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Socio-economic status modulates the link between vagal tone and chocolate consumption

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ABSTRACT

Socio-economic status (SES) correlates with patterns of food consumption, yet the underlying physiological mechanisms remain unclear. This study examines how SES modulates the relationship between vagal tone, a physiological marker of self-regulation, and chocolate consumption. Different hypotheses about how SES may be linked to vagal regulation of chocolate consumption were put to a test in a laboratory study with a socio-economically diverse group of students ($n = 96$). Vagal tone was assessed using an index of heart rate variability (HRV–HF) measured at rest (baseline) and during acute stress. Participants' chocolate consumption was measured using a bogus taste test. The results showed that socio-economic status interacted with vagal tone to influence chocolate consumption. Findings for both subjective and objective indicators of SES converged in showing that vagal tone predicted chocolate consumption among higher SES participants, with higher vagal tone associated with lower chocolate consumption. No such relationship was found in lower SES participants, suggesting a dissociation between vagal regulation and eating behaviour in this group. These findings highlight the importance of considering autonomic regulation in understanding socio-economic disparities in dietary behaviours.

The Covid-19 pandemic has underscored socio-economic disparities in health outcomes, particularly in relation to non-communicable diseases (NCDs) such as obesity, diabetes, and cardiovascular conditions. Socio-economic status (SES) is frequently associated with behavioural risk factors, including unhealthy diets (Stringhini et al., 2010). While it is well-documented that SES correlates with patterns of healthy and unhealthy food consumption (Darmon & Drewnowski, 2008), the mechanisms underlying inequalities in dietary behaviour remain complex and not fully understood.

Most prior research has focused on external factors contributing to eating behaviour. For example, lower SES groups tend to reside in environments where calorie-dense, processed foods are more accessible and affordable, which corresponds with poorer dietary choices (Pechey et al., 2013). External cues like portion sizes may also have a stronger effect on lower (vs. higher) SES individuals (Best & Papies, 2019; but see Langfield et al., 2023). This study shifts attention to internal factors by examining how SES may relate to the internal regulation of dietary behaviours, focusing on vagal tone as a marker of self-regulation.

1. Vagal tone and self-regulation

Vagal tone refers to the activity of the vagus nerve, a key component of the parasympathetic nervous system that regulates functions such as heart rate and digestion (Thayer & Lane, 2009). Vagal tone is typically measured through heart rate variability (HRV), which reflects fluctuations in the intervals between heartbeats (Kuo et al., 2005; Laborde et al., 2017). The vagus nerve receives signals from gut hormones and plays a significant role in satiety and appetite regulation (Cork, 2018), providing a neural conduit to transfer signals between the brain, gut, and pancreas (e.g., Breit et al., 2018).

The vagus nerve also modulates the hypothalamic–pituitary–adrenal (HPA) axis, which is essential to the human stress response and influences the digestive system via hormonal mechanisms. Stimulating the HPA axis is linked to reduced vagal tone, whereas stimulating the vagus nerve can modulate HPA activity (Agorastos et al., 2019; Fang et al., 2023; O'Keane et al., 2005). The HPA axis controls the release of cortisol, which boosts blood sugar levels that prompt the production of insulin in the pancreas through vagal signals (Imai et al., 2008). Thus, different branches of the vagal nerve are central to the regulation of

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physiological responses, maintaining homeostasis, and adapting to situational demands (Porges, 2001, 2007).

The sympathetic and parasympathetic branches of the nervous system work with the central nervous system to form the central autonomic network (CAN), integrating signals from the body and modulating autonomic responses. The vagus nerve transmits information to the CAN, while descending pathways enable two-way communication (Bonaz et al., 2017; Kalia & Sullivan, 1982). Drawing on this interconnectivity, the neuro-visceral integration model (Thayer et al., 2009) posits that vagal tone serves as a proxy for the inhibitory capacity of the CAN, making HRV a non-invasive measure of autonomic activity. Individuals with higher vagal tone tend to exhibit stronger top-down control over automatic processes, facilitating better emotional regulation and impulse control (Park & Thayer, 2014; Sakaki et al., 2016). These self-regulatory processes are particularly relevant for adapting to food cues, such as resisting the urge to overeat or consume unhealthy foods (Meule et al., 2012).

Conversely, lower vagal tone has been associated with difficulties in self-regulation (Zahn et al., 2016), which may manifest in impulsive behaviours, emotional eating, and reduced capacity to resist food cues. Consistent with this, studies have found that individuals with lower HRV are more prone to cravings and consume high-calorie foods (Friederich et al., 2006; Rodríguez-Ruiz et al., 2009; Spitoni et al., 2017; Wu et al., 2020), while increasing HRV through biofeedback can curb cravings (Meule et al., 2012). Fasting and healthy diets are similarly linked to improved appetite regulation and increased HRV (Cansel et al., 2014; Dai et al., 2010). These findings collectively point to a key role of vagal tone in self-regulating eating, which, as discussed next, may help to explain the association between SES and dietary behaviours.

2. Vagal tone, SES, and eating behaviour

Vagal tone has been shown to vary with socio-economic factors. Chronic stress, often associated with financial insecurity, poor living conditions, and limited social support, is linked to dysregulated physiological processes, including lower vagal tone (Kim et al., 2018; Porges, 1995). Chronic stress tied to socio-economic conditions—in particular adverse conditions experienced during childhood (Hill et al., 2016)—may correspond with difficulties in regulating eating based on bodily needs, resulting in unhealthier diets in obesogenic food environments (Mengelkoch & Hill, 2020). Consistent with this, studies show that food intake tends to be driven more by opportunity than by hunger or satiety in individuals who experienced low SES during childhood (Hill et al., 2016). Given the role of the vagus nerve in signalling satiety and regulating food intake, while also responding to socio-economic conditions, it stands to reason that socio-economic disparities in eating may be connected to vagal tone.

The literature supports at least three distinct hypotheses about the ways in which SES-related differences in the vagal regulation of eating behaviour can manifest. First, as alluded to earlier, some studies have found positive associations between baseline HRV—measured at rest or over a 24-h period—and indicators of SES, including employment grade (Hemingway et al., 2005), social class (Lampert et al., 2005), and education and income (Sloan et al., 2005). Given that, as discussed earlier, both lower (vs. higher) SES and lower baseline HRV have been linked with less effective eating regulation, one might expect that baseline HRV mediates the association between SES and eating. In this scenario, lower (vs. higher) SES corresponds with diminished (baseline) HRV, giving rise to what we term a "blunting hypothesis".

