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The role of interoception in age-related obesity: A structural equation modelling study

Anthony Brennan, David Benton, Chantelle Gaylor, Hayley A. Young [*]

Swansea University, Wales, SA2 8PP, UK

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ABSTRACT

The obesity pandemic and its adverse effect on health and quality of life are well established. In younger populations, interoception and aberrant eating behaviour contribute to overconsumption and being overweight. Although the incidence of obesity is higher in older individuals, they remain under-researched in the obesity literature. Therefore, the present study considered the role of general (interoceptive sensibility) and appetite-specific (hunger drive and satiety responsiveness) interoception and obesogenic eating behaviour (food responsivity, emotional eating, enjoyment of eating) in the association between age and BMI. A total of 1006 female adults (aged 18 to 80) completed the Adult Eating Behaviour Questionnaire and the Interoceptive Attention and Accuracy scales. Structural Equation Modelling (SEM) in AMOS was used to explore the data for multiple serial mediation effects. Despite being more overweight, older adults reported lower interoceptive attention, hunger drive, emotional overeating, food responsivity, and enjoyment of food. In contrast, compared to younger adults, older adults reported a higher interoceptive accuracy, and a similar responsivity to satiety. Importantly, two indirect pathways positively mediated the link between age and BMI: (1) age ➤(−)➤ interoceptive attention ➤(+)➤ satiety responsivity ➤(−)➤ emotional eating ➤(+)➤ BMI and (2) age ➤(−)➤ interoceptive attention ➤(+)➤ satiety responsivity ➤(−)➤ food responsivity ➤(+)➤ BMI. However, a stronger antagonistic indirect pathway was also present: age ➤(−)➤ interoceptive attention ➤(+)➤ hunger drive ➤(+)➤ emotional eating ➤(+)➤ BMI. The present findings suggested that overall reduced interoceptive attention in older adults may protect against weight gain by lowering hunger and the propensity towards obesogenic eating behaviours. These findings have implications for the design of appetite interventions in older populations.

1. Introduction

The health and societal effects of the obesity pandemic have been well-documented. (Hruby & Hu, 2014; Williams, Mesidor, Winters, Dubbert, & Wyatt, 2015). Reports indicate that obesity disproportionally affects specific populations, for example, the prevalence of obesity in older adult populations is estimated at 29.2%, compared to 21.8% of younger adults (Health, 2022). Whilst research has identified key factors that contribute to the onset of obesity, for example, disinhibition and hunger (Young & Watkins, 2016), the mechanisms of problematic eating behaviour are not fully understood. Some evidence suggests that obesity-related eating behaviour may be linked with atypical processing of interoceptive information (Simmons & Deville, 2017). For example, overweight/obese individuals had less precise satiety expectations compared to lean participants (Young, Gaylor, de-Kerckhove, & Benton, 2021). Crucially, effective communication of the physiological state of the body and its motivational needs relies upon an integrated interoceptive system (Tsakiris & Critchley, 2016), which underlies homeostatic and allostatic processes (Kleckner et al., 2017).

Interoception is a multidimensional construct referring to the process of sensing, interpreting, and integrating internal sensations from the body (Craig, 2002; Khalsa et al., 2018). It was argued that “whatever else the brain might be doing—thinking, seeing, tasting—it is also predictively regulating the body’s physiological systems in the service of allostasis” (Barrett, Quigley, & Hamilton, 2016). Therefore, the ability to accurately detect and predict specific appetite signals, such as feelings of hunger and/or fullness, may be crucial for understanding individual differences in eating behaviour (Simmons & Deville, 2017). Although research in younger adults supported that a poorer ability to detect appetite signals was associated with obesity (Robinson, Marty, Higgs, & Jones, 2021), research exploring the association between interoceptive ability and appetite in older adults is sparse. Indeed, it is plausible that

* Corresponding author.
E-mail address: h.a.young@swansea.ac.uk (H.A. Young).

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interoceptive processes may play a differential role in the eating behaviour of older and younger adults. For example, we recently reported that compared to young individuals, older adults reported lower levels of disinhibited eating, and this was associated with weaker connectivity in the frontoparietal and default mode brain networks (Brennan et al., 2022): these brain networks were associated with the prediction and representation of salient afferent signals respectively including interoceptive signals (Kleckner et al., 2017).

Regarding appetite traits, a notable observation is that older adults tend to report lower levels of obesogenic eating behaviour than younger adults (Robertson, Mullan, & Todd, 2014; Samuel & Cohen, 2018). For example, it is often presumed that the propensity to overeat in response to emotions is a predictive driving factor of obesity (Pink, Lee, Price, & Williams, 2019); an eating style that was linked to aberrant interoceptive processing (Young et al., 2017). However, the existing literature indicates that older adults report lower levels of overeating in response to emotional cues (Samuel & Cohen, 2018). In addition, younger adults are more likely to report a more negative mood (Czerwon, Lüttke, & Werheid, 2011). Therefore, there is an urgent need to better understand how emotions and associated responses are linked to eating behaviour in older populations. Additionally, older adults tend to report lower levels of disinhibited (uncontrolled) eating, assessed via the Three Factor Eating Questionnaire (TFEQ) (Karlsson, Persson, SjÖStrÖM, & Sullivan, 2000; Stunkard & Messick, 1985); an effect that may be associated with responsivity to internal sensations such as hunger (Brennan et al., 2022; Gilmour Flint et al., 2008). For example, analysis of the TFEQ factor structure, has shown that the items corresponding to 'hunger' and the 'ability to control food intake' often load together onto a single factor (Anglé et al., 2009). Therefore, lower disinhibited eating in older adult samples could in fact reflect deficits in the perception of hunger sensations (Brennan et al., 2022). Indeed, previous research indicates that older adults generally report a lower hunger drive compared to younger adults (Regan, O'Neill, Hutchings, & O'Riordan, 2019). These findings again support the idea that interoceptive deficits may be a key contributing factor in age-related differences in eating behaviour.

