Ovulatory cycle shifts in human motivational prioritisation of sex and food

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ABSTRACT

Previous research on the endogenous effects of ovarian hormones on motivational states in women has focused on sexual motivation. The Motivational Priority Shifts Hypothesis has a broader scope. It predicts a shift from somatic to reproductive motivation when fertile. In a highly powered preregistered online diary study across 40 days, we tested whether 390 women report such an ovulatory shift in sexual and eating motivation and behaviour. We compared 209 naturally cycling women to 181 women taking hormonal contraceptives (HC) to rule out non-ovulatory changes across the cycle as confounders. We found robust ovulatory decreases in food intake and increases in general sexual desire, in-pair sexual desire and initiation of dyadic sexual behaviour. Extra-pair sexual desire increased mid-cycle, but the effect did not differ significantly in HC women, questioning an ovulatory effect. Descriptively, solitary sexual desire and behaviour, dyadic sexual behaviour, appetite, and satiety showed expected mid-cycle changes that were diminished in HC women, but these failed to reach our strict preregistered significance level. Our results provide insight into current theoretical debates about ovulatory cycle shifts while calling for future research to determine motivational mechanisms behind ovulatory changes in food intake and considering romantic partners' motivational states to explain the occurrence of dyadic sexual behaviour.

1. Introduction

Motivational states energise goal-directed behaviours (Kennedy and Shapiro, 2009; Kleinginna and Kleinginna, 1981) and consequently do not only shape, for example, our social interactions, interpersonal relationships and health (Marteau et al., 2006), but also our mating and somatic efforts and ultimately our reproductive fitness (Roney, 2018). Differences in motivational states are often thought of as a consequence of interindividual differences (i.e., motive dispositions; McClelland, 1987) or situational contexts (Rauthmann, 2016). Yet, there are also endogenous, hormone-regulated mechanisms that affect intraindividual processes of motivational states and motivated behaviour. One such mechanism is the endogenous endocrine regulation of motivational states across women[1]'s ovulatory cycles (Fessler, 2003; Roney, 2016). Previous research has shown that women exhibit increased sexual

motivation during the fertile phase of the ovulatory cycle (Arslan, Schilling, et al., 2021; Bullivant et al., 2004; Gangestad et al., 2002; Grebe et al., 2016; Jones et al., 2018a; Marcinkowska et al., 2022; Roney and Simmons, 2013, 2016). These findings have given rise to a number of theories on so-called ovulatory cycle shifts in women's sexual motivation. Whereas most theories agree that ovulatory cycle shifts serve a reproductive function, there is an ongoing debate about the exact nature of these shifts (Gangestad and Dinh, 2022; Gangestad et al., 2019; Jones et al., 2018a; Jünger, Kordsmeyer, et al., 2018; Marcinkowska, Kaminski, et al., 2018; Marcinkowska et al., 2022; Roney, 2019; Stern et al., 2019; Stern et al., 2020). The Motivational Priority Shifts Hypothesis (MPSH; Roney, 2016, 2018, 2023; Roney and Simmons, 2013, 2016, 2017) extends this debate by combining findings of ovulatory cycle increases in sexual motivation with decreases in eating motivation. The hypothesis states that women evolved a motivational priority for mating

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over somatic efforts when conception is most probable. As only few studies have empirically investigated the MPSH so far (e.g. Roney and Simmons, 2013, 2017), in this study we sought to advance the current debate by directly testing the predictions of ovulatory cycle shifts in sexual and eating motivation and corresponding behaviours.

1.1. The influence of the ovulatory cycle on women's motivational states

Women's ovulatory cycles can be divided into the follicular phase (between menstrual onset and ovulation) and the luteal phase (after ovulation and before the next menstrual onset). As part of a complex interplay of various hormones, the transition from one phase to the other is characterised by intraindividual changes of women's levels of the steroid hormones estradiol and progesterone. Across the ovulatory cycle, women can only conceive during the so-called fertile window that marks the late part of the follicular phase and spans approximately five days before ovulation and the day of ovulation itself (Wilcox et al., 1998).

Unlike human's closest relative, the chimpanzee (Deschner et al., 2004), women do not show obvious cues that indicate their fertile window (e.g. anogenital swellings). Additionally, many other non-human primate species only engage in mating and sexual behaviour during oestrus, a phase of fertility that is typically characterised by heightened sexual proceptivity, receptivity and attractiveness (Beach, 1976). Yet, human women exhibit *extended sexuality*, meaning that they show sexual motivation and engage in sexual behaviour outside their fertile window across the whole ovulatory cycle (Gangestad and Dinh, 2022; Gangestad and Thornhill, 2008; Grebe et al., 2013). These distinct features of women's sexuality led researchers to believe that women have phylogenetically lost their oestrus (e.g. Burley, 1979; Symons, 1979). However, empirical evidence is growing that women show changes during their fertile window that indicate heightened sexual proceptivity (i.e. women show increased sexual motivation and initiate more sexual behaviour; Bullivant et al., 2004), sexual receptivity (e.g. women rate male bodies as more attractive; Jünger, Kordsmeyer, et al., 2018; Stern et al., 2021) and increased attractiveness (women feel more attractive; Schleifenbaum et al., 2021, and men rate female faces as more attractive; for a review see Haselton and Gildersleeve, 2016, but see Catena et al., 2019; Jones, Hahn, Fisher, Wang, Kandrik, Lao, et al., 2018; Marcinkowska et al., 2021; Schleifenbaum et al., 2022; Stern et al., 2023 for contradicting evidence on perceptible changes across the cycle). Such findings of distinct sexuality when women are fertile made researchers question the notion of a lost oestrus. Instead, Gangestad and Thornhill (2008) proposed a "dual sexuality" in women, whereby sexuality during the fertile window serves reproduction, whereas extended sexuality outside of the fertile window serves to obtain resources from the male partner and promotes pair-bond formation. Although many researchers currently agree that women's sexuality differs between fertile and non-fertile phases, the debate about the nature and function of ovulatory cycle shifts in sexual motivation is ongoing.

1.2. Debate about the nature of ovulatory cycle shifts in sexual motivation

Among multiple theoretical perspectives, the most prominent representatives of the current debate are the Good Genes Ovulatory Shift Hypothesis (GGOSH, Gangestad and Thornhill, 2008) that became very popular in ovulatory cycle research, and the more recent MPSH (Roney, 2016; Roney and Simmons, 2013, 2016, 2017). In the following, we describe both of these theories in more detail and summarise the current state of empirical evidence.