Second, while studies on vagal tone and eating have focused on baseline HRV, vagal reactivity—changes in HRV in response to situational demands—can also be linked to less effective self-regulation (Beauchaine, 2015; Thayer et al., 2009). Stressful situations activate the sympathetic nervous system and deactivate the parasympathetic nervous system. The resulting vagal withdrawal reflects an adaptive response to environmental challenges (Thayer & Lane, 2009). However, high vagal withdrawal can become maladaptive, especially when the situation demands effective executive control (Laborde et al., 2017; Thayer et al., 2012). Consistent with this, high vagal withdrawal has been associated with impulsivity and other externalising problems (Beauchaine et al., 2019).

Even though little is known about the link between vagal withdrawal and eating, stress, which triggers vagal withdrawal, predicts food intake (Araiza & Lobel, 2018); in particular, intake of foods high in sugar and fat (O'Connor et al., 2008). For example, Habhab et al. (2009) showed that experimentally induced stress increased subsequent consumption of sweet, high-fat food. Based on this, one might suspect vagal withdrawal induced by acute stress to be linked to increased subsequent food intake; most notably, 'comfort food' high in sugar and fat.

The connection between SES and vagal withdrawal is similarly less well researched. Some studies have documented an association between lower social standing and greater vagal withdrawal (Fuller-Rowell et al., 2013), especially in social interaction settings (Cundiff et al., 2016; Kraus & Mendes, 2014). However, other studies have failed to observe an association between SES and cardiac responses during acute stress (Boylan et al., 2016; Boylan et al., 2018). Thus, more research is needed to determine whether SES is linked to vagal withdrawal, and if so whether this is connected to differences in eating behaviours. In this scenario, which we term "hyperreactivity hypothesis", lower (vs. higher) SES is associated with heightened vagal withdrawal, which in turn predicts subsequent food intake.

Our third and final hypothesis posits that lower SES is associated with a disconnect between vagal tone and eating behaviour. This "dissociation" hypothesis is supported by research on SES and interoceptive sensitivity—the awareness of internal bodily signals such as hunger and satiety. Reduced interoceptive sensitivity has been associated with chronic stress and environmental unpredictability (Bonaz et al., 2021; Büttiker et al., 2021; Schulz & Vögele, 2015), both of which are more prevalent in low-SES environments. At the same time, reduced interoceptive sensitivity is linked to less effective self-regulation and is a common feature in disordered eating (Farb et al., 2015; Martin et al., 2019).

Interoceptive signalling pathways are part of phylogenetically older brain systems that control homeostatic motivations and give rise to approach and avoidance behaviours (Maniscalco & Rinaman, 2018; Strigo & Craig, 2016). Interoception facilitates the neural integration of bodily signals, including signals mediated through the vagal nerve. The higher individuals' interoceptive sensitivity, the stronger the emotional experience and homeostatic motivation that drives behaviour (Strigo & Craig, 2016; Sullivan et al., 2018). Consistent with this, boosting interoceptive sensitivity through activities such as yoga and biofeedback can increase homeostatic motivation (e.g., Zou et al., 2018).

Lower interoceptive sensitivity can affect the ability to regulate eating based on internal cues. Most relevant for the present discussion, Proffitt Leyva and Hill (2018) found that unpredictable circumstances, like those encountered by low-SES individuals, decrease interoceptive sensitivity, thereby severing the link between energy needs and calorie consumption. Empirically, this phenomenon manifests as an interaction between interoceptive sensitivity and energy needs in predicting calorie consumption (Proffitt Leyva & Hill, 2018). The interaction can explain the decoupling of energy needs and food intake in low-SES individuals, driven by lower levels of interoceptive sensitivity (Hill et al., 2016; Mengelkoch & Hill, 2020). By contrast, individuals from higher SES backgrounds, who experience less chronic stress and live in more predictable environments, tend to exhibit higher interoceptive sensitivity and regulate their eating based on internal cues like hunger (Hill et al., 2016; Mengelkoch & Hill, 2020).

In sum, different strands of research converge on a dissociation hypothesis, whereby lower (vs. higher) SES is associated with a poorer integration of vagal signals into homeostatic motivation. This manifests as a weaker alignment between vagal tone and eating behaviour in low (vs. high) SES individuals.

3. The present research

The present study explores the associations between socio-economic status (SES), self-regulation connected to the vagal system, and eating behaviour. Our sample consists of a socio-economically diverse group of students, and we use both objective (parental education) and subjective (perceived standing) indicators of SES background suitable for this sample. Objective indicators capture tangible resources, while subjective indicators capture perceptions that can shape health-related outcomes—sometimes even more strongly than objective indicators (Singh-Manoux et al., 2005). We note that there is no gold standard for measuring SES background (e.g., Krieger et al., 1997). Rather, researchers often employ more than one measure to capture different, overlapping facets of the construct (Dougall et al., 2024; Iversen & Holsen, 2008).

We focus on the consumption of chocolate—a snack food that is high in both sugar and fat—for several reasons. First, the high sugar and fat content gives chocolate a particularly rewarding quality that lends itself to the study of self-regulatory processes (DiFeliceantonio et al., 2018). Second, chocolate is part of the wider family of highly processed, calorie-dense foods that forms part of the obesogenic environment and plays a role in many non-communicable diseases (e.g., Cameron et al., 2013). By focusing on chocolate, we hope to offer a fresh insight into how SES may be linked to eating in obesogenic environments. Third, as alluded to earlier, chocolate seems ideal to test one of our research hypotheses looking at how SES may be linked to vagal reactivity during acute stress and how this may be related to subsequent food intake (Habhab et al., 2009; O'Connor et al., 2008). Finally, chocolate is widely consumed and easily standardised in experimental settings, making it a practical choice for studies of eating behaviour (e.g., Ayres et al., 2011; Erskine, 2008).

We test three complementary hypotheses, summarised in Fig. 1:

1. Blunting Hypothesis: Lower (vs. higher) SES is associated with diminished baseline vagal tone, which corresponds with more disinhibited chocolate consumption.
2. Hyperreactivity Hypothesis: Lower (vs. higher) SES is associated with greater vagal tone withdrawal in response to stressors, influencing chocolate consumption.
3. Dissociation Hypothesis: Vagal tone is more strongly linked to chocolate consumption in individuals from a higher SES background compared to individuals from a lower SES background.