To date, most studies on interoception and aging have assessed performance accuracy on a domain specific behavioural task (e.g., heartbeat detection). In general, performance on these interoception tasks declines with age (Khalsa, Rudrauf, & Tranel, 2009; Murphy, Geary, Millgate, Catmur, & Bird, 2018b). However, less is known about interoceptive sensibility; an individual's self-reported beliefs concerning their perception of bodily signals (Garfinkel, Seth, Barrett, Suzuki, & Critchley, 2015). Although some research has found that domain general interoceptive sensibility was associated with disordered eating (Jenkinson, Taylor, & Laws, 2018), other evidence indicates that appetite specific interoception i.e., hunger/satiety, may be more relevant (Poovey, Ahlich, Attaway, & Rancourt, 2022) – at least in undergraduate samples.

Interestingly,Robinson, Foote, Smith, Higgs, and Jones (2021) adopted a recent model proposed by Murphy et al. (2020a, 2020b). This model was designed to overcome some of the methodological issues in interoceptive research. Of particular relevance to the present study Murphy et al. (2020a, 2020b) identified the importance of clearly describing 'what' interoceptive dimension is being measured (interoceptive attention or accuracy) (Murphy et al., 2020b). Robinson, Marty, et al. (2021) explored the association between self-reported interoceptive sensibility (attention and accuracy) and appetitive traits in 1657 adults (Robinson, Marty, et al., 2021). As expected, lower self-report scores of interoceptive accuracy predicted less reliance on hunger cues and satiety responsivity. Self-reported interoceptive accuracy was also found to negatively correlate with emotional overeating and BMI. Meanwhile, self-reported interoceptive attention was not associated with BMI, but positively associated with trait hunger and satiety responsiveness, as well as a greater propensity to emotionally overeat (Robinson, Foote, Smith, Higgs, & Jones, 2021). Given the mean age of the sample in Robinson et al.'s study was 37.2 years (12.6 S.D.), it remains unclear whether the association between general- and appetite-specific interoception translates across younger and older adults.

In summary, obesity disproportionately affects those who are older despite reports of lower levels of disinhibited and emotional eating and hunger in this population. In young adults, it is evident that disordered eating and being overweight are associated with deficits in multiple aspects of domain general interoception. However, whether these effects translate to older populations is not known. In addition, understanding is limited by a lack of a clear conceptual framework, and a limited appreciation of the possible inter-relationships between key concepts (e.g., appetite specific versus general interoception: See Table 1). There is a need to disentangle the components of interoception and clarify how they relate to age, eating behaviour and body weight. Therefore, the aim of the present research was to investigate whether the link between age and BMI is influenced by deficits in interoceptive sensibility (attention and accuracy), appetite-specific interoception (trait hunger, satiety responsiveness), and obesogenic eating behaviour. We hypothesised that (1) general interoception (accuracy and attention) would be differentially associated with the appetitive interoceptive traits of hunger drive and satiety responsiveness; (2) age would be associated with poorer interoceptive abilities (3) obesogenic eating behaviours (emotional overeating, food responsiveness) will be positively associated with hunger drive and negatively associated with satiety responsiveness, and (4) specific pathways incorporating the intervening variables: interoceptive sensibility, appetitive specific interoception, and obesogenic eating behaviours would influence the relationship between age and BMI.

2. Method

2.1. Participants

A total of 1006 participants participated in the present online survey. Given that research has previously shown sex differences exist across the various dimensions of interoception (Grabauskaitė, Baranauskas, & Griškova-Bulanova, 2017) and appetite traits (Cornier, Salzberg, Endly, Bessesen, & Tregellas, 2010), the present research controlled for biological sex as a confounding variable by only recruiting females.

English speaking adults were recruited from the undergraduate student body at Swansea University, older participants were recruited via email, social media, the community, and the online platform Prolific (www.prolific.co). The sample size was based on previous research that has considered associations between obesity, eating behaviour and interoceptive deficits (Robinson, Marty, et al., 2021). G power 3.1.3 estimated a minimum sample size of 772 participants for sufficient power (85%, $p < .05$). The sample comprised solely of female participants given that previous research has documented sex differences in eating behaviour e.g. emotional eating (Anversa et al., 2021). Self-reported demographic data was collected, which included age, height, and weight. Body Mass Index (BMI) was calculated as [weight (lb)/height (in)^2]. Participants with an implausible BMI (i.e., >44) were excluded (23 cases removed in total). There were 545 younger adults (aged 18–35 years) and 392 older adults (aged 56–80 years) (Table 2).

2.2. Measures and procedure

2.2.1. Interoceptive accuracy/attention scale

To assess interoceptive sensibility two self-report measures were used. The Interoceptive Accuracy Scale (IACC) (Murphy et al., 2020a) and the Interoceptive Attention Scale (IATT) (Gabriele, Spooner, Brewer, & Murphy, 2022). The IACC measures perceived accuracy for detecting specific physical signals and represents one's belief in the accuracy of one's interoceptive percept. Individuals are asked to report their interoceptive accuracy across 21 items (e.g., 'I can always accurately perceive when my blood sugar is low'). Each item is accompanied

Table 1
Interoceptive taxonomy of concepts, used in the present study.