1.2.1. Good Genes Ovulatory Shift Hypothesis

The GGOSH (Gangestad and Thornhill, 2008) represents one of the most influential theoretical approaches towards ovulatory cycle shifts. From an evolutionary perspective, women should be motivated to seek male partners who are able and willing to invest in them and their offspring but also provide high genetic quality to increase their reproductive fitness (Buss, 1989; Buss and Schmitt, 2019; Gangestad and Simpson, 2000). Since men high in genetic quality are expected to have many mating opportunities and thus might be less willing to invest in partners, these two benefits might need to be traded off when in search of a partner. The GGOSH describes possible evolved adaptations in women to secure both high investment and genetic quality from partners. Based on the dual sexuality concept, the GGOSH proposes that varying fertility status across women's ovulatory cycles enables shifting mate preferences to serve goals related to securing either genetic benefits or resources. Accordingly, women can maximise their reproductive fitness by mating with men with good genes during their cycle's fertile window while securing support from a long-term mate with possibly lower genetic quality but higher resource investment when outside the fertile window. Consequently, during the fertile window, women should prefer men with features that indicate genetic quality. Suggested indicators for genetic quality are, for example, masculine faces and bodies, dominant behaviour, and facial and bodily symmetry, often summarised as short-term partner attractiveness (Gangestad and Thornhill, 2008). According to the GGOSH, this ovulatory mate preference shift should be most pronounced in short-term mating contexts and largely translate into increased motivation for sex with men other than women's primary partner (extra-pair sexual desire). In contrast, women's general sexual desire or the motivation for sex with her primary partner (in-pair sexual desire) should not be increased during women's fertile window, or increases should at least be smaller as compared to increases in extra-pair sexual desire (e.g., Gangestad et al., 2002; Gangestad et al., 2005; Pillsworth and Haselton, 2006).

1.2.2. Evidence for the Good Genes Ovulatory Shift Hypothesis

A wide range of studies has provided empirical support for ovulatory mate preference shifts in the past (for a meta-analytic review, see Gildersleeve et al., 2014) and some studies report corresponding ovulatory increases in extra-pair sexual desire for specific men (Gangestad et al., 2002; Grebe et al., 2016). However, there exist both theoretical and empirical considerations that cast doubt on the validity of the GGOSH. Regarding theoretical considerations, there are alternative hypotheses that might explain the proclaimed shifts in mate preferences and consequently target-specific sexual motivation. Other researchers have proposed that hormonal effects on women's mate preferences are rather a by-product of between-women differences in sexual desire without a specific function (Havlíček et al., 2015). Accordingly, previous findings in favour of the GGOSH could in fact follow a false attribution of between-women differences to ovulatory within-women effects. Other theoretical considerations further doubt the existence of mate preference shifts since the supposed indicators of genetic quality are questionable (Arslan and Penke, 2015; Buss and Schmitt, 2019; Lee et al., 2014; Lidborg et al., 2021; Nowak et al., 2018) and rates of cuckoldry in human populations are mostly low at around 1–2 % (Anderson, 2006; Larmuseau et al., 2013; Wolf et al., 2012). Moreover, a mating strategy partly built upon extra-pair mating runs the risk of triggering male sexual jealousy that threatens a woman's own health and both her survival and that of her offspring (Buss and Duntley, 2011; Daly et al., 1982).

Regarding empirical evidence, a growing body of research fails to support the predictions of the GGOSH (Jones et al., 2018a; Jünger, Kordsmeyer, et al., 2018; Jünger, Motta-Mena, et al., 2018; Marcinkowska et al., 2018a; Marcinkowska, Kaminski, et al., 2018; Stern et al., 2020; Stern et al., 2021; van Stein et al., 2019). One likely explanation for these inconsistencies is that many early studies suffered from methodological shortcomings that reduced their informational value. Early research often used small samples, investigated many outcomes, lacked a gold standard for fertility estimation, and took no measures to constrain researcher degrees of freedom, such as preregistration or cross-validation, potentially inflating false positive findings and

artificially increasing effect sizes (Arslan, Schilling, et al., 2021; Harris et al., 2014). This problem is aggravated by studies that apply between-subject designs to the within-subject effects of ovulatory changes since these designs have especially low statistical power. Moreover, there are various methods of estimating women's fertility that differ in their validity. Based on simulation studies, Gangestad et al. (2016) recommended abandoning operationalising fertility as a discrete window that yielded unreliable estimates and instead use a continuous probability of being in the fertile window.

Recent studies that address some of these methodological short-comings provide less empirical evidence for ovulatory mate preference shifts and consequent ovulatory increases in sexual motivation for specific men as predicted by the GGOSH (Gangestad and Thornhill, 2008). Instead, they report ovulatory shifts in women's general attraction to men and their general sexual motivation (Arslan, Schilling, et al., 2021; Jones et al., 2018a; Roney and Simmons, 2013, 2016; Shirazi, Jones, et al., 2019; Stern et al., 2020). For example, Arslan, Schilling, et al. (2021) conducted a preregistered and highly powered online diary study across 40 days analysing over 26,000 diary entries from 1054 women. Since women who take hormonal contraceptives do not experience hormonal fluctuations that lead to a fertile window (Fleischman et al., 2010), Arslan, Schilling, et al. (2021) employed a quasi-control group design that compared women taking hormonal contraceptives (625 women) to naturally cycling women (429 women). Supporting the role of ovarian hormones in ovulatory cycle shifts in sexual motivation, they found ovulatory increases in general sexual motivation for naturally cycling women, which were diminished in women taking hormonal contraceptives. Contrary to the predictions of GGOSH, however, women showed both increased in-pair sexual desire as well as increased extra-pair sexual desire. These results were supported by multiple robustness analyses, for example, by comparing different estimates to gauge women's fertility. Hence, results concerning the predictions of the GGOSH remain mixed and are part of an ongoing debate (e.g. see Arslan, Driebe, et al., 2021; Gangestad and Dinh, 2021).

1.2.3. The Motivational Priority Shifts Hypothesis

One alternative hypothesis that can explain recent findings is the MPSH (Roney, 2018, 2023). The MPSH combines ovulatory shifts in sexual motivation with a corresponding trade-off in eating motivation. These motivational shifts are informed by life history theory (e.g. Hill, 1993). Hormone-regulated prioritisations of mating and somatic efforts exist in a multitude of species (e.g. reptiles, birds and mammals, see Schneider et al., 2013 for a review). The MPSH extends these findings to humans and states that in a world with limited resources, ovarian hormones facilitate an adaptive motivational trade-off between mating and somatic efforts that depends on their respective cost-benefit-ratios (Roney, 2018, 2023).

