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Appetite 196 (2024) 107261

Contents lists available at ScienceDirect

Appetite

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

Food-related exploration across the menstrual cycle

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ARTICLE INFO

Keywords:
Novelty
Exploration
Menstrual phase
Menstrual cycle
Food choices
Decision-making

ABSTRACT

When deciding what to eat we constantly weigh different aspects of the options at hand and make trade-offs between exploiting opportunities with a known outcome (e.g., eating your usual meal) and exploring novel opportunities with a potentially better outcome (e.g., trying a new dish). Environmental factors, such as scarcity, have previously been shown to tip the balance towards either exploration or exploitation. Studies in animals have further linked female steroid hormones (including estradiol and progesterone) to exploratory behavior. Previous work in humans has suggested that food preferences and food intake also change over the menstrual cycle. However, it remains unknown whether exploratory behavior in food choices also changes across the menstrual phases in humans. In a rating phase, 112 adult women (age range 18–45 years) on or off hormonal birth control rated 40 food items on desirability. In the choice phase, participants made binary choices between food items. On some trials, a surprise box replaced one of the two food options, allowing us to examine exploratory choices. Women off hormonal birth control reported their average cycle length and time since the first day of their last menstruation. Analysis of the percentage surprise choices across the menstrual cycle indicated a small, but significant effect, with exploratory choice behavior tending to increase around the middle of/later during the cycle. This provides preliminary novel evidence that hormonal fluctuations are associated with food-related exploratory choice behavior. Importantly, these effects were observed beyond effects of other food-related factors. Future studies should investigate the nature of these effects using more direct hormonal measures.

1. Introduction

In an environment with limited resources, exploration is a crucial aspect of behavior, yet it also comes at the cost of uncertainty. Imagine that your favorite restaurant adds new dishes to their menu: Will you go with your usual choice, or will you choose a new dish that is potentially even better, but could also potentially be worse? We constantly make such trade-offs between exploiting opportunities with a known outcome and exploring novel opportunities with potentially better outcomes, while accepting the accompanying risks. Previous work has suggested that humans can adapt their behavior dynamically to deal with changes in the environment (Daw, O'doherty, Dayan, Seymour, & Dolan, 2006). Although decisions are constantly weighed against options that exploit known opportunities, a more exploratory mode may be adopted in case of scarcity (Laureiro-Martínez, Brusoni, & Zollo, 2010). For instance, natural scarcity in petroleum resources has been shown to drive exploration of alternative sources of energy (e.g., see Cleveland, 1993; Jakobsen, Söderbergh, Snowden, 2012). Not only environmental factors, but also internal states, such as hunger, may influence the exploration-exploitation trade-off (Burnett et al., 2016; Corrales-Carvajal, Faisal, & Ribeiro, 2016; Zimbardo & Miller, 1958). Several studies in animals have further linked female steroid hormones, including estradiol and progesterone, to *exploratory* behavior (e.g., Diz-Chaves et al., 2012; Frye, Llanaza & Walf, 2009; Orr, Lewis, & Frick, 2009), however, no studies up to date have investigated these effects in humans and the role of steroid hormones in exploratory behavior in humans thus remains unclear.

If estradiol or progesterone affect human exploratory behavior, then exploratory behavior should vary across the menstrual cycle. The menstrual cycle can be divided into three main phases. The first is the *follicular phase*, beginning on the first day of menstruation. Estradiol levels are basal at the beginning of the follicular phase and increase progressively during the second week; progesterone levels are basal throughout (Asarian & Geary, 2013; Hampson, 2020). The follicular phase ends with ovulation, which occurs near mid-cycle (e.g., on day 14–18 of 26–30 day cycles; Bull et al., 2019; Johnson, Marriott, &

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https://doi.org/10.1016/j.appet.2024.107261
Received 30 June 2023; Received in revised form 8 February 2024; Accepted 9 February 2024
Available online 10 February 2024

Zinaman, 2018) – though variability exists in terms of both cycle length and timing in the cycle when ovulation occurs. The *ovulatory phase* is the 3–4 days around ovulation. Surges of luteinizing hormone (LH) and follicle stimulating hormone (FSH) stimulate ovulation. Estradiol levels are maximal until the LH surge and fall thereafter. Progesterone levels remain low. The *luteal phase* follows ovulation and lasts until cycle end, the day before menstruation. Secretion of progesterone and estradiol increase to high levels in the mid-luteal phase before returning to basal levels by cycle end.

Likely due to their direct relevance for reproduction, female steroid hormones have been linked to effects associated with sexual reproduction, including effects on social behavior (Durante, Griskevicius, Hill, Perilloux, & Li, 2011), physical appearance and perception of others (Havlíček, Cobey, Barrett, Klapilová, & Roberts, 2015), and specific behaviors related to sexual reproduction (e.g., Haselton & Gildersleeve, 2011; Bobst & Lobmaier, 2012), including sexual desire (Pillsworth, Haselton, & Buss, 2004), and sexual drive (Adams, Gold, & Burt, 1978).

The effects of female sex hormones have also been observed for other types of behavior, that are not so clearly linked to reproduction. For example, one study showed that younger ovariectomized rats exhibited more exploration in an open field after estradiol treatment verus before (Diz-Chaves et al., 2012). Related to this finding, several studies have shown that ovariectomized rats receiving progesterone treatment explore novel objects longer than familiar objects (Frye, Llanaza & Walf, 2009; Orr et al., 2009), also suggesting better object recognition in the animals that received progesterone compared to animals that received a control treatment (note that novelty exploration can be used as a measure of object recognition, as such a bias could only occur if the simultaneously presented familiar item is actually recognized). Some have argued that estradiol promotes exploration via anxiolytic effects, promoting subsequent recognition memory through reduction of fear-like responses during exploration (Diz-Chaves et al., 2012). In humans, another type of decision-making across the menstrual cycle has been investigated. For example, social behavior, including changes in generosity and cooperative behavior, have been found to be modulated by estradiol and progesterone levels across the menstrual cycle (Sellitto & Kalenscher, 2022; Stenstrom, Saad, & Hingston, 2018). Here, we aim to investigate whether exploration behavior in humans is also modulated by the varying hormonal states across the menstrual cycle. As both estradiol and progesterone have been linked to exploratory behavior in animal studies, we used the time during the menstrual cycle that women are in to address the role of these hormones on human exploratory behavior.