Category	Measure	Definition	Questionnaire used in present study	The effect of age
Domain general interoception	Self-reported interoceptive accuracy	One's belief in the accuracy of their interoceptive percept.	Interoceptive Accuracy Scale (IACC) (Murphy et al., 2020b)	↓ IACC scale (Murphy et al., 2020a,b)
	Self-reported interoceptive attention	One's belief in the degree to which interoceptive signals are the object of attention	Interoceptive Attention Scale (IATT) (Gabriele et al., 2022)	There are no studies examining the effect of age on IATT scores. Similar constructs** → Attention regulation (MAIA subscale) (Elliott & Pfeifer, 2022) → Noticing (MAIA subscale) (Nusser et al., 2020) ↓ Bodily awareness (BPQ short version) (Murphy et al., 2018a).
Domain specific interoception	Hunger drive	The propensity to frequently experience hunger (e.g., stomach rumbles)	Adult Eating Behaviour Questionnaire (AEBQ) (Hunot et al., 2016)	↓ Trait Hunger (AEBQ) (Cohen et al., 2021) Similar constructs** ↓ Reliance on hunger cues (IES-2-HS) (Ahlich & Rancourt, 2022) ↓ Trait hunger (TFEQ) (Gilmour Flint et al., 2008) ↓ State hunger (VAS) (Murphy et al., 2020a, 2020b)
	Satiety responsiveness	The propensity to notice and respond to within-meal feelings of fullness (i.e., I often get full before my meal is finished)	Adult Eating Behaviour Questionnaire (AEBQ) (Hunot et al., 2016)	→ Trait Satiety Responsiveness (AEBQ) (Cohen et al., 2021) Similar constructs** ↑ State satiation associated with meal consumption (VAS) (Sturm et al., 2004)
Appetitive trait	Food responsivity	A preoccupation with food or a desire to eat in response to food related cues (e.g., smelling food makes me want to eat)	Adult Eating Behaviour Questionnaire (AEBQ) (Hunot et al., 2016)	↓ Trait Food responsivity (AEBQ) (Cohen et al., 2021) Similar constructs** ↓ Disinhibited eating (Brennan et al., 2022)
	Emotional Overeating	The consumption of food in response to emotions (e.g., I eat more when I'm anxious)	Adult Eating Behaviour Questionnaire (AEBQ) (Hunot et al., 2016)	↓ Trait Emotional Overeating (AEBQ) (Cohen et al., 2021)
	Emotional Undereating	Eating less in response to negative emotions (e.g., I eat less when I'm upset)	Adult Eating Behaviour Questionnaire (AEBQ) (Hunot et al., 2016)	↓ Trait Emotional Undereating (AEBQ) (Cohen et al., 2021)
	Enjoyment of food	Characterised by an appreciation of the pleasures associated with eating	Adult Eating Behaviour Questionnaire (AEBQ) (Hunot et al., 2016)	↓ Trait Enjoyment of Food (AEBQ) (Cohen et al., 2021)

Note. ↑ scores increase with age; → no effect of age; ↓ scores decrease with age. Abbreviations: BPQ = Body Perception Questionnaire; DEBQ = Dutch Eating Behaviour Questionnaire; IES2-HS = Intuitive Eating Scale – reliance on hunger and satiety cues subscale; MAIA = Multidimensional Assessment of Interceptive Awareness; TFEQ = Three Factor Eating Questionnaire; VAS = Visual Analogue Scale. ** ***Where there are no data concerning a particular facet of interoception/eating style and age, information is drawn from similar constructs. However, whilst these measures assess similar constructs to those used in the present study, they should not be assumed to be synonymous.***

by a five-point scale ranging from *strongly agree* (5) to *strongly disagree* (1). Total scores range from 21 to 105, whereby greater self-perceived interoceptive accuracy is reflected in a higher score. A Cronbach's alpha (α = 0.874) indicated that the IACC has good internal consistency in the present sample. The IATT also comprises the same 21 items as the IACC and similarly asks participants to report on a five-point scale ranging from *strongly agree* (5) to *strongly disagree* (1). However, the IATT requires participants to self-report how much time they spend attending to the 21 interoceptive signals. This scale seeks to quantify how much attention is focused on internal signals. For example, 'Most of the time when I am eating, my attention is focused on different tastes'. Cronbach's alpha (α = 0.927) indicates that the IATT has good internal consistency in the present sample.

2.2.2. *Adult Eating Behaviour Questionnaire*

The Adult Eating Behaviour Questionnaire (AEBQ) (Hunot et al., 2016) is a 35-item measure of appetitive traits. Each item requires a self-reported rating along a 5-point Likert scale (1 = "strongly disagree" to 5 = "strongly agree"). Moreover, the AEBQ is made up of eight characteristic appetite traits which are divided into two categories - food approach and food avoidance.

The four *food approach* traits include: Emotional Overeating (five items, e.g. "I eat more when I'm upset"); Enjoyment of Food (three items, e.g. "I look forward to mealtimes"); Food Responsiveness (four items, e.g. "When I see or smell food that I like, it makes me want to eat"); Hunger (five items, e.g. "If my meals are delayed, I get light-headed"). The four *food avoidance* traits include: Emotional Under-Eating (five items, e.g. "I eat less when I'm angry"); Food Fussiness (five items, e.g. "I am interested in tasting new food I haven't tasted before"); Satiety Responsiveness (four items, e.g. "I often leave food on my plate at the end of a meal"); and Slowness in Eating (four items, e.g. "I am often last at finishing a meal").

The current study focuses on the appetite traits commonly associated with obesity and where plausible age differences may be associated (Table 2). Cronbach's alpha for each subscale are as follows: Enjoyment of Food (α = .879), Emotional Overeating (α = 0.904), Emotional Undereating (α = 0.904), Hunger (α = 0.722), Satiety Responsiveness (α = 0.766), and Food Responsiveness (α = 0.742).