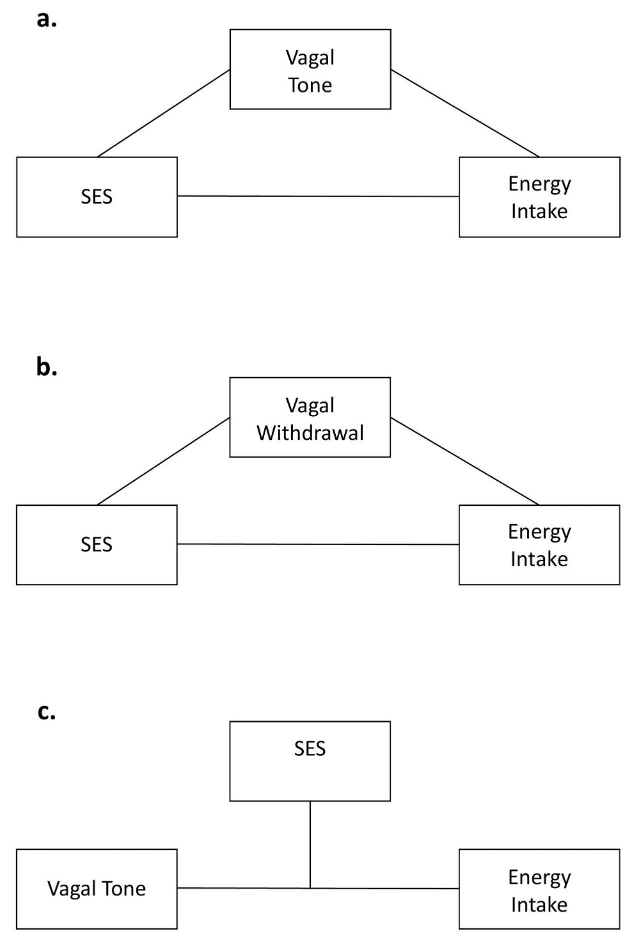

Fig. 1. Conceptual relations between study variables. Panel a. (top) depicts a blunting hypothesis, panel b. (middle) a hyperreactivity hypothesis, and panel c. (bottom) a dissociation hypothesis. See text for further details.

4. Method

4.1. Participants

One hundred and eleven students from a British university enrolled in the study for course credit. Only participants without current cardiovascular disease and food allergies were eligible to participate. For health and safety reasons, participants were additionally screened for food allergies before consuming chocolates. This screening resulted in the exclusion of two participants who were not permitted to proceed because they reported being lactose intolerant (1×) or having nut allergies (1×). Furthermore, physiological data were unusable for 13 participants, thus leaving a final sample of 96 participants (80 females; $M_{age} = 20.24$, $SD_{age} = 4.50$). Importantly for the present investigation, participants had a diverse socio-economic background, as shown by the Index of Multiple Deprivation (IMD) derived from the postcodes where participants grew up (Department for Communities and Local Government, 2010). Specifically, out of those growing up in the UK (72.9 %), some ($n = 7$) were raised in the most deprived areas in England, some ($n = 16$) in the least deprived areas, and the remainder grew up in roughly equal numbers in areas with varying, intermediate levels of deprivation. See Table 1 for a breakdown of these and other participant characteristics. The sample size was determined a priori, aiming for 100 participants, which was the limit of what was deemed feasible to conduct the project over the course of one academic year (Giner-Sorolla et al., 2024). The sample size matches or exceeds the sample size of similar key studies (e.g., McGeown et al., 2024; Proffitt Leyva & Hill, 2018) and provides 80 % power ($\alpha = 0.05$) to detect potential effects ranging from small-to-medium to medium ($fs^2 = 0.083$ to 0.136).

4.2. Procedure

Participants were invited to take part in a study of coping and health. At least one day before their arrival in the laboratory, participants completed a background questionnaire online, which included measures of SES and explicit food restraint (see Measures). The main part of the study was completed in the laboratory between the hours of 9 am and 5 pm. The study commenced with a relaxation phase that lasted 10 min. Next, to test the hyperreactivity hypothesis, participants completed two challenging tasks, the order of which was counterbalanced. The first task was described as a test of numeric fluency that was said to be predictive of academic success and achievement in life. Participants were instructed to count backwards in 7 s starting from 3431 at a pace that was dictated by an acoustic signal. The counting task lasted for 2 min during which the pace of the acoustic signal gradually increased. Mistakes or a failure to keep up with the pace triggered an acoustic warning signal and a message instructing participants to start again. The second challenging task involved participants giving a 2-min speech on what it would be like to be terminally ill and dying from cancer. Prior to the speech, participants read background statistics on the topic as well as a personal account of a terminal cancer patient. The challenging tasks were followed

Table 1
Participant characteristics.

Characteristic	n	%
Gender		
Male	16	16.7 %
Female	80	83.3 %
Age		
18–20	77	80.2 %
21–30	15	15.6 %
31–40	2	2.1 %
40+	2	2.1 %
Ethnicity		
White	71	74.0 %
Black	11	11.5 %
Asian	8	8.3 %
Mixed	6	6.3 %
BMI		
Overweight and obese	17	17.7 %
Healthy	68	70.8 %
Underweight	11	11.5 %
IMD Quintile		
Q1 (most deprived)	7	7.3 %
Q2	17	17.7 %
Q3	13	13.5 %
Q4	16	16.7 %
Q5 (least deprived)	16	16.7 %
Unknown	27	28.1 %
Parental Education		
No qualification	4	4.2 %
4 GCSEs	11	11.5 %
1 A Level	8	8.3 %
2+ A Level	8	8.3 %
University	53	55.2 %
N/A	12	12.5 %

NB: BMI = Body Mass Index; IMD = Index of Multiple Deprivation.

by another relaxation phase that lasted 8 min. Finally, participants were given a white paper-plate (19 cm Ø) that contained seventy milk chocolate droplets (approx. 32 g). Their task was to evaluate the chocolate by means of a questionnaire. Participants were told they could eat as many chocolates as they liked, in their own time, whilst the experimenter left the room. No time constraints were placed on participants to complete this task. After the taste test, participants were probed for suspicion and debriefed.

4.3. Measures

SES. Subjective SES was measured with five items asking participants to indicate their standing relative to other students in terms of their financial resources, education, status, family background, and overall standing. Answers were provided on a slider scale anchored at 1 (lower) and 100 (higher). Participants also indicated all educational qualifications of their parent(s) or main guardian(s), with options provided ranging from no qualification to degree level (BA, BSc, or higher). The highest level of education achieved by any parent served as a measure of objective SES (Shavers, 2007).