Previous work has shown that food-related choices change across the menstrual cycle. For instance, one study showed that women spent more money on food-related products during the non-fertile luteal phase, than during other phases of the menstrual cycle (Saad & Stenstrom, 2012). Similarly, a double-blind study estimated food intake via self-report and found that women reported eating more food during the 10 days after ovulation (i.e., in the luteal phase) compared to the 10 days before ovulation (i.e., including the follicular and ovulatory phases; Dalvit, 1981). Furthermore, during the luteal phase, women tend to be prone for overconsumption and more often exhibit specific food cravings, for example for foods rich in carbohydrates (Dye & Blundell, 1997). In line with this, another study found that in the post-compared to pre-ovulation phase especially more carbohydrates are consumed (McPhillips, 1983). Potentially, these variations serve an adaptive purpose related to reproducibility (i.e., with varying demands in the different phases of the menstrual cycle). Psychophysiological studies suggest the effects on food preferences and consumption may be explained by a modulating effect of the menstrual cycle on attention towards food items: An EEG study suggested that healthy women in the mid-luteal phase versus the late follicular phase exhibited an attentional bias towards appealing food items, and away from disgusting food items (Yao, Zhuang, Shen, & Wang, 2022). Findings from a neuroimaging study further suggested that corticolimbic brain responses (including the nucleus accumbens, amygdala and hippocampus) to visual food cues may underlie these variations in food intake across the menstrual cycle (Frank, Kim, Krzemien & van Vugt, 2010), with both low and high calorie foods activating corticolimbic structures during the follicular phase, and high calorie foods only activated these regions in the luteal phase. The current literature thus suggests there is a link between female steroid hormones and food-related choices across the menstrual cycle, with higher food spending, higher food intake (especially carbohydrates), more overconsumption and increased food cravings during the luteal/post-ovulation phase versus the follicular phase. In addition, higher estradiol levels - that are rising during the follicular and ovulatory phases - have been linked to higher craving of sweet and carbohydrate cravings as well (Krishnan, Tryon, Horn, Welch, & Keim, 2016). Although previous work thus provides strong evidence for changing food-related preferences and spending/consumption behavior across the menstrual cycle, no study so far has investigated the effects on exploratory behavior on food choices.

Exploration of novel food choices is probably highly linked to our innate fear of unknown foods. This reluctance to try unknown food items is known as *food neophobia* and from an evolutionary perspective has been adaptive to prevent intake of potentially poisonous or harmful items. However, food neophobia may become maladaptive in certain eating disorders that are characterized by restrictive and/or limited intake of food items, such as in anorexia nervosa or avoidant restrictive food intake disorder (Corey, 1978; Ley, 2010; Pliner & Salvy, 2006). To attain and maintain a high variety in food intake, it is crucial that unknown food items are part of the diet over the lifespan. Certain eating disorders that are characterized by restrictive or unvaried eating, such as anorexia nervosa, are more prevalent in women. Understanding how exploratory eating behaviour changes over the menstrual cycle may thus have clinical value for the treatment of such disorders.

The current study aimed to investigate 1) whether exploratory behavior changes across the menstrual cycle, and 2) whether females on hormonal birth control (resulting in low estradiol and high progesterone levels) differ from fertile women off hormonal contraceptives in terms of exploratory behavior. To this end, we used an experimental paradigm in which ovulating adult women (18–45 years of age) on or off birth control (i.e., oral contraceptives) made binary choices between food items; however, on some trials a surprise box was presented instead of one food item. Before a choice was made the content of the box was unknown, but after participants chose this surprise box the item inside would be revealed. We used the proportion of surprise boxes chosen as a measure of exploratory behavior (see Petzke & Schomaker, 2022). Our design allowed us to investigate food choices and exploratory behavior across the menstrual cycle and in women on hormonal birth control, while taking into account other factors that have previously been shown to influence food choices (such as valence, motivation, and perceived healthiness).

2. Methods

2.1. Participants

A total of 141 participants volunteered in the current study. All participants reported to be of the female sex and to not be undergoing any other form of hormonal treatment other than the birth control pill. Inclusion criteria were females 18–45 years of age and proficiency in English. Participants who reported to be (potentially) pregnant ($n = 6$), breastfeeding ($n = 1$), post-menopausal ($n = 1$), or who did not complete the demographics questionnaire ($n = 21$) were excluded from the analyses. As such, the final sample comprised 112 participants (18–44 years old; mean age = 25.9 years; SD = 7.0 years). Fourteen participants reported a very short cycle length of $\leq$7 days. Feedback via Prolific chat suggested that these individuals misunderstood cycle length to be the average duration of their menstruation. We therefore substituted cycle lengths of a week or less ($\leq$7 days) by the mean rounded average of 28 days. After correction, the cycle length ranged between 14 and 36 days (mean = 27.9; SD = 3.0). Participants reported to be 0–40 days (mean = 13 days; SD = 10.5 days) after the first day of their last menstruation. Eleven participants reported to not have a regular cycle (with a cycle length estimated between 20 and 36 days), but as these fell in the average ± 2SD cycle range, their data were still included in the analyses. This study was a sub-project of previously published work (Petzke & Schomaker, 2022), and no specific power analyses were ran for the current study's research questions. We aimed to reach a minimum of 30 participants per group (Pallant, 2007, pp. 179–200) but, as we had no control over the menstrual cycle phase that our participants were in, we did not reach this number for all groups, even after a second data collection round (see details below).

To determine where participants were in their cycle, we calculated the percentile of the current day with regard to the participant's average cycle length. As an example, a participant who is on day 6 of her cycle and has an average cycle of 30 days will have a percentile phase score of 20% (which would presumably be in the early follicular phase).

Of the included participants, sixteen participants were unable to provide an estimate of their typical cycle length. If participants did not report cycle duration it was estimated to be 28 days (the rounded average of the cycle length in the current study), allowing us to calculate a percentile menstrual cycle score. A total of 33 women reported to be on some form of hormonal contraception (birth control pill = 27; hormonal intrauterine device = 3; hormonal implants = 1; hormonal ring = 1; hormone patch = 2). In an open-end question participants indicated which type of hormonal birth control pill they were taking. Answers included combination pill with levonorgestel/ethinylestadiol (including Microgynon 30 and Rigevidon; n = 14), cyproterone acetate/ethinylestradiol (including Minerva; n = 2), mini-pill/progestin-only (including drospirenone; n = 2), unknown/unspecific (n = 7). Participants were recruited via Prolific (February 2022 and in July 2022 with use of the birth control pill as extra exclusion criterion) and received 3.5 Euros as compensation. Ethical approval was obtained from the Research Ethics Committee of the Faculty of Social and Behavioural Sciences at Leiden University. The study was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki and its later amendments.