2.3. *Procedure*

Participants accessed a link to the secure online survey platform

Table 2
Demographic data of younger and older adult groups (mean and standard deviations [SD]).

Participant Characteristics	Younger Adult Group	Older Adult Group	F ratio	*p*-value
Age Group	n = 545	n = 392		
Mean Age (S.D.)	28.19 (4.12)	64.98 (5.16)	–	–
Age Range (years)	18–35	56–80	–	–
BMI (kg/m^2)	25.86 (4.75)	26.80 (4.58)	9.19	.002*
Healthy 18-25	259 (47.52%)	154 (39.29%)	–	–
Overweight 26–30	177 (32.48%)	136 (34.69%)	–	–
Obese 31-35	74 (13.58%)	78 (19.9%)	–	–
Severely obese >35	35 (6.42%)	24 (6.12%)	–	–
Interoceptive Accuracy	81.80 (9.45) [51–105]	83.46 (9.66) [56–105]	6.90	.009*
Interoceptive Attention	49.22 (13.52) [21–105]	42.20 (13.78) [22–103]	60.55	<.001**
Hunger	16.12 (3.66) [5–25]	13.91 (4.06) [5–25]	76.15	<.001**
Enjoyment of Food	13.21 (2.44) [3–15]	12.48 (2.09) [5–15]	22.94	<.001**
Emotional Over Eating	15.03 (5.58) [5–25]	13.00 (5.51) [5–25]	31.03	<.001**
Emotional Under Eating	14.82 (5.27) [5–25]	14.05 (5.18) [5–25]	4.92	.027*
Food Responsiveness	14.10 (3.15) [4–20]	11.74 (2.99) [4–20]	132.66	<.001**
Satiety Responsiveness	10.33 (3.34) [4–20]	10.24 (3.41) [4–20]	0.178	.673
Food Fussiness	10.23 (4.90) [5–25]	10.86 (4.64) [5–25]	3.89	.049*
Slowness in Eating	10.56 (4.00) [4–20]	10.73 (3.99) [4–20]	0.40	.530

Note *$p < .05$ **$p < .001$.
NB: The minimum and maximum values for each subscale measure are denoted by [square brackets] within the table.

(Qualtrics), providing their written informed consent, and completed a series of demographic questions (height, weight, age etc.). Subsequently, participants continued to complete the questionnaires online. Questionnaires were presented to the participants in a set order, attentional checks were distributed throughout each questionnaire (e.g., *Attention Check: Please select "A Moderate amount"*). The procedure took approximately 25 min to complete. Ethical approval was gained from the Swansea Psychology Department Ethics Committee (approval number: 2022-5314-4494) and the study was carried out in accordance with the Declaration of Helsinki—Ethical Principles for Medical Research Involving Human Subjects.

2.4. Data preparation and analytic strategy

Of the 1006 participants, only 983 had provided complete data for the variables of interest in the present study. Initially, a multivariate ANOVA was used to detect age group differences (Table 2).

Then, to examine whether the age-related differences in BMI may be explained by deficits in general and specific interoception and eating behaviour, a serial mediation regression was conducted using structural equation in IBM® SPSS® AMOS™ 28.0.0. A bootstrap sample specified at 5000, and a 95% confidence interval (CI) was applied. To overcome problems of multicollinearity, variables were mean centred. Additionally, robust standard errors were used to overcome any issues of homoscedasticity. BMI was defined as the outcome variable (Y) and age was defined as a group variable (X) (younger adults vs older adults). Mediator variables were specified and organised in accordance with previous research. Here general interoceptive sensibility (attention and accuracy) was specified as (M_1), specific interoception i.e., trait hunger and trait satiety responsiveness were specified as (M_2), and lastly, eating behaviours i.e., subscales of the AEBQ (e.g., emotional overeating) were specified as (M_3) in the association between age and BMI. A False Discovery Rate (FDR) procedure was used to correct the *p*-values of the univariate tests. Significance was set at an $\alpha = 0.05$ with FDR correction (Yoav & Yosef, 1995). Potential outliers were determined using the Cooks distance diagnostics. To avoid removal of natural variability, we specified a conservative Cook's distance threshold of 0.0042 (Bollen & Jackman, 1985).

3. Results

3.1. Demographic/group comparisons

Upon inspection of the data, 23 cases were identified with an implausible BMI (e.g., BMI <16), these cases were excluded from further analysis. Next, cases exceeding the Cooks' distance threshold of 0.0042 were identified (46 cases in total) and removed from the analysis (N = 937). Descriptive statistics of the sample were calculated using IBM SPSS statistics version 28.0. Compared to older adults, younger adults reported significantly lower interoceptive accuracy (IACC) ($F(1, 935) = 6.90$, $p = .009$, $\eta = 0.007$) but higher interoceptive attention (IATT) ($F(1, 935) = 60.55$, $p < .001$, $\eta = 0.061$). Younger adults were more likely to score higher on food approach traits i.e., emotional overeating (EOE) ($F(1, 935) = 31.03$, $p < .001$, $\eta = 0.032$), enjoyment of food (EOF) ($F(1, 935) = 22.94$, $p < .001$, $\eta = 0.024$), and responsivity to food cues (FR) ($F(1, 935) = 132.66$, $p < .001$, $\eta = 0.124$). However, older adults self-reported significantly greater fussiness for food (FF) ($F(1, 935) = 3.89$, $p = .049$, $\eta = 0.004$), but lower emotional undereating (EUE) ($F(1, 935) = 4.92$, $p = .027$, $\eta = 0.005$) (see Table 2). The results indicated no age differences for the trait slowness in eating (SE) ($p = .530$).