Control Measures. Participants completed the Eating Disorder Examination Questionnaire (EDE-Q; Fairburn & Beglin, 2008). Six items pertaining to restricted food intake and diet were chosen as a measure of explicit foot restraint. Participants described their behaviour during the past 28 days (e.g., “Have you tried to exclude from your diet any foods that you like in order to influence your shape or weight (whether or not you have succeeded)?”) on a scale ranging from 1(zero days) to 7(every day). Before commencing the taste task, participants indicated how hungry they were at this very moment (1 = not at all, 7 = very much). Finally, participants rated the chocolate in terms of its taste, sweetness, creaminess, and likeability (1 = not at all, 7 = very much). These items served as a measure of chocolate liking.

Cardiac vagal tone. ECG data were collected at the left lower and right upper chest using disposable Ag/AgCl electrodes and digitised at 1000 Hz. Data were amplified online using low- and high-pass filters of 50 and 0.05 Hz, respectively (ECG100; BioPac Systems Inc.). A BioPac MP150 data acquisition system was used to digitise the electric signals, and an AcqKnowledge 4.3 software to perform a power spectral analysis to separate the variance of R-R intervals of the QRS complex into frequency bands (sec2). The high-frequency (HF) band ranges between 0.15 and 0.40 Hz and reflects cardiac vagal tone. We derived HF scores in normalised units (n.u.)—hereinafter referred to as HRV (HF)—which denotes the relative contribution of HF to the total power in the 0–0.40 Hz range (Task Force of the European Society of Cardiology the North American Society of Pacing Electrophysiology, 1996). Below, we report the resulting proportions that have a theoretical range of 0 to 1, which is equivalent to a percentage range of 0 to 100. HRV (HF) scores were calculated for the last two minutes of the initial and final relaxation phases and for the two challenging tasks. ECG recordings were inspected visually for any artefacts, which were discarded prior to data processing.

5. Results

5.1. Data preparation

Participants consumed a minimum of 1, and a maximum of 70 chocolate drops (M = 13.40, SD = 16.96). As shown in Fig. 2, the distribution was positively skewed (Z = 8.20, $p < .001$) and log transformed (ln) in preparation for subsequent parametric tests (M_{ln} = 1.91, SD_{ln} = 1.19). As detailed below, further sensitivity analyses were performed using the untransformed raw data. We averaged and standardised participants’ ratings of subjective SES (α = 0.74, M = 51.89, SD = 11.91). About half of the sample (55.2 %) had at least one parent with a degree-level qualification (see Table 1). Thus, we created a dummy variable (D1) to denote high and low levels of parental education (0 = below degree-level; 1 = degree-level). Responses from twelve participants (12.5 %) who selected a non-applicable option were excluded for all analyses involving objective status but were otherwise retained. Furthermore, we created composites of explicit food restraint (α = 0.86) and of chocolate liking (α = 0.78) after removing ‘sweetness’ ratings that lowered the internal consistency of the scale. We also computed BMI scores from participants’ height and weight (bmi = kg/m^2).

HRV (HF) scores aligned with normative reference values (e.g., Nunan et al., 2010). Three HRV (HF) scores (0.8 %) were identified as univariate outliers ($>\bar{x} \pm 2.5SD$) and replaced with the next highest, non-extreme value in the distribution (Tabachnick & Fidell, 2001). To examine changes in vagal tone during active coping—vagal withdrawal (e.g., Laborde et al., 2017)—we subtracted the baseline HRV (HF) scores from the HRV (HF) scores during the two challenging tasks. Thus, lower scores indicate greater withdrawal. Initial inspection of the HRV (HF) withdrawal scores revealed no systematic differences in the results between the two challenging tasks. Hence, we created an overall composite of HRV (HF) withdrawal during active coping, which had one outlier (1 %) that was substituted with the next lowest non-extreme score. There were no systematic variations between the two indices of HRV (HF) at rest before and after the coping tasks, Ms = 0.470 vs. 0.472, t(95) = 0.105, p = .916, so we created a single composite of baseline HRV (HF). As anticipated, HRV (HF) was significantly higher at baseline than during active coping, Ms = 0.471 vs. 0.350, t(95) = 6.984, $p < .001$. Table 2 displays descriptive statistics for all predictor and criterion variables.

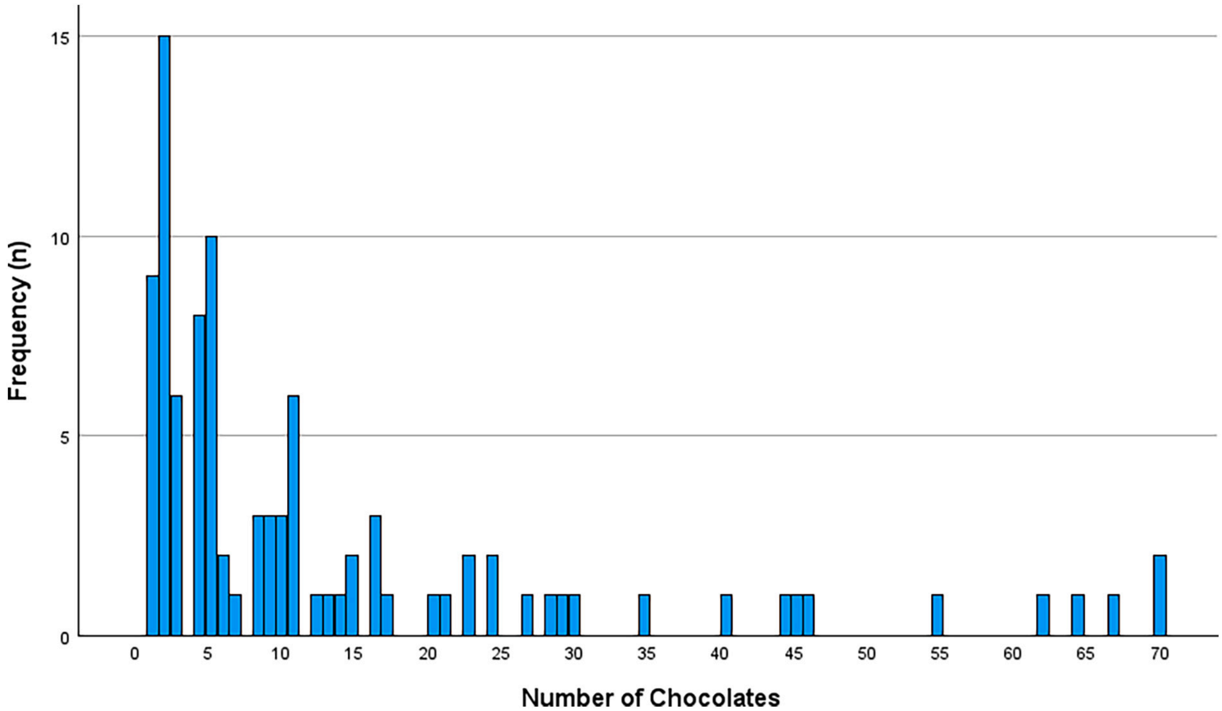

Fig. 2. Distribution of chocolate droplets consumed by participants.