2.2. Stimuli & apparatus

The experiment was programmed in OpenSesame version 3.2.8 (Mathôt, Schreij, & Theeuwes, 2012) and presented on the participants home computer (we recommended the use of a PC or laptop and excluded participation via tablet or phone). The food stimuli consisted of images taken from the Natural and Ultra-Processed Food (NUPF) database, including food items photographed on a grey background. The NUPF database includes ratings on approachability (approach/avoid), desirability, popularity, and healthiness, valence, arousal, and recognizability (Schomaker, Jarva & Vriens, 2022). Data were analyzed using SPSS 27 and logistic models were run in R.i386 4.0.0.

2.3. Procedure

At the beginning of the experiment, participants provided informed consent by checking a box. They then indicated their age, rated their hunger on a 7-point scale, and indicated how much time had passed since their last food intake. In the following experimental task, participants first rated the desirability of 40 food items during a *rating phase* (see Fig. 1A). During this phase, a trial started with the presentation of a fixation dot for 500 ms. The fixation was followed by the presentation of a food item, that was shown at the center of the screen for 2000 ms. After this, participants could indicate the desirability of the previously shown item on a 7-point Likert scale (from "Not at all" to "Very much") using the number keys on their keyboard. The rating screen was shown until a response was given. All 40 food items were presented in a random order

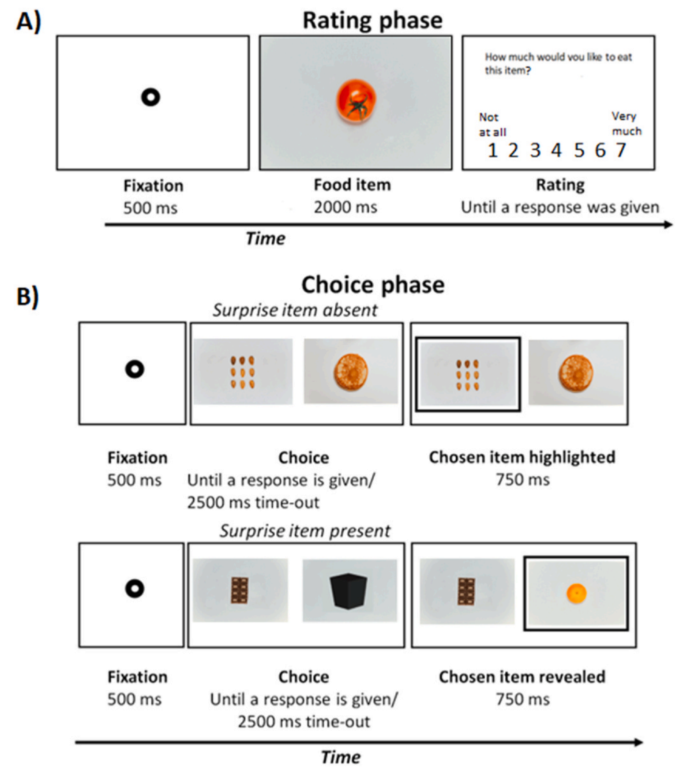

Fig. 1. *Experimental procedure.* A) During the rating phase all food items were shown, and participants indicated how much they would like to eat the shown item on a 7-point Likert scale (from "Not at all" to "Very much"). B) In the following choice phase participants chose between two items. On *surprise box absent* trials both options would be visible. On *surprise box present* trials one item would be hidden by a box. If the surprise box was chosen, the contents of the box would be shown. In case the visible item was chosen the surprise box would not be revealed.

and the total duration of this phase was ~2 min. Participants could take a self-paced break after the rating phase. In the following *choice phase* (see Fig. 1B), trials again started with a 500 ms fixation dot. After fixation, one food item was shown at the left and one at the right side of the screen. Choice options were counterbalanced throughout the experiment (e.g., such that not two identical items would be shown, all 40 food items would be presented equally often, and choice combinations would not be repeated), but all participants were given the same choices. Participants were asked to choose between the two options, by pressing the "x" key for the left item or the "m" key for the right item, using their left and right index fingers respectively. They were instructed to pick the more desirable item. The surprise box option was not mentioned in the instructions. A new trial started when a response was given or after a time-out of 3000 ms. A picture of a black box indicated that a food item was "hidden" in it. After choosing this box, participants were shown what was "inside" for 750 ms. Participants made 80 choices during the choice phase and a surprise item was present on 50% of the trials (the food combinations were pseudorandomized; i.e., every participant was presented food and surprise item combinations). The sequence of food stimuli was fully randomized. The average duration of the choice phase was ~8 min.

After this experimental phase, participants were redirected to a Qualtrics questionnaire including demographic questions, a lockdown questionnaire (see Petzke & Schomaker, 2022), and the novelty seeking subscale of the Tridimensional Personality Questionnaire (Cloninger, 1987; Cloninger, Przybeck, & Svrakic, 1991). Filling out these questionnaires took about 5–8 min.

2.4. Statistical analyses

We used the stimulus information and item ratings from the NUPF database (Schomaker, Vriens, & Jarva, 2022) to investigate which factors influenced decision-making on *surprise box absent* trials for all participants, to confirm that they made meaningful and value-based decisions. We ran *t*-tests to compare chosen versus unchosen items on the valence, arousal, recognizability, desirability, approach/avoidance measure, popularity (i.e., subjective estimate of how often the item is consumed), calorie density (i.e., calories per 100 g of the portion), portion calories, and perceived healthiness. To investigate the effects of personal preferences (as quantified with the desirability scores from the rating phase in this experiment) we compared the desirability ratings for chosen and unchosen items. As these analyses suggested that these ratings capture aspects that participants considered when making choices, we included these measures as predictors in our choice and response time models.

To investigate the effects of menstrual cycle (percentile score) in naturally cycling women (i.e., women *off* birth control) on the characteristics of the chosen items we furthermore ran a multivariate analysis of covariance (MANCOVA) with valence, arousal, recognizability, desirability, approach/avoidance measure, popularity (i.e., subjective estimate of how often the item is consumed), calorie density (i.e., calories per 100 g of the portion), portion calories, and perceived healthiness of the chosen items as dependent variables, and menstrual cycle percentile score as a covariate. Note, in all analyses including menstrual cycle as a factor or predictor, women *on* birth control were excluded, as no percentile score could be calculated for them.