As expected, older adults reported significantly lower trait hunger (H) ($F(1, 935) = 76.15$, $p < .001$, $\eta = 0.075$), yet surprisingly, no age differences were observed for trait satiety responsiveness (SR) ($F(1, 935) = 0.178$, $p = .673$, $\eta = 0.000$). For a detailed overview of sample characteristics – see Table 2. In the Supplementary Information Table S3 illustrates the age group differences for the individual items of the AEBQ, grouped by subscale.

3.2. Structural equation model (SEM)

Zero order correlations between all variables are available as supplementary information (S1). As expected, the total effect of the model showed a significant positive relationship between age and BMI ($\beta = 0.135$, $p = .004$, LLCI 0.081, ULCI 0.186). Full details of the direct and indirect effects that emerged from the SEM can be found in the online supplementary information (Table S2). The full SEM model including all standardised effects is depicted in Figs. 1a and 1b. Key findings are highlighted below.

3.2.1. Associations between general and specific interoception

Table 3 and Fig. 1b show the coefficients associated with specific pathways of the SEM model. Specifically, age was negatively associated with interoceptive attention ($\beta = -0.238$, LLCI -0.288, ULCI -0.187), but positively associated with interoceptive accuracy ($\beta = 0.071$, LLCI 0.017, ULCI 0.123). There was a positive direct association between interoceptive attention and both hunger drive ($\beta = 0.314$, LLCI 0.265, ULCI 0.368) and satiety responsivity ($\beta = 0.106$, LLCI 0.053, ULCI 0.165). Meanwhile, interoceptive accuracy was unrelated to hunger drive ($\beta = -0.052$, LLCI -0.109, ULCI 0.005) and satiety responsivity ($\beta = -0.047$, LLCI -0.103, ULCI 0.009) (Table 3).

3.2.2. Associations between specific interoception and eating style

As expected, hunger drive was positively associated with food approach traits, including emotional overeating ($\beta = 0.253$, LLCI 0.198, ULCI 0.303), food responsivity ($\beta = 0.548$, LLCI 0.051, ULCI 0.059), and enjoyment of food ($\beta = 0.141$, LLCI 0.093, ULCI 0.193). However, hunger did not influence emotional undereating ($\beta = 0.027$, LLCI -0.029, ULCI 0.081). Likewise, poorer responsiveness to satiety was associated

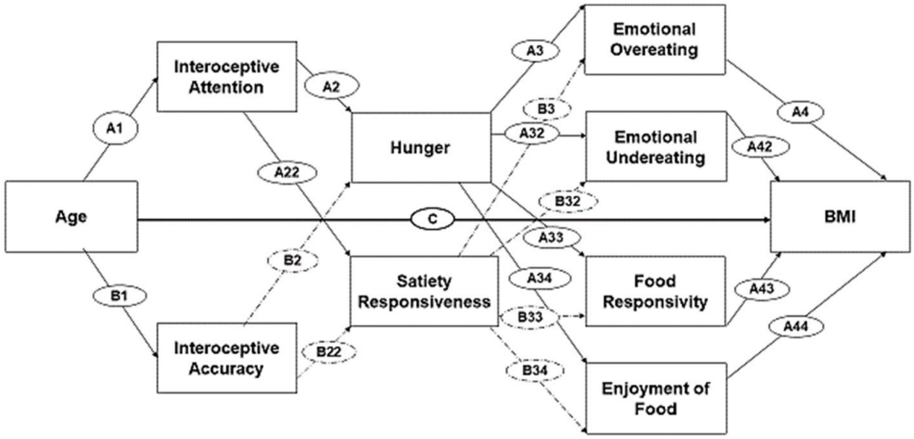

Fig. 1a. Serial mediation in (AMOS, v.26). The full structural equation model (SEM) representing all mediating pathways: Age → Interoceptive sensibility dimensions → Hunger/Satiety Responsiveness → Appetite trait → BMI[1]

[1] Serial mediation structural equation model (n = 937). Indirect effects of Age on BMI through domain general interoceptive sensibility, appetite specific interoceptive sensibility, and appetite traits. Standardised effects are presented. Dotted lines depict the pathways via interoceptive accuracy and satiety responsiveness. A/B1 depicts the standardised effects of age on interoceptive attention/accuracy. A/B 2/22 depict the standardised effects of domain general interoceptive sensibility on appetite specific interoceptive sensibility. A/B 3/32/33/34 depict the standardised effects of appetites specific interoceptive sensibility on the four appetite traits. A4/42/43/44 depict the standardised effects of appetite traits on BMI.

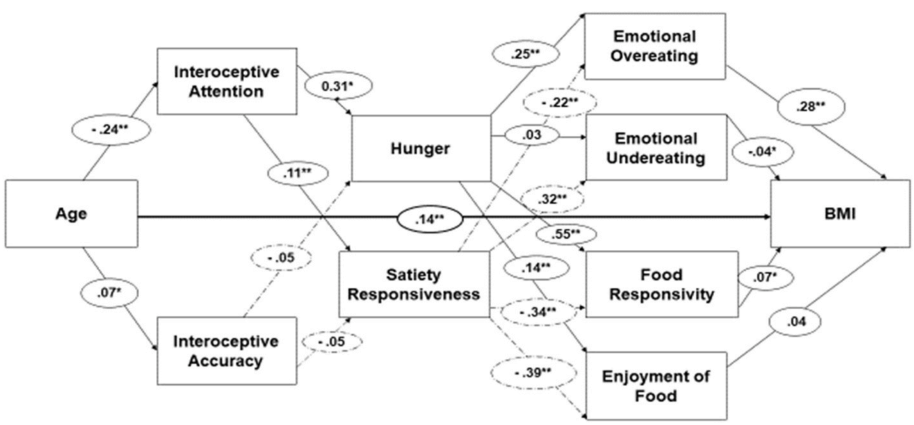

Fig. 1b. Regression coefficients representing the direct effects per pathway of the SEM. The effects on the direct path from Age to BMI (C) depict the direct effect. *P < .05, ***P < .001.

with higher food approach behaviours, including emotional overeating (β = −0.224, LLCI -0.272, ULCI -0.172), food responsivity (β = −0.335, LLCI -0.372, ULCI -0.029), and enjoyment of food (β = −0.388, LLCI -0.433, ULCI -0.338). Meanwhile, satiety responsiveness had a positive direct effect on emotional undereating (β = 0.321, LLCI 0.265, ULCI 0.369). Interestingly, when eating traits were considered in parallel, only emotional overeating exerted a direct effect on BMI (β = 0.279, LLCI 0.219, ULCI 0.339) (Fig. 1b).