According to the MPSH, while mating effort (e.g. seeking and courting a partner, sexual behaviour) can yield a direct reproductive fitness benefit, it also entails certain costs (e.g. spent resources, risk of injury, risk of infection and opportunity costs with regard to other activities e.g. foraging and feeding). On this basis, MPSH makes two central predictions: First, women should show endogenous increases in sexual motivation in general during the fertile window when conception is possible and potential fitness benefits of sexual behaviour outweigh its costs. Thus, ovulatory increases in general sexual motivation are expected to translate into overall increases of sexual behaviour, i.e. not only target-specific sexual desire for certain men (predicted by GGOSH), but ovulatory increases in solitary *and* dyadic sexual behaviour that includes both increased in-pair as well as extra-pair sexual desire. Second, somatic efforts (incl. foraging and eating motivation and behaviour) should be decreased during the fertile window, as they incur opportunity costs. After ovulation, when women can no longer conceive, resources are expected to be re-prioritised and re-allocated towards somatic investment during the non-fertile luteal phase. Thus, women can invest into foraging and food intake, thereby securing their survival and enabling future reproductive opportunities. Importantly, the MPSH does not claim that sexual motivation and behaviour occur only when women are fertile. Instead, and similar to the concept of dual sexuality introduced by Gangestad and Thornhill (2008), the MPSH acknowledges external factors such as social and relationship aspects that enable extended sexuality to promote formation and maintenance of long-term bonds in humans (Roney, 2018, 2023).

1.2.4. Evidence for the Motivational Priority Shift Hypothesis

The aforementioned studies showing a robust ovulatory increase in general sexual motivation in women provide strong support for the first prediction of the MPSH of an ovulatory increase in general, not specific, sexual motivation, or increases in in-pair and extra-pair desire simultaneously (Arslan, Schilling, et al., 2021; Jones et al., 2018a; Roney and Simmons, 2013, 2016; Shirazi, Jones, et al., 2019; Stern et al., 2020). Moreover, several studies reporting ovulatory increases in dyadic (Bullivant et al., 2004; Caruso et al., 2014; Harvey, 1987; van Goozen et al., 1997; Wilcox et al., 2004), female-initiated (Adams et al., 1978; Bullivant et al., 2004; Gangestad et al., 2002; Harvey, 1987), and solitary sexual behaviour (Brown et al., 2011; Burleson et al., 2002; van Goozen et al., 1997) add to this picture. Yet, other studies failed to detect ovulatory changes in sexual behaviour (Brewis and Meyer, 2005; Elaut et al., 2016; Roney and Simmons, 2013). Reasons behind these mixed results are likely methodological differences between studies such as assessment of ovulation (Brown et al., 2011) and statistical power. However, these inconsistent findings could also point to the relevance of external factors that affect sexual behaviour. Dyadic sexual motivation and behaviour, in particular, are not only influenced by hormones but are affected by relationship dynamics (Caruso et al., 2014; Roney and Simmons, 2016) such as emotional intimacy (Basson, 2001), and are limited by partner availability (Arslan, Schilling, et al., 2021) and free time (e.g. increased self-reported sexual motivation and behaviour on weekends compared to weekdays; Roney and Simmons, 2013). This way previous research emphasizes the need to account for these factors in the statistical analyses.

Studies that focus on changes in women's eating motivation and behaviour provide support for the second prediction of the MPSH. In a review, Fessler (2003) summed up empirical evidence that women show an ovulatory nadir in food intake. Based on animal models, he suggests that this nadir follows a hormone-regulated decrease in satiation thresholds. He further relates this ovulatory nadir in food intake to increased investment in mating activities seen in other non-human primates such as increased locomotion as part of mate-seeking in chimpanzees, baboons, and macaques. Importantly, Fessler argues that a decrease in food intake is unrelated to energy expenditure because it occurs at a time of increased energy demands of the growing endometrium. In line with the notion that other factors than energy expenditure affect women's cyclical eating motivation, the ovulatory decrease in food intake is even more pronounced in sexually active compared to sexually inactive women (Fleischman and Fessler, 2007). However, if food intake decreases pre-ovulatorily to spend more time on mating activities, Fessler (2003) also argues that this particular time for mating activities may facilitate "shopping for alternatives to those current or potential mates who are readily at hand" (p.15). Thus, decreases in food intake that occur at the same time as increases in extra-pair (but not or less strongly in-pair) sexual desire might rather be related to the GGOSH.

Supporting a post-ovulatory shift towards somatic investment as proclaimed by the MPSH, women report increased food intake, appetite and food cravings in their luteal phases, especially of highly caloric, protein-rich and sweet food (Asarian and Geary, 2006; Barr et al., 1995; Gorczyca et al., 2016; Pliner and Fleming, 1983). These changes might follow heightened food cue reactivity in the brain (Strahler et al., 2020)

and also translate into corresponding weight gain of women during the luteal phase (Kammoun et al., 2017; Pliner and Fleming, 1983). Thus, there is empirical evidence of both sexual and eating related changes across the ovulatory cycle from different lines of research.

Although previous research provides empirical evidence for the MPSH, most previous studies have investigated ovulatory cycle shifts in either sexual or eating motivation and corresponding behaviour individually. To test the MPSH, however, it is crucial to test the existence of these ovulatory changes concurrently in the same sample. To our knowledge, this has only been tested in the same sample using 52 women so far (Roney and Simmons, 2013, 2017). In this sample, the authors found evidence for a mid-cycle peak in (general) sexual desire that were regulated by the ovarian hormones estradiol (positively) and progesterone (negatively). At the same time, there was a pre-ovulatory nadir in food intake, that was negatively predicted by estradiol, but positively predicted by progesterone levels. In fact, sexual desire and food intake were "mirror images of one another" (Roney and Simmons, 2017, p. 11) and a difference score between both variables further suggested trade-offs in motivational priority shifts across the cycle.

In addition, the methodological shortcomings described above hold in this literature too. Hence, it remains unclear whether the expected patterns can be found in a larger sample, with a preregistered analysis plan, and whether results are robust across different analytical decisions.

1.3. Aims of the current study

In this study, we tested the predictions of the MPSH of ovulatory changes in sexual and eating motivation and thereby sought to advance the current debate about ovulatory cycle shifts in five important ways: First, we assessed sexual and eating motivation simultaneously. Second, to address previous methodological shortcomings, we conducted a highly powered, within-subject diary study for which we preregistered our hypotheses, study materials, variable transformations and statistical analyses. Third, we probed the robustness of our results for several exclusion criteria that might confound our findings (e.g. trying to become pregnant), different fertility estimators, and different model specifications. Fourth, we implemented exploratory analyses on the separate components of in-pair and extra-pair sexual desire to uncover which components might account most for respective ovulatory changes. Finally, we implemented a smallest effect size of interest (SESOI, Lakens, 2014) to gauge the practical relevance of ovulatory cycle shifts. In order to enable a large sample size, we used backward counting from the next observed onset of menstrual bleedings to determine the day of ovulation as a valid method to assess women's probability of being fertile (Gangestad et al., 2016). Additionally, we compared naturally cycling women (NC women) to the quasi-control group of women taking hormonal contraceptives (HC women) to rule out non-ovulatory changes across the cycle as confounders.