Furthermore, we investigated whether these factors and menstrual cycle (as percentile score) in naturally cycling women influenced exploratory choice behavior on *surprise box present* trials. Note, women *on* birth control were excluded in this analysis. To deal with issues of multicollinearity a general measure of motivation and affective valence was created, by averaging across the valence, desirability, and approach/avoid ratings for each item. A similar approach was used in a study by Schomaker, Rau, Einhäuser, and Wittmann (2017) in which a principal component analysis revealed that ratings related to motivation and valence of objects were highly associated. Previous work suggests that effects of the menstrual cycle may follow a quadratic pattern (Kuukasjärvi et al., 2004), with males rating females' odor as more attractive mid-cycle versus earlier or later during the cycle (and a non-significant trend for females rating males as more attractive), and a preference for immediate rather than delayed reward (increased discounting) for women in the peri-ovulatory phase (Vincent, Sztwiertnia, Koomen, & Warren, 2023). However, as the effects of menstrual cycle on exploratory behavior have not yet been investigated it is also possible that the effects may be linear. Therefore, for the models including cycle percentile we ran two versions: One including a linear (model 1A) and one including a quadratic cycle percentile predictor (model 1B).

First we centered the data and then we set up two generalized logistic mixed models (GLMMs; model 1, either with a linear [model 1A] or quadratic [model 1B] cycle percentile predictor) with this motivation and valence compound score, arousal, recognizability, approach/avoid, popularity, calorie density, portion calories and menstrual cycle (i.e., a continuous percentile score) either as a linear or quadratic term (estimated percentile score^2) as predictors of exploratory choice (visible item chosen = 0; surprise box chosen = 1). Variance inflation factors (VIFs) were <6.5, suggesting low to moderate multicollinearity. In addition, we were interested in potential differences between women who were on hormonal birth control and those who were not (irrespective of cycle). For this purpose, we ran a *t*-test comparing the percentage of exploratory choices between women *on* and *off* birth control.

To investigate whether specific food-related factors (including food-specific aspects as well as affective factors) and the time during the menstrual cycle in naturally cycling women (women on birth control were excluded in this analysis) influenced response times, we also ran two general linear models (model 2; either with a linear [model 2A] or quadratic [model 2B] cycle percentile predictor) with a motivation and valence compound score, arousal, recognizability, approach/avoid, popularity, calorie density, portion calories and time during the menstrual cycle either as a linear or quadratic term as predictors of response times for surprise box absent trials (surprise box present trials were not included, as the subjective ratings of the surprise box were unknown for these trials until a choice was made). VIFs were all <6, again suggestion low to moderate multicollinearity. Analyses of the lockdown questionnaire are not reported in this article (for a study reporting results from this questionnaire, see Petzke & Schomaker, 2022).

Finally, two general linear models (model 3; with a linear [model 3A] or a quadratic [model 3B] cycle percentile predictor) was ran, with time during the menstrual cycle (as percentile score) in naturally cycling women (again, women on birth control were excluded in this analysis) either as a linear or quadratic predictor, surprise box choice as dummy variable (with 0 = visible item chosen; 1 = surprise box chosen) and the interaction between the two as a predictors of response times during surprise box present trials. VIFs were <2, suggesting low multicollinearity.

We ran two versions of each model (model 1–3), either including a linear or a quadratic cycle percentile predictor. We compared these versions of each model using the Akaike Information Criterion (AIC). Lower AIC values suggest a better model fit, with a difference of 2 or less being considered weak evidence in favor of the lower AIC model, and a difference of 4 being considered stronger evidence.

3. Results

3.1. Factors influencing choices

We investigated whether different food item characteristics (calorie density, portion calories), NUPF ratings (approach/avoid; desirability; popularity; healthiness; recognizability; valence; arousal), and individuals' subjective value of the items (as obtained via desirability ratings in this experiment) influenced choice behavior (see Fig. 2). Across all participants, results showed that caloric density was lower for chosen than unchosen items $t(110) = -2.62$, $p = .010$ (Cohen's $d = -0.258$), but the portion calories were higher for chosen than unchosen items, $t(110) = 2.80$, $p = .006$ (Cohen's $d = 0.266$). Additionally, motivational factors influenced choice behavior. Chosen items had a higher approachability and desirability rating than unchosen items, $t(110) = 3.34$, $p = .002$ (Cohen's $d = 0.317$) and $t(110) = 4.23$, $p < .001$ (Cohen's $d = 0.401$) respectively. Furthermore, valence was higher for chosen than unchosen items, $t(110) = 4.13$, $p < .001$ (Cohen's $d = 0.392$). Similarly, personal preferences influenced choice behavior (see Fig. 3): Chosen items were rated as more desirable (as quantified by the question "How much would you like to eat this item?") during the rating phase than unchosen items, $t(110) = 26.58$, $p < .001$ (Cohen's $d = 2.52$). In addition, chosen items were associated with higher recognizability ratings than unchosen items, suggesting that participants were more inclined to choose items that they recognized. Arousal, perceived healthiness, and popularity did not influence choice behavior (all *ps* > .246). Overall, these results suggest that participants were making choices that truly reflected their preferences.

Finally, the MANCOVA did not reveal any effect of time in the menstrual cycle (percentile mean = 49.4, SD = 37.0) for the naturally cycling women on the characteristics (i.e., caloric density, portion calories, approachability, desirability, arousal, valence, recognizability, popularity, and perceived healthiness) of the chosen items (all *ps* ≥ .404).