Table 2
Means, standard deviations and zero-order correlations for all measures.

		1[1]	2	3	4[1]	5	6	7	8	9	10
1	Chocolates Consumed[1]	1	1	0.036	0.067	−0.086	0.108	−0.086	−0.025	0.179*	0.249***
2	Chocolates Consumed (ln)		1	0.084	0.067	−0.136	0.189	−0.115	−0.080	0.242*	0.363***
3	Subjective SES			1	0.364***	−0.161	0.119	−0.091	−0.253*	−0.156	−0.047
4	Objective SES[1]				1	−0.007	−0.019	−0.048	−0.288**	0.038	−0.126
5	Baseline HRV (HF)					1	−0.737***	0.066	−0.016	0.080	−0.192
6	HRV (HF) withdrawal[2]						1	−0.099	−0.082	−0.152	0.165
7	Explicit Food Restraint							1	0.286**	−0.067	0.119
8	BMI								1	−0.015	0.137
9	Hunger									1	0.234*
10	Chocolate Liking										1
	M	13.40	1.91	51.89	–	0.47	−0.12	3.02	22.66	3.83	4.82
	SD	16.96	1.19	11.91	–	0.18	0.19	1.58	4.54	1.73	1.67

NB: * $p < .05$; ** $p < .01$, *** $p < .001$; [1] non-parametric correlation coefficients (Kendall's tau-b); objective SES is a dummy variable coded 0 (low) and 1 (high); [2] lower scores indicate higher withdrawal.

5.2. Main analysis

We commenced the analysis after all data were collected and processed. In what follows, we discuss empirical tests of our three research hypotheses. For this analysis, we focus on the log-transformed chocolate count data.

Blunting Hypothesis. As a test of the blunting hypothesis, we interrogate the associations between SES, baseline HRV (HF), and chocolate consumption depicted in Fig. 1a. As can be seen in Table 2, the association between subjective and objective SES and baseline HRV (HF) was not significant $rs \geq -0.161$, $ps \geq 0.116$. Baseline HRV (HF) differences correlated negatively with the numbers of chocolates eaten as anticipated, but again the correlation was not significant, $r(94) = -0.136$, $p = .135$. Finally, associations between subjective and objective SES and eating behaviour were small and not significant, $rs \leq 0.084$, $ps \geq 0.414$. In sum, there was insufficient evidence to support the blunting hypothesis.

Hyperreactivity Hypothesis. To examine the hyperreactivity hypothesis, we probe the same associations as for the blunting hypothesis but substituting baseline HRV (HF) for HRF (HF) withdrawal. As shown in Table 2, the data did not confirm the hypothesised association between subjective and objective SES and HRV (HF) withdrawal, $|rs| \leq 0.119$, $ps \geq 0.246$. HRV (HF) withdrawal was associated with fewer chocolates eaten, although the association failed to reach significance, $r(94) = 189$, $p = .065$. Thus, the data did not lend support to the hyperreactivity hypothesis.

Dissociation Hypothesis. Turning to the third and final hypothesis, we regressed the log-transformed chocolate consumption scores on the measures of SES, baseline HRV (HF), and the interaction between the two variables. We performed separate analyses for the measures of subjective and objective SES since the shared variance between these variables is of theoretical interest. As shown in Table 3, the analyses revealed significant interactions between both subjective and objective status and baseline HRV (HF), $ps = 0.015$ and 0.005, respectively. Simple effects indicated that baseline HRV (HF) scores were negatively related to consumption for high SES participants, $B_{SubjectiveSES} = -0.447$, $SE = 0.169$, $t(92) = -2.639$, $p = .010$, $sr = -0.263$, $B_{ObjectiveSES} = -0.372$, $SE = 0.146$, $t(80) = -2.554$, $p = .013$, $sr = -0.269$. The direction of this effect is consistent with a self-regulatory function of vagal tone among high SES participants. In contrast, baseline HRV (HF) scores

Table 3
Multiple regressions predicting variations in chocolate consumption (ln) from subjective SES (top) and objective SES (bottom) and baseline HRV (HF).

	B	SE	t	p	VIF	sr [95 % CI]
(Constant)	1.870	0.120	15.637	<0.001		
Subjective SES	0.083	0.125	0.660	0.511	1.027	0.065 [−0.142, 0.266]
Baseline HRV (HF)	−0.135	0.120	−1.123	0.264	1.029	−0.114 [−312, 0.093]
Subjective SES x Baseline HRV (HF)	−0.312	0.125	−2.492	0.015	1.002	−0.249 [−0.432, −0.047]
R^2	0.084					
F(df1, df2)	2.825(3, 92)					
(Constant)	1.787	0.208	8.570	<0.001		
Objective SES	0.210	0.262	0.801	0.425	1.005	0.084 [−0.138, 0.298]
Baseline HRV (HF)	0.425	0.236	1.798	0.076	3.627	0.189 [−0.032, 0.392]
Objective SES x Baseline HRV (HF)	−0.797	0.278	−2.872	0.005	3.629	−0.302 [−0.489, −0.088]
R^2	0.112					
F(df1, df2)	3.378(3, 80)					

did not predict consumption in low SES participants, subjective SES: *sr* = 0.099, *p* = .323, objective SES: *sr* = 0.189, *p* = .076. Thus, in line with the dissociation hypothesis, vagal tone modulated the eating behaviour of high but not of low SES participants (see also Fig. 3).

5.3. Sensitivity analysis

In a further step, we sought to probe the robustness of our findings in two ways. First, we re-examined all associations, this time also controlling for variations in explicit food restraint, BMI, hunger, and chocolate liking. Second, we also modelled consumption by fitting a negative binominal function to the untransformed chocolate count data depicted in Fig. 2 using a Generalised Linear Model (e.g., Green, 2021; Hughes et al., 2009). As before, we discuss the evidence for each research hypothesis in turn.

Blunting Hypothesis. Controlling for explicit food restraint, BMI, hunger, and chocolate liking, subjective and objective SES were neither related to baseline HRV (HF), *srs* ≥ −0.151, *ps* ≥ 0.138, nor to chocolate consumption, *srs* ≤ 0.111, *ps* ≥ 0.273. Similarly, fitting a negative binominal function to the untransformed chocolate count data, there was no evidence that subjective or objective SES predicted consumption, Wald $\chi^2(1) \leq 2.269$, *ps* ≥ 0.132. The association between baseline HRV (HF) differences and the (untransformed) number of chocolates eaten also did not reach significance, Wald $\chi^2(1) = 3.480$, *p* = .062.