Assuming that endogenous signals lead to increases in broad motivational states as proclaimed by the MPSH, we expected ovulatory increases in general sexual desire (H1), solitary sexual desire (desire to masturbate, H2), and ovulatory increases in both in-pair sexual desire (H3) and extra-pair sexual desire (H4), as opposed to effects primarily for extra-pair sexual desire expected according to the GGOSH.[2] Following the functional properties of motivational states (Zygar et al., 2018), we expected concurrent behavioural changes of ovulatory increases in dyadic sexual behaviour (H5), solitary sexual behaviour (masturbation frequency, H6), and female initiation of dyadic sexual behaviour (H7). Addressing shifts in eating motivation, we extended

previous constructs of eating motivation and predicted ovulatory decreases in appetite (H8), corresponding to an ovulatory increase in satiety (H9), and an ovulatory decrease in self-reported food intake[3] (H10). We expected these to be higher in NC women compared to baseline changes in our quasi-control group HC women.

2. Methods

We conducted a large-scale, preregistered online diary study to properly account for the within-subject effects of ovulatory cycle shifts (Schmalenberger et al., 2021). This observational study was implemented using the online survey framework formr (Arslan et al., 2020d) that enabled the study's complexity and guaranteed anonymity of participants by automated handling of sensitive information. All participants signed a written consent form and the local ethics committee approved the study protocol (no. 228). For this study, we analysed data of women who took part in the Goettingen Ovulatory Cycle Diary 3 that assessed romantic couples in heterosexual relationships. More information on their partners and the related research questions can be found in Schleifenbaum et al. (2022). All materials including preregistration, survey files, data cleaning and processing code, codebooks, and analysis code are accessible in our online supplement (https://osf.io/v98t2). For easy access, we also provide an excerpt of central graphs and tables in a pdf file as supplementary material. Data were anonymised and can be accessed online under doi:https://doi.org/10.7802/2330 after consenting to restrictive scientific use due to the sensitive nature of these data.

2.1. Sample size rationale and recruitment

We based our targeted sample size on a-priori power simulations (https://rubenarslan.github.io/ovulatory_shifts/1_power_analysis.html). These showed that for an unstandardised effect size of 0.2 reported before (Arslan, Schilling, et al., 2021), a statistical power of 99 % can be achieved with 150 naturally cycling women across 30 diary days and an alpha rate of 0.01. However, because these power analyses did not include random slopes or behavioural outcomes, we used this as a close approximation of overall statistical power in our study and sought to recruit a minimum of 150 naturally cycling women and their romantic partners (the latter are unrelated to the current study).

We recruited romantic couples from October 2019 until April 2020 via different strategies, such as distributing posters and flyers locally, using digital media (contacting mailing lists of German university students, posting advertisements on Facebook and on the study platform psytests.de), inviting participants who had taken part in similar studies before, and by referring to the study in other media. As preregistered, we stopped data collection in May 2020 (so participants who began the study in April 2020 could finish all study parts).

2.2. Exclusion criteria and participants

Since we were interested in ovulatory cycle shifts that presumably evolved to serve reproductive functions, all participants had to confirm that they were predominantly heterosexual and in a heterosexual relationship before taking part in the study. Of the total of $N = 615$ women who started the study, following our preregistration, we excluded those who were likely not experiencing ovulation, i.e. because of pregnancy, breast-feeding, or menopause ($n = 29$). Additionally, we excluded

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[2] In order to sharpen the focus of the paper, we omitted one preregistered hypothesis concerning ovulatory increases in self-perceived desirability, but for transparency, we conducted and report preregistered analyses in our online supplement.

[3] Due to an unfortunate copy-paste error, one of our central hypotheses regarding food intake decreases for naturally cycling women when they are fertile is missing in the final version of our preregistration. As can be seen by reading the short theoretical introduction in the respective preregistration, we clearly phrased our goal of investigating ovulatory changes in direct food intake as one central outcome.

women who reported that they or their partners were infertile or sterilised ($n = 11$), who switched to or from hormonal contraceptives during the study ($n = 11$), and who reported other irregular contraception such as morning-after pill use ($n = 14$). We also excluded women without any diary entries ($n = 39$), without data on menstrual bleedings (women who declined having a menstrual bleeding "sometimes or regularly", $n = 62$), and women for which data were not sufficient to estimate fertility ($n = 47$, e.g. 79 % reported no menstrual bleeding during the diary). Considering individual diary entries, we excluded those that were not usable, i.e. unfinished diary entries, diary entries for which fertility could not be estimated and those where participants indicated to have answered dishonestly. Women without any such usable diary entry were excluded completely ($n = 9$). Adding to our preregistered exclusion criteria but in line with our research plan, we excluded women whose ovulatory cycle might have been affected by taking steroid hormones besides hormonal contraceptives ($n = 3$). A detailed participant flow illustrating our application of exclusion criteria is provided in the pdf supplement (Fig. S1). Robustness analyses including different exclusion criteria are described below.

Our final sample consisted of $n = 390$ women (54 % naturally cycling) who filled out 12,996 analysable diary entries with on average $M = 33.17$ ($SD = 9.47$) diary entries per person. Women were on average $M = 23.7$ years old ($SD = 4.2$, range 18–47), they first had sexual intercourse at the age of $M = 16.9$ ($SD = 2.7$), and they had $M = 5.09$ ($SD = 6.90$) lifetime sexual partners. Most women were students (80 %) with on average $M = 14.5$ years of education ($SD = 4.2$). The vast majority of women were in a committed relationship with one partner (94.36 %), had no children (96 %) and had been, on average, in a relationship for $M = 3.1$ ($SD = 3.0$) years. Spanning the time from the menstrual onset reported in the demographic survey until the menstruation follow-up, we collected data of menstrual bleedings of on average $M = 2.26$ ($SD = 0.58$) number of cycles. The mean observed cycle length across the study was $M = 29.04$ days ($SD = 2.86$). Details on the different contraception methods of HC and NC women can be accessed in the pdf supplement (Figs. S2 and S3).