3.2. Exploratory choices

The effects of menstrual phase on the proportion of exploratory choices on *surprise box present trials* was investigated with a GLMM, with

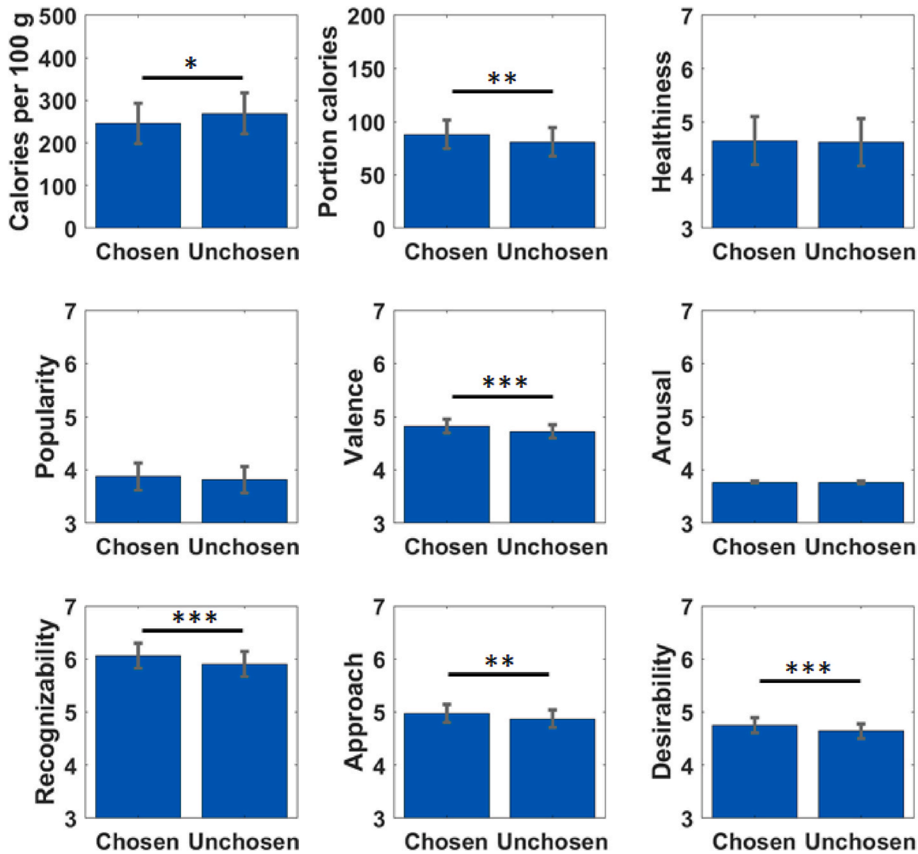

Fig. 2. *Item characteristics of chosen and unchosen items on surprise box absent trials.* Mean calories per 100 g and portion calories are shown for chosen and unchosen items. Also mean ratings from the Natural and Ultra-Processed Food (NUPF) database are shown for chosen and unchosen items including perceived healthiness, popularity, valence, arousal, recognizability, approach and desirability (note, these standardized ratings are included in the NUPF database and were thus collected in a different sample). Note, error bars reflect standard deviations. *: $p < .05$; **: $p < .01$; ***: $p < .001$.

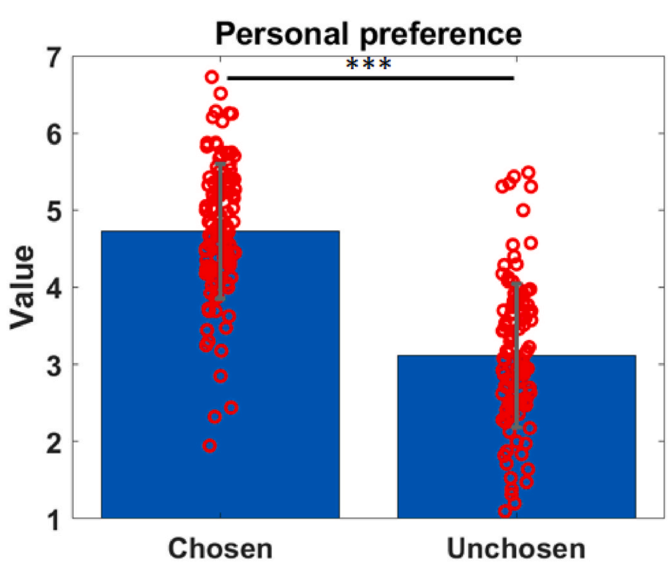

Fig. 3. *Personal preference ratings*. Mean value and individual data points for chosen and unchosen items as derived from the "How much would you like to eat this item" scores from the rating phase of this study. Red dots reflect individual data points, and error bars reflect the standard deviations. ***: $p < .001$.

a motivation and valence compound score, arousal, recognizability, approach/avoid, popularity, calorie density, portion calories and menstrual cycle either as a linear or quadratic term as predictors. Results of this model are presented in Table 1. In the model including menstrual

Table 1
Model 1: Factors predicting exploratory choice behavior in women off hormonal birth control.

	Exploratory choices	b-value	z-value	p-value
	df = 3684			
Model 1A: Linear				
Motivation and valence		**−0.4**	**−5.8**	**<.001**
Cycle percentile (linear)		**<.01**	**−4.9**	**<.001**
Calorie density		**0.2**	**3.7**	**<.001**
Arousal		**0.12**	**2.8**	**<.001**
Portion calories		**−0.2**	**2.7**	**<.001**
Popularity		0.1	1.8	.075
Perceived healthiness		0.1	1.2	.243
Recognizability		<-0.1	−0.6	0.526
			AIC	4333
Model 1B: Quadratic				
Motivation and valence		**−0.4**	**−5.8**	**< .001**
Cycle percentile (quadratic)		**<-0.1**	**−4.2**	**< .001**
Calorie density		**0.2**	**3.7**	**< .001**
Arousal		**0.1**	**2.8**	**.006**
Portion calories		**−0.2**	**−2.7**	**.007**
Popularity		0.1	1.8	.075
Perceived healthiness		0.1	1.2	.241
Recognizability		<-0.1	−0.1	.523
			AIC	4334

Note, predictors reflect the average ratings of the visible (not the invisible surprise) item. Cycle percentile was entered as a linear or quadratic term and reflects the estimated percentile within the menstrual cycle (with lower percentiles at the start and higher percentiles later in the cycle). Significant predictors printed in bold. AIC = Akaike Information Criterion.

cycle as a quadratic predictor, cycle percentile predicted exploratory choice behavior ($p < .001$), with a concave (i.e., negative coefficient) relationship, with women off birth control around the middle of their cycle making more exploratory choices than women earlier or later in their cycle (see Table 1 and Fig. 4; note, the size of the *b* suggests a minimal impact). In the model including the linear term for cycle percentile, a positive *b*-value suggested that women later in the menstrual cycle made more exploratory choices than women earlier in the cycle. The two models (including either a linear or quadratic term for cycle percentile) showed the same pattern of results for the other predictors. The proportion of surprise box choices was lower when the visible item had more rather than fewer portion calories. In contrast, when calorie density of the visible item was higher rather than lower, this increased chances that the surprise box was chosen. Using the NUPF database scores, we found that visible items with higher mean motivation and valence ratings decreased the chances that the surprise box was selected, suggesting higher competition. Higher levels of associated arousal as based on the NUPF ratings for the visible item, however, increased chances that the surprise box was chosen. The NUPF ratings popularity, perceived healthiness, and recognizability of the visible item had no effect on exploratory choices. The linear model had an AIC-value of 4333, and the quadratic model had an AIC of 4334 (difference = 1), suggesting that both models performed similarly (with slightly weaker evidence for the linear model).