3.2.3. *Indirect effect of age on BMI through interoception and eating style*

The following indirect effects were also significant: (1) age → interoceptive attention → hunger → emotional overeating → BMI (β = −0.057, p = .003, LLCI -0.091, ULCI -0.035); (2) age → interoceptive attention → satiety responsiveness → emotional overeating → BMI (β = 0.017, p = .002, LLCI 0.007, ULCI 0.035); (3) age → interoceptive attention → satiety responsiveness → food responsivity → BMI (β = 0.006, p = .036, LLCI 0, ULCI 0.017). The user defined estimates of the specific indirect pathways are summarised in Table 4 and Fig. 1a. These findings indicated that lower interoceptive attention in older adults may contribute to alterations in the way hunger and satiety are experienced with consequences for eating behaviour and obesity.

4. Discussion

The aim of the present study was to determine whether interoception contributes to age-related changes in eating behaviour and BMI. In particular, the mediating effects of domain general (accuracy and attention) and domain specific (hunger and satiety) interoception were established. Key findings included: (1) older adults self-reported poorer interoceptive attention but better interoceptive accuracy than younger adults. Despite having a higher BMI, older adults also reported lower hunger drive, emotional overeating, food responsivity and enjoyment of food; (2) higher self-reported interoceptive attention was associated with a greater hunger drive and responsivity to satiety. However, perceived interoceptive accuracy was not associated with appetite-specific interoception; (3) hunger drive was positively associated with emotional overeating, food responsivity and enjoyment of food, whereas satiety responsiveness was negatively associated with the same three eating behaviours; (4) the SEM indicated that the positive association between age and BMI was partially mediated by antagonistic indirect pathways involving interoception and appetitive traits. Overall, the present findings suggested that reduced interoceptive attention in older adults may protect against weight gain by reducing the propensity towards some obesogenic eating behaviours.

Table 3
Direct effects, associations between the sequential observed variables as defined within the Structural Equation Model.

Parameter		β	Standard Error	95% Confidence Interval		Pathway Label
				LLCI ULCI	LLCI ULCI	
AGE	→ IATT	−0.238	0.885	−0.288	−0.187	A1**
	→ IACC	0.071	0.624	0.017	0.123	B1*
IATT	→ H	0.314	0.009	0.265	0.368	A2**
	→ SR	0.106	0.008	0.053	0.165	A22**
IACC	→ H	−0.052	0.013	−0.109	0.005	B2
	→ SR	−0.047	0.011	−0.103	0.009	B22
H	→ EOE	0.253	0.042	0.198	0.303	A3**
	→ EUE	0.027	0.039	−0.029	0.081	A32
	→ FR	0.548	0.02	0.51	0.59	A33**
	→ EoF	0.141	0.017	0.093	0.193	A34**
SR	→ EOE	−0.224	0.05	−0.272	−0.172	B3**
	→ EUE	0.321	0.046	0.265	0.369	B32**
	→ FR	−0.335	0.024	−0.372	−0.29	B33**
	→ EoF	−0.388	0.02	−0.433	−0.338	B34**
EOE	→ BMI	0.279	0.029	0.219	0.339	A4**
EUE	→ BMI	−0.041	0.03	−0.103	0.021	A42
FR	→ BMI	0.069	0.051	0.008	0.126	A43
EoF	→ BMI	0.041	0.07	−0.012	0.097	A44
AGE	→ BMI	0.14	0.323	0.087	0.191	C**

Abbreviations: β standardised coefficient, EOE = Emotional Overeating, EoF = Enjoyment of Food, EUE = Emotional Undereating, FR = Food responsiveness, H = Hunger, IACC = Interoceptive Accuracy, IATT = Interoceptive Attention, LLCI = Lower Limit Confidence Interval, SR = Satiety Responsiveness, ULCI = Upper Limit Confidence Interval.
Note $^{*}p < .05$ $^{**}p < .01$.

Table 4
Estimates of pathways for all observed variables defined with the structural equation model: the specific indirect effects in the association between age and BMI.

Parameter	β	LLCI	ULCI	*P*
Age → IATT → H → EOE → BMI	−0.057	−0.091	−0.035	0.003**
Age → IATT → H → EUE → BMI	0.001	−0.001	0.007	0.284
Age → IATT → H → FR → BMI	−0.030	−0.064	0.002	0.056
Age → IATT → H → EoF → BMI	−0.005	−0.014	0.002	0.210
Age → IATT→ SR→ EOE → BMI	0.017	0.007	0.035	0.002**
Age → IATT → SR → EUE → BMI	0.004	−0.002	0.014	0.145
Age → IATT → SR → FR → BMI	0.006	0.001	0.017	0.036*
Age → IATT → SR → EoF → BMI	0.004	−0.002	0.015	0.182
Age → IACC → H → EOE → BMI	−0.003	−0.011	0.001	0.131
Age → IACC → H→ EUE → BMI	0.000	0.001	0.001	0.196
Age → IACC → H → FR → BMI	−0.001	−0.008	0.001	0.106
Age → IACC → H → EoF → BMI	0.000	−0.002	0.001	0.176
Age → IACC → SR → EOE → BMI	0.002	0.001	0.009	0.103
Age → IACC → SR→ EUE→ BMI	0.000	0.001	0.004	0.126
Age → IACC → SR → FR → BMI	0.001	0.001	0.005	0.067
Age → IACC → SR → EoF → BMI	0.001	0.001	0.005	0.160