Comparing demographic and personality data of HC and NC women, on average, HC women were significantly younger ($t(375.18) = 4.59$, $p < .001$), had a shorter relationship duration ($t(386.1) = 3.03$, $p = .003$), and had fewer lifetime sexual partners ($t(373.64) = 2.15$, $p = .032$). HC women also had shorter cycle lengths ($t(341.92) = 5.66$, $p < .001$) which might be a consequence of hormonal contraceptive use. As a possible self-selection factor, HC women were more conscientious ($t(385.26) = -3.09$, $p = .002$) as measured with the Big Five Inventory (John et al., 1991). When predicting hormonal contraceptive use by including the demographic and personality variables depicted in Table 1 (except for average cycle length) in a probit regression, age and conscientiousness emerged as significant predictors ($p < .05$). These results resemble those of a detailed investigation of selection effects on hormonal contraceptive use (Botzet et al., 2021).

2.3. Procedure

Following the study link, participants received detailed information about the study entitled "Goettingen Couple's Study". The study was introduced as a dyadic quiz investigating emotions and needs in romantic relationships and how well romantic partners perceived these in everyday life. After having provided their informed consent, participants answered a demographic presurvey where we assessed general information such as age, gender and educational status. Women also provided information about their menstrual cycles and contraception methods and completed the Big Five Inventory (John et al., 1991). All personal and identifying data such as email addresses and mobile phone numbers were collected and stored separately using formr features to further guarantee anonymity.

After the presurvey, the diary part of the study began on the next day. The diary encompassed 40 consecutive days and assessed women's

Table 1
Descriptive statistics according to hormonal contraceptive use.

Variable	Mean (standard deviation)		Hedges' g	p
	HC women	NC women		
Age	22.71 (3.35)	24.59 (4.69)	−0.40	<.001
Age at first time	16.97 (2.82)	16.79 (2.68)	0.07	.524
Years of education	14.15 (3.95)	14.83 (4.47)	−0.15	.113
Religiosity (0–5)	2.17 (1.27)	2.25 (1.33)	−0.07	.506
Relationship duration (years)	2.61 (2.61)	3.51 (3.24)	−0.28	.003
Relationship satisfaction	4.75 (0.59)	4.73 (0.63)	0.04	.715
Average cycle length (days)	27.82 (2.17)	29.55 (3.73)	−0.46	<.001
Number sexual partners	4.30 (5.54)	5.77 (7.84)	−0.19	.032
BFI-Openness (0–5)	4.06 (0.68)	4.17 (0.64)	−0.16	.121
BFI-Conscientiousness (0–5)	3.90 (0.68)	3.68 (0.73)	0.30	.002
BFI-Extraversion (0–5)	3.74 (0.82)	3.61 (0.81)	0.16	.107
BFI-Agreeableness (0–5)	3.20 (0.87)	3.07 (0.83)	0.16	.124
BFI-Neuroticism (0–5)	3.34 (0.89)	3.41 (0.87)	−0.08	.449

Note. NC = naturally cycling women, HC = women using hormonal contraceptives, BFI = Big Five Inventory. Variables are printed in bold if they remained significant after multivariate adjustment in a probit regression.

sexual and eating motivation and behaviour, information about women's menstrual bleedings as well as daily self- and partner-ratings of well-being, health, stress and relaxation as part of the study's cover story. The diary could be accessed by personalised invitation links that were sent at 5:00 pm every day via email and/or text messages and could be filled out until 3:00 am in the morning. We asked women to answer diary entries by referring to the time between the last entry and the current one if a previous diary entry was present. If no data entry was present from the day before, we asked women to answer the diary referring to the time spanning the previous 24 h. That way we sought to cover the period of the diary continuously for women with high participation rates but to avoid aggregating across a longer time than one day. We randomised the order of the daily items within grouped blocks to address possible measurement reactivity biases (Arslan, Reitz, et al., 2020).

After the diary, women took part in three consecutive follow-up surveys. First, one day after the last diary entry, we asked them to answer a general follow-up survey assessing, for example, illness and (hormonal) medication use, changes in contraceptive methods, and whether they guessed the study's focus on the ovulatory cycle. Afterwards, women received compensation for their participation, such as illustrated feedback of their own data, course credit, chances of winning lottery prices, or direct monetary compensation that depended on the amount of participation. Women were fully debriefed once both partners had answered the follow-up surveys. Second, women who had not indicated an onset of menstrual bleedings within the last five days of the diary were then directed to a menstruation follow-up. Every four days, we asked women to report the date of their next onset of menstrual bleedings until they indicated a new onset. Third, due to the COVID-19 pandemic, we launched an additional COVID-19 follow-up survey in April 2020. As the final survey, we asked women to report the extent to which COVID-19 affected their daily lives and their social and romantic relationships. A detailed overview of the study design is given in Fig. 1.

2.4. Measures and variable transformations

2.4.1. Measures

Due to the high number of daily questions, we mostly used single-item measures to minimise participant burden and achieve a high compliance. Yet, as the comparison of in-pair and extra-pair sexual desire is one focus of the ongoing debate in ovulatory cycle research, we measured both outcomes using multiple items capturing different desire
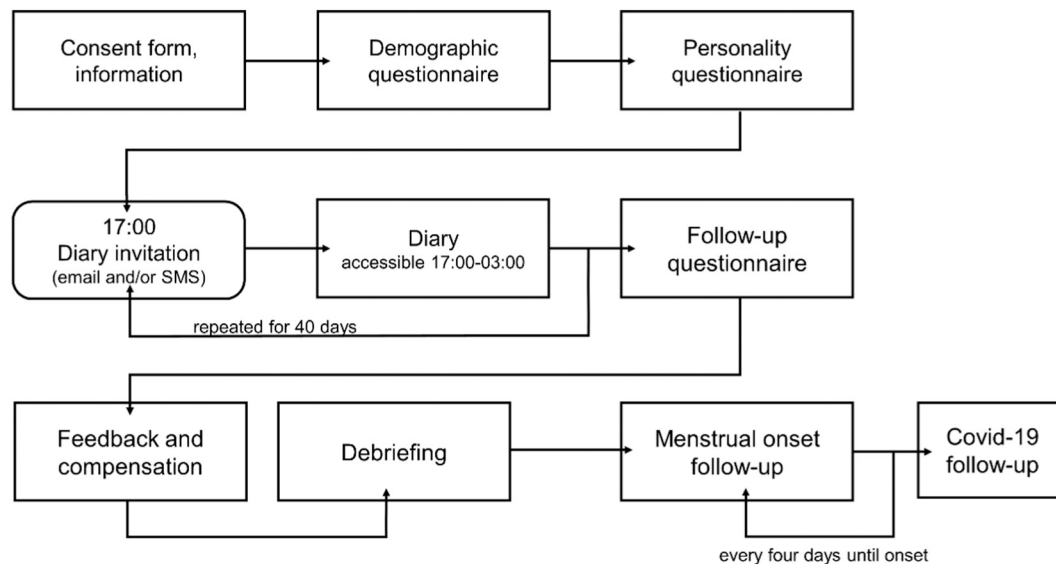
Fig. 1. Overview of the study design of the Goettingen Couple's Study.
Note. The diary spanned 40 consecutive days with one daily measurement.

components. Consequently, based on Haselton and Gangestad (2006) and Arslan, Driebe, et al. (2020), we used four items of extra-pair sexual desire regarding sexual fantasies, sexual attraction and interest in sexual behaviour that could be easily parallelised for in-pair sexual desire as well. We computed the generalisability of within-subject change aggregated across items (Shrout and Lane, 2012) using the psych (Revelle, 2021) and codebook (Arslan, 2019) packages. The main outcome measurements of the diary part of this study and their reliabilities are documented in Table 2.