Table 2 shows the mean proportion of surprise choices for *surprise box present trials* for women *on* and *off* hormonal birth control. No difference in the proportion of exploratory choices was observed between women *on* and *off* (across all cycle phases) hormonal birth control, $t(102) = -0.8$, $p = .403$ (Cohen's $d = -0.2$).

3.3. Response times

Response times for choices on *surprise box absent trials* were investigated with a GLM (model 2), with a motivation and valence compound score, arousal, recognizability, approach/avoid, popularity, calorie density, portion calories and menstrual cycle as a quadratic term as predictors (see Table 3). Model 2A, with a linear cycle percentile predictor suggested that women later in the cycle were slower than women earlier in the cycle. The same pattern of results was observed for the other predictors in the models with a linear and quadratic cycle percentile predictor. Choices for items with more rather than less portion calories were faster. In contrast, choices for items with a higher rather than lower calorie density were slower. Higher motivation and valence of the visible item were associated with faster response times than lower motivation and valence. When the chosen item had a higher perceived healthiness, responses were slower than when the chosen item had a lower perceived healthiness. No effect was found of the other

Table 2
Proportion of surprise box choices for individuals on and off hormonal birth control.

Proportion of surprise choices	Range (min – max)	Mean	SD	n
On hormonal birth control	0–.9	.4	.2	35
Off hormonal birth control	0–.8	.3	.2	74

Note: SD = standard deviation. Proportion of surprise choices for surprise box present trials.

Table 3
Model 2: Factors predicting response times for surprise box absent trials in women off hormonal birth control.

	Response time	Estimate	t-value	p-value
	df = 3537			
Model 2A: Linear				
Cycle percentile (linear)		**0.9**	**4.4**	**< .001**
Calorie density		**46.2**	**4.0**	**< .001**
Portion calories		**−30.2**	**−2.7**	**< .001**
Perceived healthiness		**43.3**	**2.6**	**.010**
Motivation and valence		**−46.0**	**−2.2**	**.031**
Arousal		14.0	1.4	.161
Recognizability		16.3	1.2	.228
Popularity		−15.8	−1.0	.331
			AIC	53,684
Model 2B: Quadratic				
Cycle percentile (quadratic)		**0.01**	**4.4**	**<.001**
Calorie density		**46.4**	**4.1**	**<.001**
Portion calories		**−30.2**	**−2.8**	**.005**
Perceived healthiness		**43.5**	**2.6**	**.010**
Motivation and valence		**−45.1**	**−2.1**	**.032**
Arousal		13.7	1.4	.172
Recognizability		16.2	1.2	.231
Popularity		−16.5	−1.0	.311
			AIC	53,684

Note, predictors reflect the average ratings of the chosen item. Cycle percentile was entered as a linear or quadratic term and reflects the estimated percentile within the menstrual cycle (with lower percentiles at the start and higher percentiles later in the cycle). Significant predictors printed in bold. AIC = Akaike Information Criterion.

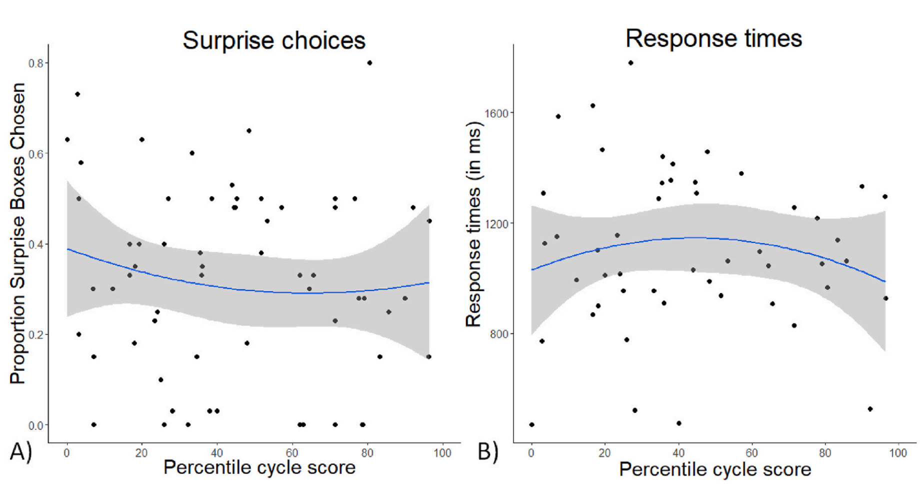

Fig. 4. *Effect of menstrual cycle on surprise choices and response times in women off birth control.* A) Proportion of surprise box choices and B) response times (in milliseconds) as a function of the menstrual cycle percentile score. The solid line reflects a quadratic regression fit, and the grey area a 95% confidence interval. For surprise choices we found both a linear (model 1A) and a quadratic effect (model 1B) of percentile cycle score, (with neither model clearly superior). For response times we found strong evidence for a quadratic over a linear effect of percentile cycle score (model 3B > model 3A). Note that we included other predictors in our model 1 (for choice behavior) and model 3 (for response times), that are not taken into account in the trendlines shown here.

predictors (all *ps* > .172). In model 2B, with a quadratic cycle percentile predictor, menstrual cycle percentile was a significant predictor of response times, with a convex (or concave down; i.e., positive coefficient) relationship; with women around the middle of their cycle making faster choices than women earlier or later in their cycle. No winning model could be identified, as both the linear and quadratic model yielded an AIC-value of 53,684.