Abbreviations: β standardised coefficient, EOE = Emotional Overeating, EoF = Enjoyment of Food, EUE = Emotional Undereating, FR = Food responsiveness, H = Hunger, IACC = Interoceptive Accuracy, IATT = Interoceptive Attention, LLCI = Lower Limit Confidence Interval, SR = Satiety Responsiveness, ULCI = Upper Limit Confidence Interval.
Note $^{*}p < .05$ $^{**}p < .01$.

An important finding was that this study found that age was negatively associated with interoceptive attention, and positively associated with interoceptive accuracy. Thus, while older adults believe their interoceptive perceptions are accurate, they report paying less attention to them. However, these findings are not in line with some previous research that found older adults report lower interoceptive accuracy (Murphy et al., 2020b: see Study 5). Yet, in Murphy et al.'s study, establishing the effect of age was not a primary aim. Across the sparse literature involving older adults and interoception, age parameters remain poorly defined. For example, in Murphy's study the oldest participant recruited was 56 years old, yet references are made to older adults. Poorly defined samples may explain some inconsistencies. The present study calls for further exploration of the dimensions and factors of interoception in ageing populations.

To the best of our knowledge, the present study is the only one to assess interoceptive attention in older adults using the IATT. However, previous research using the Porges Body Perception Questionnaire similarly reported that older adults reported being less aware of their bodily sensations during most situations (Murphy, Geary, Millgate, Catmur, & Bird, 2018a). Given the link between interoception and mental health, the wider implications of the age-related differences require future exploration. However, the present data indicated that lower interoceptive attention in older adults may have both beneficial and harmful effects regarding obesogenic eating behaviours in later life. For example, older adults had both lower interoceptive attention and a reduced hunger drive, and these two factors were associated (see Tables 2 and 3). This reduced hunger drive in older adults aligns with evidence suggesting that older adults report lower levels of subjective hunger while fasting (Johnson et al., 2020). Evidence also indicates that older adults have higher postprandial levels of the appetite regulating hormones insulin, leptin, cholecystokinin and peptide-YY (Johnson et al., 2020), and a higher satiation during a standardised meal (Sturm et al., 2004). Although we found similar reported levels of satiety responsiveness across age groups, we did observe a significant negative association through interoceptive attention (indirect effect) – older individuals reported lower interoceptive attention which was associated with greater satiety responsivity. Thus, the effect of appetite regulating hormones on satiety responsivity might be modified by reduced interoceptive attention in older adults. Future research combining biological and subjective interoceptive measures may be profitable.

Notably, the present pattern of results between general- and appetite-specific interoception indicates that interoceptive attention may be a key facet in explaining eating behaviour. Specifically, interoceptive attention was positively associated with both hunger drive and satiety responsivity, however, interoceptive accuracy was not. In line with the findings by Robinson, Marty, et al. (2021) who reported that in a sample with an average age of 37.2 (12.6), interoceptive accuracy was not associated with trait hunger or satiety responsiveness, but interoceptive attention was associated with both (Robinson, Foote, et al., 2021). Notably, the coefficients depicted in Fig. 1b highlight a stronger association between hunger and interoceptive attention, emotional eating, and food responsivity, compared to the associations with satiety responsiveness. Seemingly, hunger drive and interoceptive attention are crucial mediators in the association between age and BMI. This is further highlighted and resulted in the three indirect pathways noted in Table 4. Given the consistency of these observations, interoceptive attention could represent a viable target for altering appetitive sensations in older adults (e.g., through self-compassion (Young, Davies, Freegard, & Benton, 2021) or physical activity (Seabury, Benton, & Young, 2023).

For example, some research has highlighted the benefits of mindfulness training on improving interoceptive attention (Li, Lu, Wu, Liu, & Wu, 2021). In addition, directing attention to the body (body scan intervention) increased feelings of hunger (but not satiety) (Palascha, 2021). Similarly, physical activity interventions have been recommended as a way of ameliorating age-related declines in appetite (Clegg & Godfrey, 2018). King et al. (2009) presented evidence to support a dual-process model of exercise and appetite regulation. Specifically, it was suggested that while exercise results in an increased hunger drive it also increases the satiating efficiency of a meal (King et al., 2009). These previous observations suggest that mindful attention to the body and/or exercise could improve interoceptive attention and/or ameliorate reduced hunger in older populations, although currently data in older adults are limited (Clegg & Godfrey, 2018). However, while increasing interoceptive attention and hunger drive in frail older adults may prove beneficial (Clegg & Godfrey, 2018), the present data suggested that in otherwise healthy older adults it could exacerbate unhealthy weight gain. In addition, the overall consequence of these interventions on increasing both hunger and satiety in different populations needs to be determined. Future research combining interventions and statistical modelling to determine antagonistic indirect pathways might prove profitable in that regard. Overall, it will be important for future intervention studies to consider tailoring interventions depending on desired individual health outcomes.

An important question that remains is whether lower interoceptive attention in older adults is a cause or a consequence of hunger and satiety signalling. For example, computational evidence indicates that when sensory sensitivity is low (or the signal itself is weakened), the result is diminished attentional processing of that sensory channel (in favour of more reliable sources of information) (Mirza, Adams, Friston, & Parr, 2019). However, the fact that older adults in the present study also reported higher levels of interoceptive accuracy suggests that they have more confidence in the accuracy of their interoceptive percept and argues against this possibility.