Hyperreactivity Hypothesis. Repeating our sensitivity analyses, substituting baseline HRV (HF) for HRF (HF) withdrawal, there was no evidence for an association between subjective and objective SES and HRV (HF) withdrawal, *srs* ≤ 0.068, *ps* ≥ 0.500. HRV (HF) withdrawal

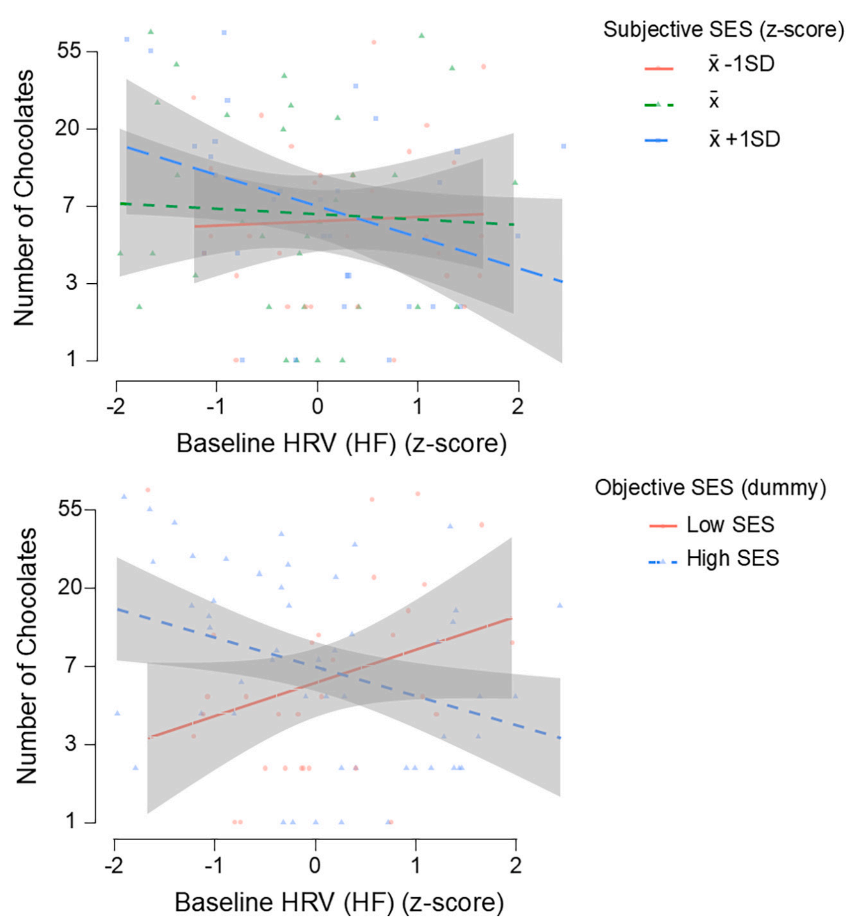

Fig. 3. Interaction between subjective (top) and objective (bottom) SES and baseline HRV (HF) predicting the number of chocolate droplets (ln) consumed by participants.

also did not predict the number of chocolates eaten, $sr(90) = 0.140$, $p = .138$. Fitting a negative binominal function to the untransformed chocolate count data, HRV (HF) withdrawal did account for variation in the (untransformed) number of chocolates eaten, B = 1.571, SE = 0.522, Wald $\chi^2(1) = 9.059$, $p = .003$. Recall that this effect just failed to reach statistical significance in the earlier analysis of the log-transformed chocolate count data. Since subjective and objective SES neither predicted consumption nor HRV (HF) withdrawal, the overall pattern of results remains inconsistent with the hyperreactivity hypothesis.

Dissociation Hypothesis. Controlling for explicit food restraint, BMI, hunger, and chocolate liking, the interactions between both subjective and objective status and baseline HRV (HF) remained significant, $ps = 0.006$ and 0.011, respectively. The interactions also emerged when fitting a negative binominal function to the untransformed chocolate count data, Wald $\chi^2(1) \geq 6.252$, $ps \leq 0.012$. Simple effects obtained using the generalised linear model replicated the pattern of results obtained in our primary analysis, showing an association between consumption and baseline HRV (HF) for high SES participants, $B_{SubjectiveSES} = -0.434$, SE = 0.152, Wald $\chi^2(1) = 8.210$, $p = .004$, $B_{ObjectiveSES} = -0.341$, SE = 0.119, Wald $\chi^2(1) = 8.191$, $p = .004$, but not for low SES participants, $B_{SubjectiveSES} = 0.219$, SE = 0.175, Wald $\chi^2(1) = 1.570$, $p = .210$, $B_{ObjectiveSES} = 0.170$, SE = 0.164, Wald $\chi^2(1) = 1.069$, $p = .301$. Thus, the sensitivity analysis affirmed the conclusions derived from the primary analysis.

5.4. Exploratory analysis

In our test of the dissociation hypothesis, we focused on the link between chocolate consumption and baseline HRV (HF) measured at rest, prior and after a stress induction. This is in keeping with the literature on vagal tone and self-regulation, which has emphasised what is known as *tonic* vagal tone – the baseline activity of the vagus nerve (see Smith et al., 2020; Young & Benton, 2018). However, we also sought to explore the dissociation hypothesis with vagal tone derived from all phases of the study, including the stress induction (the cancer speech task and the maths task, respectively). To that end, we repeated our primary analysis testing the dissociation hypothesis, this time incorporating HRV (HF) from four phases: initial rest, cancer speech task, maths task, final rest. Differences between the four phases were modelled with fixed effects using three dummy variables (i.e., number of phases minus one)—initial rest: $D_1 = 0$, $D_2 = 0$, $D_3 = 0$; cancer speech task: $D_1 = 1$, $D_2 = 0$, $D_3 = 0$; maths task: $D_1 = 0$, $D_2 = 1$, $D_3 = 0$; final rest: $D_1 = 0$, $D_2 = 0$, $D_3 = 1$. We analysed both the log-transformed and untransformed chocolate count data using Ordinary Least Square (OLS) regressions and Generalised Linear Models (GLM), respectively. As can be seen in Table 4, the analyses unveiled interactions between subjective SES and HRV (HF), $p_{OLS} = 0.054$, $p_{GLM} = 0.033$, and between objective SES and HRF (HF), $p_{OLS} = 0.019$, $p_{GLM} = 0.054$. Simple effects indicated that HRV (HF) scores were negatively related to consumption for high SES participants, consistent with a regulatory function of vagal tone, OLS: $B_{SubjectiveSES} = -0.324$, SE = 0.157, $t(367) = -2.066$, $p = .040$, $sr = -0.107$, $B_{ObjectiveSES} = -0.252$, SE = 0.132, $t(319) = -1.909$, $p = .057$, $sr = -0.106$, GLM: $B_{SubjectiveSES} = -1.689$, SE = 0.723, Wald $\chi^2(1) = 5.459$, $p = .019$, $B_{ObjectiveSES} = -1.219$, SE = 0.560, Wald $\chi^2(1) = 4.745$, $p = .029$. In contrast, HRV (HF) scores were unrelated to consumption in low SES participants, OLS: $B_{SubjectiveSES} = 0.123$, SE = 0.161, $t(367) = 0.767$, $p = .443$, $sr = 0.040$, $B_{ObjectiveSES} = 0.343$, SE = 0.214, $t(319) = 1.600$, $p = .111$, $sr = 0.089$, GLM: $B_{SubjectiveSES} = 0.793$, SE = 0.751, Wald $\chi^2(1) = 1.118$, $p = .290$, $B_{ObjectiveSES} = 0.630$, SE = 0.780, Wald $\chi^2(1) = 0.652$, $p = .419$. There was no indication that the interaction between SES and HRV (HF) varied between the four assessment phases, $ps_{OLS} \geq 0.306$, $ps_{GLM} \geq 0.259$. In other words, the dissociation hypothesis is also supported when considering HRV (HF) measured at rest and during active coping.