Response times for surprise box choices on *surprise box present* trials for naturally cycling women was investigated with a GLM, with time during the menstrual cycle (as linear or quadratic percentile score), surprise box choice as dummy variable (with 0 = visible item chosen; 1 = surprise box chosen) and the interaction between the two as a predictors (model 3; see Table 4). The linear cycle percentile predictor was not significant (p = .974; model 3A). Quadratic menstrual cycle percentile was a significant predictor of response times (model 3B), with a concave (i.e., negative coefficient) relationship, with women around the middle of their cycle making slower choices than women earlier or later in their cycle. No effect of the other predictors was found (for both model 3A and 3B all *ps* > .692). The model with the quadratic cycle percentile predictor (AIC = 58,003) outperformed the model with a linear cycle percentile predictor (AIC = 58,009), with an AIC difference of 6, suggesting strong evidence for the quadratic rather than linear model.

Fig. 5 shows the mean response times for surprise and visible item choices for females *on* and *off* hormonal birth control. Responses were faster for visible items (mean = 1103 ms) than surprise box items (mean = 1028 ms), $F(1,84) = 5.5$, $p = .022$, $\eta^2 = 0.061$. Neither a main effect of hormonal state ($p = .907$) nor an interaction between the type of choice (surprise box or visible item) and hormonal state (*on* or *off* hormonal birth control; $p = .812$) was found on response times.

4. Discussion

In this study we investigated whether food-related exploratory choice behavior is predicted by the menstrual cycle. We asked women on and off birth control to rate a set of food items, and subsequently asked them to make a series of choices between two simultaneously presented food items. On half of the choice trials a surprise box was presented, which held an unknown item – by evaluating the proportion of choices for these items, we could evaluate exploration behavior. We found that chosen options had higher motivational value, as demonstrated by higher mean ratings for approachability and desirability, as well as a more positive evaluation (i.e., valence) as estimated with the NUPF

Table 4
Model 3: Factors predicting response times for surprise choices on surprise box present trials in women off hormonal birth control.

	Response time	Estimate	t-value	p-value
	df = 3684			
Model 3A: Linear				
Cycle percentile (linear)		<0.1	<.01	.974
Cycle percentile * Surprise box chosen		0.3	.4	.692
Surprise box chosen {0, 1}		−0.2	<-0.1	.995
			AIC	58.009
Model 3B: Quadratic				
Cycle percentile (quadratic)		**<-0.1**	**−2.4**	**.015**
Cycle percentile * Surprise box chosen		<0.1	0.3	.734
Surprise box chosen {0, 1}		−2.0	0.1	.946
			AIC	58.003

Note, cycle percentile was entered as a linear or quadratic term and reflects the estimated percentile within the menstrual cycle (with lower percentiles at the start and higher percentiles later in the cycle). Women on birth control were not included in this analysis. Significant predictors printed in bold. AIC = Akaike Information Criterion.

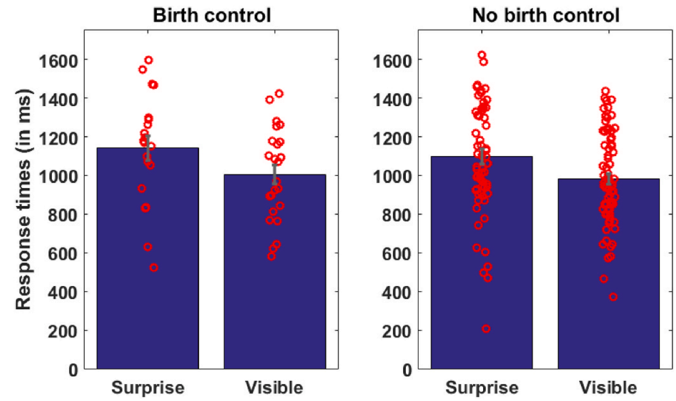

Fig. 5. *Mean response times for surprise and visible item choices.* Mean value and individual data points for visible and surprise box choice for females *on* and *off* hormonal birth control. Red dots reflect individual data points, and error bars reflect the standard deviations.

database ratings (Jarva et al., 2022). Similarly, the personal preference ratings (as reflected by individuals' ratings in the current study) were also higher for chosen than unchosen items. Chosen items also had higher subjective recognizability than unchosen items, while response times were not predicted by recognizability. Arousal, popularity, and perceived healthiness did not influence choice behavior, though responses were slower when the chosen item had higher rather than lower perceived healthiness. These findings confirm that food-related and affective NUPF ratings are useful predictors of choice behavior and they confirm that participants were making value-based decisions in the experiment, despite choices being hypothetical.

Previous work has suggested that variations in ovarian hormones across the menstrual cycle predict changes overall food intake (Asarian & Geary, 2013) and emotional eating (Klump et al., 2013). Our data suggest that time within the menstrual cycle predicted food-related exploratory choice behavior. Previous literature suggested that the effects of the menstrual cycle in naturally cycling may follow a quadratic pattern (Kuukasjärvi et al., 2004), with presumably a peak around the presumed time of ovulation. Therefore, in our study we investigated whether any effects of menstrual cycle on food-related exploratory behavior exhibited a linear or quadratic effect.

Specifically, we observed a quadratic effect that may suggest that women estimated to be in the middle of their cycle (presumably around ovulation, when estradiol levels are high, and progesterone levels are low) made more exploratory choices than women either earlier (potentially the early follicular phase, when estradiol and progesterone levels are low) or later (potentially the mid-luteal phase, when progesterone and estradiol levels are high) in their menstrual cycle. However, a linear cycle percentile predictor was also found to exhibit a positive relationship with exploratory choice behavior, that women later in the menstrual cycle made more exploratory choices than women earlier in the cycle. Model comparisons suggested weaker evidence for the model including a linear than the quadratic cycle percentile predictor.

These findings provide, for the first time, indications that the female menstrual cycle may be linked to food-related exploration behavior in humans. Although it is difficult to translate work from animals to this work in humans, studies in rodents have shown that high levels of estradiol promote exploration of an open field, suggesting that estradiol may play a role in exploratory behavior in other mammals too (Diz--Chaves et al., 2012). No difference in the proportion of surprise choices was observed between women on and off hormonal birth control. Hormonal birth control mimics the high progesterone levels of the luteal phase. Previous work in animals has suggested that progesterone treatment in ovariectomized rats can promote exploration of novel (unknown) objects (Frye, Llanaza & Walf, 2009; Orr et al., 2009), which could potentially explain why we did not observe differences between the groups of women that were either on or off hormonal birth control. It remains unclear, however, how individuals viewed our surprise box (e.g., in terms of novelty or uncertainty), and for better comparison between the literatures, future studies in human could include novel rather than surprise boxes. Also note that the women off hormonal birth control were tested across different timepoints in their cycle, making it hard to interpret these findings in terms of hormonal levels. Future studies should include more direct measures of hormone levels (e.g., via blood, saliva, or urine tests) and potentially test women across the cycle to investigate the role of estradiol and progesterone in exploration behavior in more detail and conceptually replicate the current findings.

