherent to the present study stems from the exclusive sampling of the university population, inherently yielding a narrower range of sociodemographic diversity in comparison to the broader general population. Nonetheless, it is noteworthy that university students are notably exposed to factors that can contribute to the development of addiction (El Ansari et al., 2015), making them a pertinent demographic for investigating this facet of preclinical substance use and for shaping pertinent public health strategies and preventive interventions. A second limitation is the young age and the relatively limited experience of smoking of participants, which may had impacted the results. Furthermore, an additional constraint lies in the temporal context within which the study was conducted – amidst the global COVID-19 pandemic. The rapidly evolving dynamics of this situation may have potentially influenced participants' smoking habits due to stress, social isolation, or altered daily routines. Regrettably, this influential variable remained unaccounted for in the scope of the current research.

5. Conclusions

Addiction and interoception are intricately intertwined, however, the presence of distinct drug-taking behaviors and the subjective nature of craving pose challenges to comprehending this relationship. In our study, we have demonstrated that heightened cigarette consumption corresponds to the interplay between IA and desire thinking about smoking. In fact, our results show that participants with lower IA showed a higher relationship between desire thinking and cigarette consumption. These results point out the significance of considering cognitive and interoceptive components of craving in tandem with tobacco use, thereby enhancing the precision of our conceptualization of cigarette smoking. In forthcoming research endeavors, it would be valuable to not only replicate our findings across diverse forms of

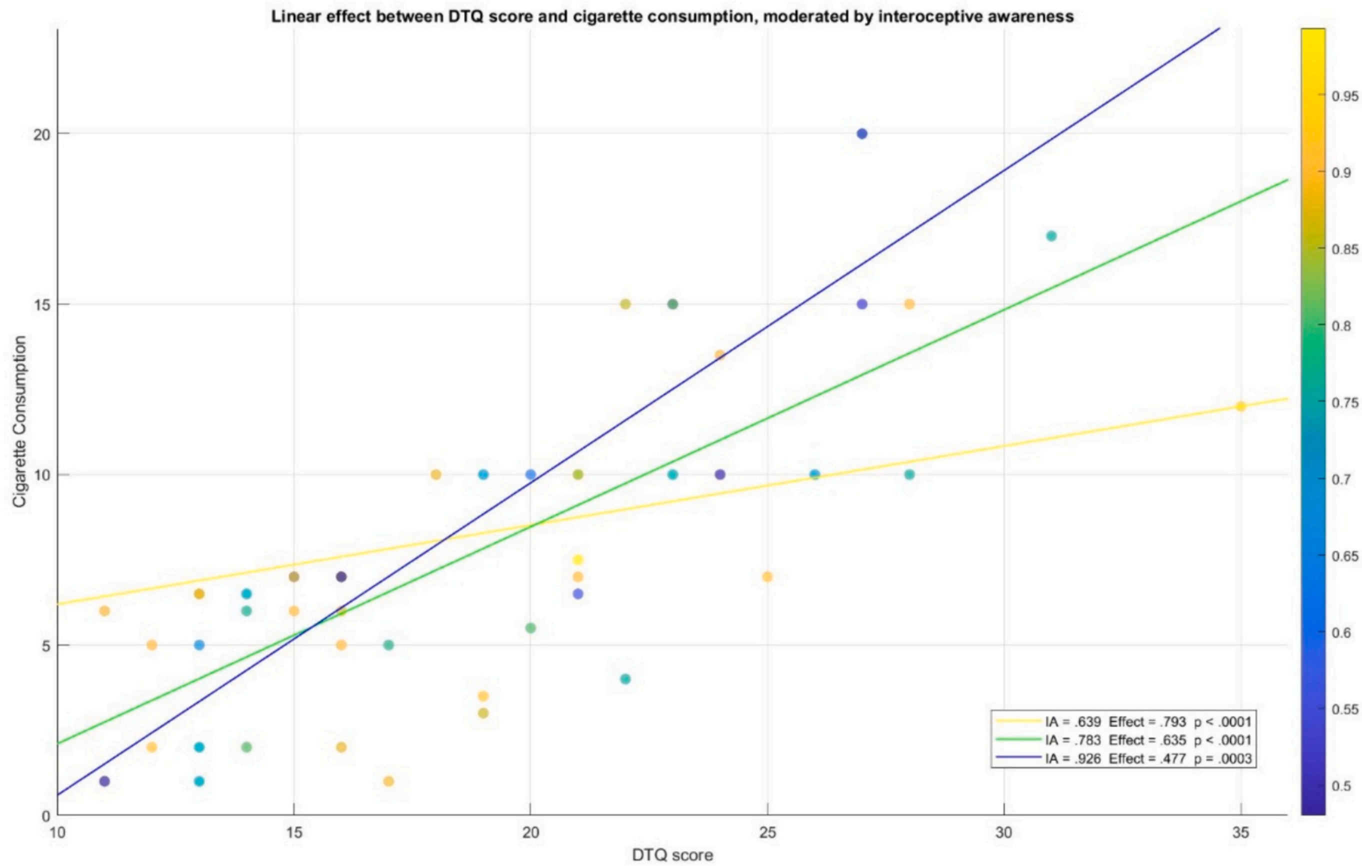

Fig. 4. Results of the moderation analysis showing the influence of IA on the relationship between DTQ score and cigarette consumption. The color of the dots corresponds to the level of IA for each subject, as indicated by the bar on the right. For visualization purposes, the regression estimates are presented at discrete values of the moderator: high IA (1 SD above mean, yellow line), medium IA (mean level, green line), and low IA (1 SD below mean, blue line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Moderation analysis considering the effect of IA on the relationship between DTQ scores and cigarette consumption.

Model	coeff	se	t	p	95 % Confidence Interval	
					Lower bound	Upper bound
Constant	−17.84	6.78	−2.63	0.012	−31.50	−4.17
DTQ	1.49	0.40	3.76	0.001	0.69	2.30
IA	17.31	8.96	1.93	0.060	−0.75	35.36
DTQ * IA	−1.10	0.52	−2.12	0.040	−2.14	−0.05

addiction but also encompass various manifestations of perseverative thinking. This encompasses the continuous cognitive representation of stressors aimed at managing the adverse consequences of negative emotions, such as worry and rumination. Such investigations would provide valuable insights into whether the interplay between perseverative thinking and interoception could potentially serve as a preclinical transdiagnostic factor, extending its influence beyond maladaptive behaviors and encompassing a broader spectrum of cognitions.

Funding statement

This study was supported by the "Departments of Excellence 2018–2022" initiative of the Italian Ministry of Education, University and Research for the Department of Neuroscience, Imaging and Clinical Sciences (DNISC) of the University of Chieti-Pescara.

CRediT authorship contribution statement

Lorenzo Mattioni: Writing – original draft, Investigation, Conceptualization. **Carlo Sestieri:** Writing – review & editing, Supervision. **Mauro G. Perrucci:** Software. **Marcantonio M. Spada:** Writing – review & editing. **Francesca Ferri:** Writing – review & editing, Visualization, Supervision.

Declaration of competing interest

None.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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