Table 4
Multiple regressions predicting variations in chocolate consumption from subjective SES (top) and objective SES (bottom) and HRV (HF) measured in different phases.

	OLS		GLM	
	t	p	Wald χ^2	p
Subjective SES	1.201	0.231	0.979	0.322
HRV (HF)	−0.918	0.359	5.272	0.022
Subjective SES x HRV (HF)	−1.936	0.054	4.557	0.033
Cancer Speech Dummy	−0.047	0.963	1.059	0.303
Maths Task Dummy	0.554	0.580	3.486	0.062
Final Rest Dummy	−0.048	0.962	0.004	0.951
Subjective SES x Cancer Speech Dummy	−0.496	0.620	0.000	0.997
Subjective SES x Maths Task Dummy	−0.396	0.693	1.118	0.290
Subjective SES x Final Rest Dummy	0.217	0.829	0.538	0.463
HRV (HF) x Cancer Speech Dummy	0.535	0.593	1.467	0.226
HRV (HF) x Maths Task Dummy	1.706	0.089	5.457	0.019
HRV (HF) x Final Rest Dummy	−0.314	0.754	0.049	0.824
Subjective SES x HRV (HF) x Cancer Speech Dummy	0.203	0.839	0.022	0.881
Subjective SES x HRV (HF) x Maths Task Dummy	1.025	0.306	1.212	0.271
Subjective SES x HRV (HF) x Final Rest Dummy	−0.794	0.428	0.670	0.413
Objective SES	1.377	0.169	2.681	0.102
HRV (HF)	1.600	0.111	0.652	0.419
Objective SES x HRV (HF)	−2.363	0.019	3.709	0.054
Cancer Speech Dummy	0.530	0.596	0.444	0.505
Maths Task Dummy	1.332	0.184	2.544	0.111
Final Rest Dummy	0.039	0.969	0.180	0.672
Objective SES x Cancer Speech Dummy	−0.627	0.531	0.008	0.927
Objective SES x Maths Task Dummy	−1.445	0.150	0.615	0.433
Objective SES x Final Rest Dummy	0.186	0.852	0.742	0.389
HRV (HF) x Cancer Speech Dummy	−0.546	0.585	0.728	0.394
HRV (HF) x Maths Task Dummy	1.059	0.291	3.850	0.050
HRV (HF) x Final Rest Dummy	0.178	0.859	0.217	0.642
Objective SES x HRV (HF) x Cancer Speech Dummy	0.956	0.340	0.000	0.989
Objective SES x HRV (HF) x Maths Task Dummy	−0.612	0.541	1.276	0.259
Objective SES x HRV (HF) x Final Rest Dummy	−0.625	0.532	0.990	0.320

NB: OLS = Ordinary Least Square; GLM = Generalised Linear Model.

6. Discussion

This research investigated how socio-economic status (SES) intersects with vagal tone, a marker of physiological self-regulation, to influence chocolate consumption. Heart rate variability (HF) provided an index of vagal tone, assessed in a laboratory setting at rest (baseline) and during active coping when participants were exposed to acute stress. SES was assessed through both subjective and objective measures, and chocolate consumption was measured through the number of chocolates consumed in a bogus taste test. We formulated and tested three hypotheses about the association between vagal tone, SES, and chocolate consumption. Below, the findings are discussed in relation to each hypothesis, followed by a consideration of the study's strengths, limitations, and broader implications.

The results did not support our *blunting hypothesis*, which posited that lower SES would be associated with diminished vagal tone, contributing to disinhibited chocolate consumption. Instead, we found no significant association between either subjective or objective SES and baseline HRV (HF). Furthermore, baseline HRV (HF) did not predict consumption across the whole sample. Together, these results suggest that the link between SES and chocolate consumption might not be as straightforward as a simple reduction in vagal tone among lower (vs. higher) SES individuals.

We also examined a *hyperreactivity hypothesis*, whereby lower SES individuals would exhibit greater vagal withdrawal in response to acute stress, which in turn would be linked to the consumption of chocolates. Greater vagal withdrawal was associated with *lower* chocolate consumption, with the caveat that this relationship did not reach statistical significance in the primary analysis. Importantly, HRF (HF) withdrawal was not significantly correlated with SES. This may suggest that vagal withdrawal, while relevant in acute stress responses and potentially predictive of chocolate consumption, may not be a critical factor in explaining SES related differences in dietary behaviour.

In contrast, the results provided support for the *dissociation hypothesis*, which posited that vagal tone would be more closely related to eating behaviour in individuals from a higher SES background compared to individuals from a lower SES background. Consistent with this hypothesis, both subjective and objective SES interacted significantly with baseline HRV (HF) in predicting chocolate consumption. Specifically, higher HRV (HF) was associated with reduced chocolate consumption in higher SES participants, but not in lower SES participants. A similar pattern emerged when HRV (HF) was assessed at rest and during active coping. The results point to socio-economic disparities in the extent to which vagal tone plays a role in regulating eating.