Our logistic model further suggested that food-related and affective factors influenced the proportion of surprise box choices. When the visible item had more rather than fewer portion calories, chances that a surprise box was chosen were lower, while higher calorie density of the visible item was associated with increased chances that the surprise box was chosen. These findings are in line with the surprise box absent analyses, that chosen items had lower calorie density but higher portion calories than unchosen items. Visible items with higher mean motivation and valence ratings also decreased the chances that the surprise box was selected, suggesting higher competition when the motivational and affective aspects of the alternative were more positive. Higher levels of associated arousal for the visible item, however, increased chances that the surprise box was chosen, potentially reflecting attentional deflecting. In the main analyses, no effect of arousal was observed, but a reason for this discrepancy may be that the NUPF arousal ratings were all very close to each other, and as a result individual differences were also small (all mean ratings between 3.7 and 3.8 on a 7-point Likert scale; also see Fig. 2). Future studies interested in the role of arousal in food-related choices could aim to use a subset of stimuli that induce a wider range of arousal responses. Popularity, perceived healthiness, and recognizability of the visible item had no effect on exploratory choice behavior.

Responses were slower when participants chose a surprise, rather than a visible item. This may suggest that picking the surprise box was increasing the cognitive load (e.g., maybe participants were trying to remember which item the box held on previous trials), or generally that the trade-off between a certain option versus an uncertain outcome slowed responses (Gutiérrez-Dávila, Rojas, Antonio, & Navarro, 2013; Luque, Vadillo, Le Pelley, & Beesley, 2017). Response times were not different between women *on* or *off* hormonal birth control in our sample. A quadratic predictor in our response times GLM (i.e., model 2B), suggested that for surprise box absent trials women around the middle of their cycle made faster choices than women earlier or later in their menstrual cycle. The model with a linear cycle percentile predictor suggested that women later in the cycle were slower than women earlier in the cycle. Model comparisons did not favor one model over the other; we can thus not interpret the nature of this relationship (i.e., linear, or quadratic) with a lot of confidence.

The surprise box present trials suggested a clearer pattern: Responses for surprise box choices on surprise box present trials were faster for women earlier (left tail of the curve) or later (right tail of the curve) in their menstrual cycle, rather than in the middle. In the linear model, no significant contribution of cycle percentile was observed. The finding of faster responses for females earlier in the menstrual cycle is in line with previous work by Diekhof (2015) suggesting that women in the early rather than late follicular phase made more impulsive choices, with impulsivity associated with faster responses. However, in contrast with the Diekhof (2015) study, we did not differentiate between the late and the early follicular phase.

Even though motivational affective factors were shown to influence choice behavior, individuals may have picked more socially acceptable options. In line with this idea is the finding that the calorie density (which is typically higher for unhealthy processed foods; Jarva et al., 2022) was lower for chosen than unchosen items, however, perceived healthiness did not differ between chosen and unchosen items. Another potential explanation may be that people picked natural foods, which have typically lower calorie density, more often as they were more recognizable (also see Jarva et al., 2022). Indeed, recognizability ratings were higher for chosen than unchosen items, suggesting that participants preferred familiar over unfamiliar options. In contrast to the finding for calorie density, portion calories were higher for chosen versus unchosen choices, suggesting that options reflecting a portion with a higher caloric value were nonetheless preferred. A reason for this discrepant finding may be that participants took the portion calories into account – as these reflected the actual caloric value of the option – while calorie density was not directly relevant for the choice at hand (as choices were made between the items shown, not the food items in general that they reflected).

A limitation of the current study is that we estimated the time within the menstrual cycle based on self-reported cycle durations and time since the first day of the last menstruation. As there is variation in the duration of phases both within and between women (Bull et al., 2019; Johnson et al., 2018), it is possible that ovulation not always occurred in the middle of their cycle. Unfortunately, our methods did not allow us to objectively determine the current menstrual phase of our participants. We recommend that future studies adopt a within-subjects design – with repeated measures across the cycle – and use a more direct hormonal measure (e.g., as derived from a blood sample) to estimate steroid hormone levels. Another limitation is that the choices in the current study were hypothetical. Future studies should confirm whether similar results can be obtained for real food choices. Finally, it is possible that cultural differences may have influenced food choices in our international online sample. However, recognizability – which may reflect the familiarity of food items – did not predict exploratory choice behavior of response times as suggested by our models.

Taken together, the current findings provide preliminary evidence that suggests that food-related exploratory behavior in humans is influenced by the menstrual cycle. Females around the middle of the menstrual cycle (presumably around ovulation) more often chose an option with an unknown outcome than women in the earlier (e.g., early- to mid-follicular) or later (e.g., mid-to late-luteal) phases. Our results are in line with studies in animals that have linked estradiol and progesterone to exploration behavior in animals, but studies with direct measures of hormone levels in humans are currently lacking.

Ethical Statement

Hereby, I, Dr. Judith Schomaker, consciously assure that for the manuscript “Food-related exploration across the menstrual cycle“ the following is fulfilled.

1) This material is the authors’ own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors’ own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
7) All authors have been personally and actively involved in substantial work leading to the paper and will take public responsibility for its content.

The violation of the Ethical Statement rules may result in severe consequences.

To verify originality, your article may be checked by the originality detection software iThenticate. See also http://www.elsevier.com/edit ors/plagdetect.

I agree with the above statements and declare that this submission follows the policies of Appetite as outlined in the Guide for Authors and in the Ethical Statement.

CRediT authorship contribution statement

A.C.S. Nijboer: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Investigation, Project administration. **M. Sellitto:** Writing – original draft, Writing – review & editing. **M.F.L. Ruitenberg:** Writing – original draft, Writing – review & editing. **K.I.L. Kerkkänen:** Conceptualization, Methodology, Writing – review & editing, Resources. **J. Schomaker:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare no financial interests/personal relationships which may be considered as potential competing interests. If there are other authors, they 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

Data will be shared on DataVerseNLperi.

Acknowledgements

JS was funded by a Gratama Stichting Leiden University Fund.

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