2.4.2. Estimating women's fertile window

Following the recommendations of Gangestad et al. (2016), we operationalised the fertile window as a continuous estimator of fertility, i.e. the probability of being in the fertile window (PBFW). As the basis for PBFW, we estimated women's day of ovulation by backward counting 15 days from the next observed onset of menstrual bleedings. Such a combination of backward counting of known cycle lengths with a continuous estimator of fertility displays high accuracy with a validity of estimating fertility as high as ~0.70 (Gangestad et al., 2016).

We collected information on menstrual bleedings continuously throughout all study parts. In the demographic presurvey and during the diary, we asked women to enter the exact dates of onsets and offsets of their menstrual bleedings. Thus, information on menstrual bleedings could be collected even if women skipped diary entries in-between. At the end of the diary, those women who had not reported menstrual bleedings within the last five days of the diary were directed to the menstruation follow-up described above. That way, we collected data on the next onsets of menstrual bleedings after the diary and could use backward counting to assess the day of ovulation for all diary days.

Adhering to the procedure of Gangestad et al. (2016), we applied the continuous estimates reported by Stirnemann et al. (2013) to compute PBFW. We describe the procedure in more detail in the pdf supplement (Table S1). Unlike Gangestad et al. (2016), however, we did not standardise women's observed cycle length to a 29-day cycle for our main analyses. Since ovulatory cycles naturally show considerable inter- and intraindividual variation (Bull et al., 2019; Marcinkowska, 2020), we found no compelling reason for such a standardisation. Yet, we included such a squished estimator in our robustness analyses described below

where we gauged the impact of different researcher degrees of freedom on result patterns. Parallel to the study conducted by Arslan, Schilling, et al. (2021), however, we controlled for grave cycle irregularities by only considering cycles that were between 20 and 50 days long. Additionally, we did not count further back than 40 days from the next onset of menstrual bleedings. Yet, using a continuous fertility estimator results in including days of the premenstrual phase and menstruation as well that might affect our outcomes independently of fertility, for example via mood changes and somatic complaints (Yonkers et al., 2008). Therefore, we dummy-coded premenstrual phase (six days preceding menstrual onset) and menstruation (calculated by menstrual onset and offset dates per woman) to control for them in our analyses.

2.5. Analyses

We preregistered general mixed effects models using a Gaussian error distribution for all of our outcomes. We adhered to this preregistered analysis protocol with one minor exception: For the count variables dyadic and solitary sexual behaviour, data indicated that the most appropriate analysis method is applying generalised mixed effects models using a Poisson error distribution (Coxe et al., 2009). Consequently, for both outcomes, we chose the most appropriate way of analysis instead of our preregistered one, but report the preregistered analyses in our robustness checks (results were virtually identical).

For all models, the main predictor was PBFW. To control for the premenstrual phase and menstruation that might affect our outcomes independently, we added these as predictors to our models. We implemented hormonal contraceptive users as quasi-control group to distinguish changes related to ovulation from other mid-cycle changes. We added hormonal contraceptive use as a dummy variable (set to zero for NC women) interacting with all predictors to properly apply interaction controls (Rohrer and Arslan, 2021). We included random intercepts, random slopes and their correlation for PBFW, premenstrual phase and menstruation to account for interindividual variation between women and the repeated measurement of our outcome variables. In Wilkinson notation (Wilkinson and Rogers, 1973), our main models were specified as follows:

$$\text{outcome} \sim \left(\text{PBFW} + \text{premenstrual\_phase} + \text{menstruation}\right)*\text{no\_hormonal\_contraception} + \left(1 + \text{PBFW} + \text{premenstrual\_phase} + \text{menstruation} \mid \text{woman}\right)$$

We accounted for multiple testing in two ways, first by adjusting the significance threshold to an alpha rate of 0.01 with two-tailed statistical testing. Second, we sought to extend the current debate about ovulatory cycle shifts by also evaluating the effect sizes of our outcomes for practical relevance. Hence, we defined a smallest effect size of interest (SESOI; Lakens, 2014), for unstandardised effects of PBFW for Likert-scaled outcomes. Since neither theoretical approach to ovulatory cycle shifts we based this study on makes any predictions about effect sizes, we adopted the conventional SESOI of 0.1 and an established 90 % confidence interval as threshold for negligibility. Thus, if an effect size of PBFW and its 90 % confidence interval is below the SESOI, the effect is deemed as negligible and the hypothesis is discarded irrespective of its statistical significance. If an effect size of PBFW is above 0.1, but its confidence interval includes the SESOI, the respective hypothesis can neither be accepted nor discarded. Consequently, we are only confident in the existence of a relevant ovulatory cycle shift if the following three conditions are fulfilled 1) PBFW shows a significant influence of fertility on our preregistered alpha rate of 0.01 and a corresponding 99 % confidence interval, 2) the interaction of PBFW and hormonal contraception is significantly in the opposite direction (effect of PBFW not present for HC women), and 3) the 90 % confidence interval lower-bound on the effect size of PBFW is at least 0.1. Main analyses were conducted using the statistical software R 4.0.2 (R Core Team, 2020) and the respective R packages lme4 (Bates et al., 2015) and lmerTest (Kuznetsova et al., 2017). All analysis code is documented and can be downloaded from our online supplement (https://osf.io/v98t2; file 4_main_analyses).

3. Results

To facilitate comprehensibility, we summarise the main results for all

hypotheses in the relevant sections but provide full tables in our pdf supplement (Tables S4–S13). Since we preregistered comparing unstandardised estimates to the SESOI, we report and base our conclusions on unstandardised estimates. We provide standardised estimates in parentheses and in the online supplement except for dyadic and solitary sexual behaviour, where standardisation would disrupt the non-negative integer nature of these data.