In line with previous research, the present study confirmed that older adults tend to experience lower levels of emotionally cued eating (Samuel & Cohen, 2018), food responsivity (Brennan et al., 2022), and food enjoyment (Spence & Youssef, 2021), despite being more overweight. Importantly, the current study highlighted that differences in the way interoceptive signals are processed, probably contribute to these observations. Specifically, spending more time paying attention to interoceptive signals was associated with having higher levels of emotional eating, food responsivity and food enjoyment. In addition, appetite signals mediated the association between interoceptive attention and both emotional overeating and food responsivity, a similar pattern to that observed in (Robinson, Marty, et al., 2021). As older adults in the present study reported lower interoceptive attention this might explain their reduced propensity towards these obesogenic eating behaviours.

Reduced interoceptive attention and lower emotional overeating in older adults may reflect age related differences in the degree to which ‘bottom-up’ interoceptive signalling contributes to emotional experience. Mendes (2010) introduced the idea of maturational dualism, which posits that aging is accompanied by a weakened connection between the body and mind that has a significant impact on the way emotions are experienced. Specifically, the ability to perceive internal bodily sensations diminishes as individuals grow older, primarily due to the increased vulnerability of the peripheral nervous system and a resulting decrease in physiological reactivity. Consequently, older adults become less skilled at recognising the physiological changes that occur when they are emotionally stimulated. In the absence of being able to identify these internal bodily changes, older adults’ emotional experiences become more ‘cognitive’. That is, they rely more on external representations from the present context, and prior experience, and knowledge about emotion categories to assess their emotional responses (Barrett, 2017). Furthermore, less intense interoceptive experiences might make it easier to regulate one’s emotions (Charles, 2010). This view aligns with observations that emotional regulation improves with age (Orgeta, 2009), and could explain lower levels of interoceptive attention, hunger, and emotional eating amongst older adults in the present study. In support of this suggestion previous research that found heightened interoceptive signalling and decreased meta-cognitive awareness of interoceptive capacities, are characteristic of emotional eaters (Young et al., 2017).

Regarding BMI, older adults are more likely to be classified as being overweight and obese; an effect confirmed in the present study. However, rather than exacerbating weight gain, the results of our SEM suggested that reduced interoceptive attention in older adults may in fact be protective. That is, in older adults lower interoceptive attention and hunger were associated with lower obesogenic eating behaviours and therefore a lower BMI (negative indirect pathway). Crucially, the direct effect, that is the effect of age on BMI after the indirect pathways have been considered, was significant and positive, indicating partial mediation. This suggested that other factors besides interoception (e.g., lean muscle mass, basal metabolic rate, other lifestyle factors) may also be implicated in age related obesity. Additionally, reproductive hormones such as estrogen, play a key influential role in appetite, obesity, and ageing (Hirschberg, 2012). Some research has shown that during the follicular phase of menstruation reproductive hormones may have an antagonistic effect on energy intake and appetite regulation (Campolier et al., 2016; Stelmanska & Sucajtys-Szulc, 2014). Yet less is known about the luteal phase of menstruation (Kamemoto et al., 2022). Furthermore, there is little to no research exploring these ovarian cycle effects in relation to general interoceptive sensibility. Intuitively, experiencing painful and unpleasant menstrual symptoms may correlate with attention to symptoms and self-regulation abilities (Borlimi et al., 2023). Though the measures used in the present study have yet to be explored in relation to menstrual phases and menopause, therefore at present these associations remain speculative. This research gap may be salient for future exploration, particularly in modelling studies.

The current study benefited from a theoretical framework of the mechanisms underlying obesity, a large sample size, SEM modelling, well validated and reliable measures, and the recruitment of an under-researched population. However, limitations require consideration. Firstly, given the cross-sectional design, causality cannot be inferred. Secondly, we concentrated on participants whose birth sex is female due to sex differences in eating behaviour and interoception. This study should be replicated in male samples. Thirdly, we used self-reporting methods of BMI, the problems and questions of reliability using this method have long been documented. However, some research has found a positive association between reporting inaccuracies and BMI, particularly in adolescent samples (Allison et al., 2020). The present research recruited adults only and implausible BMI data was removed. Lastly, the present research may have benefitted from further demographic information e.g., social economic status, ethnicity, health status etc.

4.1. Conclusion

Despite being more susceptible to obesity related harms older adults are under-represented in eating behaviour research. The present study indicated a complex pattern of associations connecting age, interoception, appetite and BMI. Older adults were more overweight and an indirect pathway involving age-related reductions in interoceptive attention, lower satiety responsivity, and more emotional eating and food responsivity mediated this effect. However, a stronger antagonistic indirect pathway was also present; age-related reductions in interoceptive attention were associated with a lower hunger drive, less emotional eating, and a lower BMI. This suggested that overall reduced interoceptive attention in older adults may protect against weight gain by lowering hunger and the propensity towards obesogenic eating behaviours. These findings highlight that the interoceptive mechanisms driving aberrant eating behaviour and obesity in older adults may not be the same as in young adults. Further research aimed at understanding the role of interoception will likely shed light on mechanisms underlying pathological eating behaviour and pave the way towards innovative treatment methods. A deeper understanding of the complex mechanisms underlying obesity in this cohort is required to tailor age-related- and novel-therapeutic approaches, with beneficial implications for public health.

Ethics statement

The procedures in this study were approved by Swansea University Faculty of Medical, Human and Life Sciences ethics committee.

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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 data that has been used is confidential.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.appet.2023.107045.

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