6.1. Strengths and limitations

Prior research has often focused on external factors as potential drivers of socio-economic disparities in dietary behaviours, focusing on aspects such as affordability and availability of (un)healthy food (e.g., Best & Papies, 2019; Pechey et al., 2013). This study shifts attention to physiological processes invoked in self-regulation, specifically vagal tone, as a factor that may influence dietary behaviours. We articulated and tested several complementary hypotheses about the relationship between vagal tone, SES, and chocolate consumption, providing future studies with a framework to distinguish candidate pathways (i.e., blunting, hyperreactivity, and dissociation). Our empirical study had some notable strengths, including the use of both subjective and objective measures of SES yielding convergent results (Iversen & Holsen, 2008), as well as the use of a laboratory setting, which allowed for the precise measurement of eating behaviour under controlled conditions. Additionally, even though we sampled students, participants had a diverse socio-economic background.

There are also several limitations to the study. First, future studies should aim to recruit more balanced samples in terms of gender and age to provide a fuller picture of the relationship between SES, vagal tone, and eating behaviour in the general population. This would also allow for testing other facets of SES, most notably SES derived from current income, education, and/or occupation (see Krieger et al., 1997, for a review). Second, the present study focused solely on the consumption of chocolate, which may neither speak to the consumption of other snack foods, nor to the full spectrum of self-regulatory behaviour in eating. For reasons outlined earlier, chocolate seemed ideal to test our research hypotheses. However, future research should investigate whether these findings generalise to other food items, including unhealthy and healthy foods, and to different contexts and meal settings. Relatedly, in the present study chocolate consumption was always assessed following a stressful experience, so it remains to be seen whether the same pattern of results can also be observed in other scenarios. Finally, our measurement approach prevents us from drawing conclusions about causal relationships. Future research should study SES and/or vagal tone experimentally.

6.2. Implications and future directions

Prior work has documented a decoupling of eating with energy needs in people from lower (vs. higher) SES backgrounds (Hill et al., 2016), pointing to interoceptive sensitivity as a likely proximate cause (Proffitt Leyva & Hill, 2018). The present work dovetails these findings and provides a critical extension suggesting that lower (vs. higher) SES may be associated with a poorer integration of vagal signals into homeostatic motivation and associated eating behaviours. The present findings are consistent with prior studies showing a decoupling between physiological responses and emotional experiences in disadvantaged and powerless individuals (e.g., Leach & Weick, 2020; Petrova et al., 2021).

A sizable body of research has associated low SES with poorer health outcomes that are linked to dietary behaviour such as obesity or cardiovascular disease (e.g., Darmon & Drewnowski, 2008; de Mestral & Stringhini, 2017; Pickering, 1999). Economic, environmental, evolutionary, and socio-cultural factors can account for these complex and multi-faceted relationships (e.g., Caldwell & Sayer, 2019; Hajat et al., 2015; Sobal, 1991). The present work encourages us to also consider autonomous regulation as an internal factor that may contribute to SES-related inequalities in health outcomes (see also Seeman et al., 2010), and that may make it more challenging for low SES individuals to regulate their eating behaviour.

Disadvantages in early life are likely linked to a shorter life history and promote phenotypes (traits) that encourage maximising energy when food is available, irrespective of, or disregarding, internal signals such as hunger (Maner et al., 2017; Mengelkoch & Hill, 2020). Food consumption that is dissociated from vagal tone fits in with this emerging ecological perspective and can provide a proximate explanation for SES-related variations in eating. However, more research is needed to put this perspective to a test, for example, using more direct measures of childhood ecologies, including measures of childhood food scarcity. Relatedly, future research should examine whether social mobility in adulthood can counteract dysregulated eating attributed to early childhood disadvantage (Chen et al., 2022).

Future research should also investigate the physiological mechanisms linking SES and vagal regulation of eating in more depth. For instance, exposure to chronic stress during childhood, often prevalent in low SES environments, may have long-term effects on physiological systems like the autonomic nervous system in ways that compromise self-regulation (Porges, 1995). Chronic inflammation, frequently associated with both low SES and stress, could play a critical role in disrupting interoceptive sensitivity thereby impairing appetite regulation (Bonaz et al., 2021).

The present work encourages us to look beyond executive control mediated via the prefrontal cortex as a source of disparities in low and high SES individuals' self-regulation (e.g., Kim et al., 2013). While the vagal nerve plays a central role in autonomous self-regulation, there are also other elements of the gut-brain connections through which the body maintains an energy balance (Cork, 2018). For example, glutamate metabolism pathways have recently attracted attention owing to the popularity of weight loss medication that contain GLP-1 agonists. GLP-1 is a hormone that is produced in the gut in response to rising blood sugar levels. GLP-1 is responsive to stress and linked to both the HPA axis and compulsive overeating. Future research could explore how SES intersects with the glutamate metabolism pathway to influence eating behaviours (Zhang et al., 2023). Future research should also explore practices such as mindfulness, yoga, or biofeedback as potential interventions to boost interoceptive sensitivity and enhance vagal regulation in individuals from a lower SES background (Gibson, 2019; Sullivan et al., 2018; Zou et al., 2018). Such practices could be accessed through community programmes or mobile platforms, and—pending future investigations—may offer a route to counter autonomic dysregulation, potentially lowering risks of obesity, cardiovascular disease, and other diet-related conditions that are disproportionately affecting lower-SES groups. Encouragingly, evidence suggests that similar community-based interventions can be effective and may reduce inequalities (Bambra et al., 2015; Hillier-Brown et al., 2014).

In conclusion, this study provides new insights into how socio-economic status may interact with physiological mechanisms, specifically vagal tone, to influence eating behaviour. While higher SES individuals show a stronger connection between vagal regulation and chocolate consumption, lower SES individuals may not benefit from this form of self-regulation, potentially contributing to health disparities.

There is a need for future research to advance our understanding of how physiological regulation is shaped by socio-economic factors.

Ethics statement

Ethics approval for this research was granted by the Psychology Research Ethics Committee at the University of Kent (20112131). Participants were provided with an information sheet outlining the details of the study before participation. They were informed of their right to withdraw at any point during or after the study and were assured that all collected data would be kept anonymous and confidential. After reading the information sheet they provided informed consent. Participants were fully debriefed about the aims of the study at the end.

Author contributions

Both authors contributed to conceiving and developing the methodological design of the study, analysis of the data, drafting of the paper and revisions of the manuscript. Both authors read and approved the final version of the manuscript.

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CRediT authorship contribution statement

Mario Weick: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Milica Vasiljevic:** Writing – review & editing, Resources, Methodology, Conceptualization.

Declaration of competing interest

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

Data availability

The dataset and associated codebook are available within the OSF project folder: https://osf.io/htnfk/.

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