3.1. Ovulatory shifts in sexual motivation

In order to investigate possible ovulatory shifts in sexual motivation, we ran general mixed effects models predicting our different sexual motivation outcomes from women's PBFW. The main results are shown in Table 3. Regarding associations of our main predictor PBFW, we found small to medium significant ovulatory increases in general sexual desire, in-pair sexual desire and extra-pair sexual desire. Although PBFW was positively associated with solitary sexual desire and was below a classical significance threshold of 0.05, the effect did not reach our preregistered alpha rate of 0.01. Considering the interaction of PBFW with hormonal contraceptive use that compares the effect of PBFW between NC and HC women, descriptively, HC women showed effect sizes that were in the opposite direction to NC women for all outcomes. However, this difference in the effect of PBFW between NC and HC women only became significant for general sexual desire and in-pair sexual desire. Comparing the effect size of PBFW to the SESOI, all effect sizes were above 0.1 in absolute value. Yet, considering their 90 % confidence intervals, the lower limit of the extra-pair sexual desire 90 % CI ([0.04, 0.19]) fell below the SESOI. Only confidence intervals of PBFW for general sexual desire (90 % CI [0.30, 0.71]) and in-pair sexual desire (90 % CI [0.23, 0.53]) exceeded the SESOI. Accordingly, naturally

Table 2
Main measurements in the diary part of the study.

Construct	Item (English translation)	Response format	Rcn
Onset of menstrual bleedings	After having indicated to have had menstrual bleedings since the last diary entry:	Date entered	–
	"The first day of menstruation was on…"		
General sexual desire	"I was interested in sexual behaviour."	5-point Likert scale "not at all" – "very much"	0.86
Solitary sexual desire	"I was interested in masturbating."	5-point Likert scale "not at all" – "very much"	0.86
In-pair sexual desire	"I had fantasies about sex with my partner."	5-point Likert scale "not at all" – "very much"	0.76
	"I had fantasies about exchanging caresses with my partner."		
	"I felt sexually attracted to my partner".		
	"I was interested in being sexually active with my partner."		
Extra-pair sexual desire	"I had fantasies about sex with another man."	5-point Likert scale "not at all" – "very much"	0.78
	"I had fantasies about exchanging caresses with another man."		
	"I felt sexually attracted to another man".		
	"I was interested in being sexually active with another man."		
Dyadic sexual behaviour	After having indicated to have been sexually active:	Number entered	–
	"I was sexually active with my partner (e.g. petting, oral, anal, sexual intercourse, …) this many times:"		
Solitary sexual behaviour	After having indicated to have been sexually active:	Number entered	–
	"I masturbated this many times:"		
Initiation of dyadic sexual behaviour	"I initiated sexual activity with my partner."	5-point Likert scale "not at all" – "very much"	0.87
Appetite	"I felt like eating."	5-point Likert scale "not at all" – "very much"	0.86
Satiety	"I quickly felt full whilst eating."	5-point Likert scale "not at all" – "very much"	0.86
Food intake	"I ate a lot."	5-point Likert scale "not at all" – "very much"	0.87

Note. Rcn = Reliability of change or generalisability of within person variations averaged over items. Since we assessed count data for dyadic and solitary sexual behaviour, we did not compute a reliability of change for these outcomes. Instead, we provide details on respective frequencies in the pdf supplement (Tables S2 and S3).

Table 3
Overview of preregistered analyses of women's self-reported sexual motivation.

Outcomes	PBFW			HC			PBFW * HC		
	Unstd. Est. (Std. Est.)	99 % CI	p	Unstd. Est. (Std. Est.)	99 % CI	p	Unstd. Est. (Std. Est.),	99 % CI	p
General sexual desire	0.51 (0.36)	0.19, 0.82	<.001	0.41 (0.30)	0.18, 0.64	<.001	−0.73 (−0.52)	−1.2, −0.26	<.001
Solitary sexual desire	0.26 (0.21)	−0.02, 0.53	.017	−0.01 (−0.01)	−0.23, 0.21	.885	−0.37 (−0.30)	−0.78, 0.04	.019
In-pair sexual desire	0.38 (0.31)	0.14, 0.62	<.001	0.41 (0.34)	0.18, 0.64	<.001	−0.62 (−0.51)	−0.98, −0.27	<.001
Extra-pair sexual desire	0.12 (0.20)	0.001, 0.23	.009	−0.05 (−0.08)	−0.16, −0.07	.292	−0.11 (−0.20)	−0.28, 0.06	.094

Note. PBFW = probability of being in the fertile window, HC = dummy-coded whether women use hormonal contraceptives or not (0 = false, 1 = true), Unstd. Est. = unstandardised regression coefficient, Std. Est. = standardised regression coefficient, CI = confidence interval. Outcomes are printed in bold if an ovulatory change was significant, its 90 % confidence interval above 0.1 and if it was significantly diminished in women using hormonal contraceptives. For better readability, we do not report results of control variables here but they can be obtained in the pdf supplement (Tables S4–S7).
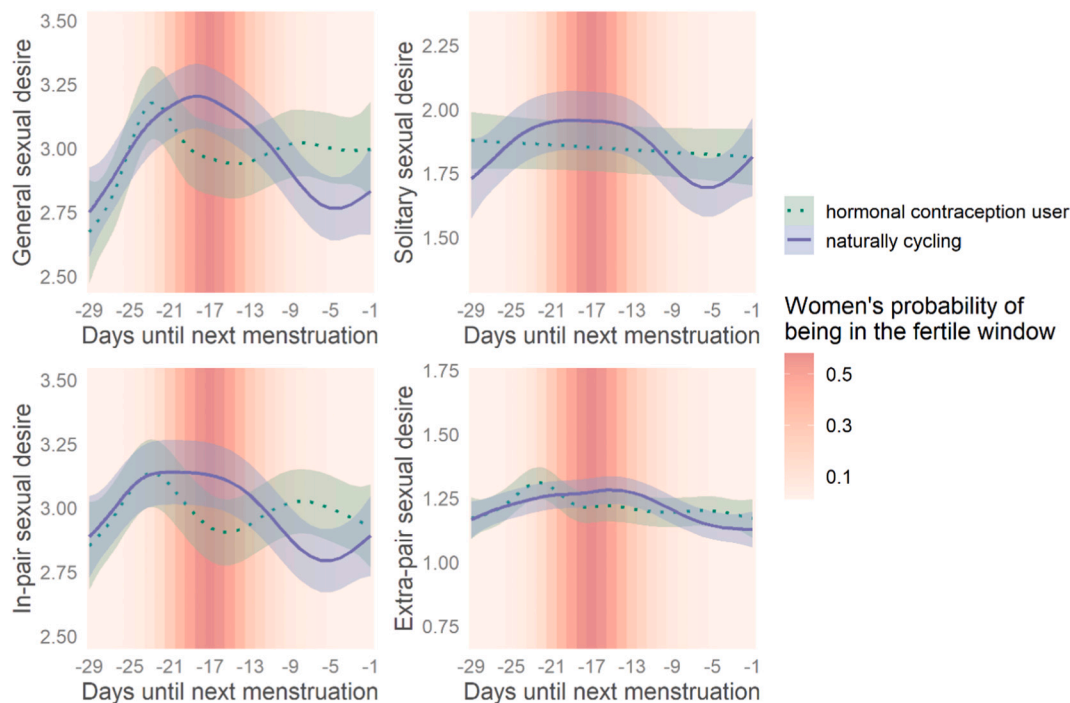

Fig. 2. Women's self-ratings of sexual motivation across the ovulatory cycle.
Note. Smoothed curves were calculated by generalised additive models. Days until next menstruation are reverse cycle days backward counted from the next observed onset of menstrual bleedings. Bands represent a 99 % confidence interval. As outcomes had different means, we always displayed a y-axis range of one standard deviation around respective means.

cycling women who were more likely to be in their fertile window reported higher general and in-pair sexual desire. Higher PBFW was also related to intraindividual increases in extra-pair sexual desire, but these associations were less clear. When plotting a smoothed spline across backward counted cycle days, all outcomes showed small to moderate mid-cycle increases as depicted in Fig. 2.

3.2. Exploratory analyses for sexual motivation

Additionally, in a set of exploratory analyses, we investigated the effect of PBFW on single items of in-pair and extra-pair sexual desire individually (see Table 2 for the single items). Following a reviewer's request, we also investigated possible moderator effects of partner short-term attractiveness on ovulatory increases in general, in-pair and extra-pair sexual desire. All exploratory models and results described below can be accessed in the pdf supplement (Tables S14–S27).

For in-pair sexual desire, the effect of PBFW was highest for women's

interest in sexual behaviour ($b = 0.51$, 99 % CI [0.20, 0.82], $p < .001$, $\beta = 0.35$) and their fantasies about sexual behaviour with their own partner ($b = 0.43$, 99 % CI [0.15, 0.71], $p < .001$, $\beta = 0.30$). Effects of PBFW were smaller for women's sexual attraction to their partner ($b = 0.25$, 99 % CI [−0.01, 0.52], $p = .015$, $\beta = 0.19$) and her fantasies about exchanging caresses with him ($b = 0.29$, 99 % CI [0.01, 0.57], $p = .009$, $\beta = 0.19$). For extra-pair sexual desire, effect sizes were overall smaller than for in-pair sexual desire. Additionally, cycle shifts in women's interest in sexual behaviour ($b = 0.09$, 99 % CI [−0.03, 0.21], $p = .054$, $\beta = 0.15$) and her fantasies about sexual behaviour with another man (other than her partner; $b = 0.08$, 99 % CI [−0.07, 0.23], $p = .159$, $\beta = 0.12$) were comparably lower than her sexual attraction to other men ($b = 0.14$, 99 % CI [0.00, 0.27], $p = .009$, $\beta = 0.20$) and her fantasies about exchanging caresses with another man ($b = 0.14$, 99 % CI [−0.01, 0.30], $p = .019$, $\beta = 0.19$). Thus, descriptively, ovulatory increases in women's in-pair sexual desire were best characterised by interest in sexual behaviour with their partners, whereas changes in extra-pair sexual

Table 4
Overview of preregistered analyses of women's self-reported sexual behaviour.

Outcomes	PBFW			HC			PBFW * HC		
	Unstd. Est. (Std. Est.)	99 % CI	p	Unstd. Est. (Std. Est.)	99 % CI	p	Unstd. Est. (Std. Est.),	99 % CI	p
Dyadic sexual behaviour[a]	0.24 (−)	−0.21, 0.68	.172	0.38 (−)	0.12, 0.64	<.001	−0.71 (−)	−1.30, −0.11	.002
Solitary sexual behaviour[a]	0.20 (−)	−0.65, 1.05	.543	−0.37 (−)	−0.88, 0.13	.059	−0.28 (−)	−1.30, 0.74	.476
Initiation of dyadic sexual behaviour	0.33 (0.23)	0.02, 0.64	.006	0.26 (0.18)	0.05, 0.46	.001	−0.59 (−0.41)	−1.05, −0.13	.001

Note. PBFW = probability of being in the fertile window, HC = dummy-coded whether women use hormonal contraceptives or not (0 = false, 1 = true), Unstd. Est. = unstandardised regression coefficient, Std. Est. = standardised regression coefficient, CI = confidence interval. [a]Count variables were modelled using a Poisson error distribution with a corresponding log link; no comparison with a smallest effect size of interest was preregistered. Outcomes are printed in bold if an ovulatory change was significant, its 90 % confidence interval above 0.1 and if it was significantly diminished in women using hormonal contraceptives. For better readability, we do not report results of control variables here but they can be obtained in the pdf supplement (Tables S8–S10).

desire, which were generally smaller than in-pair sexual desire changes, were descriptively best characterised by an attraction to other men.

For possible moderating effects of partner short-term attractiveness, we included women's ratings of their partners' attractiveness for a short-term sexual affair in a three-way interaction with PBFW and hormonal contraception. We found no moderating effects of partner short-term attractiveness on women's ovulatory increases in general sexual desire ($b = 0.01$, 99 % CI [−0.31, 0.32], $p = .962$), in-pair sexual desire ($b = −0.05$, 99 % CI [−0.29, 0.19], $p = .622$), nor extra-pair sexual desire ($b = 0.03$, 99 % CI [−0.09, 0.14], $p = .578$) (see pdf supplement Tables S22–S24).

3.3. Ovulatory shifts in sexual behaviour

To investigate possible ovulatory shifts in sexual behaviour, we ran linear and generalised mixed effects models predicting our different sexual behaviour outcomes from women's PBFW. The main results are shown in Table 4. Regarding associations of our main predictor PBFW, we found a significant, medium-sized ovulatory increase in women's initiation of dyadic sexual behaviour with their male romantic partners. Although PBFW was positively associated with dyadic and solitary sexual behaviour, neither effect was statistically significant. Considering the interaction of PBFW with hormonal contraceptive use that compares the effect of PBFW between NC and HC women, descriptively, HC women showed effect sizes that were in the opposite direction to NC women for all outcomes. However, this difference in the effect of PBFW between NC and HC women only became significant for dyadic sexual behaviour and initiation of dyadic sexual behaviour. We did not pre-register a SESOI for count data. Hence, we only compared the effect size of PBFW to the SESOI for initiation of dyadic sexual behaviour. Both

absolute value and 90 % confidence intervals (90 % CI [0.13, 0.53]) exceeded the SESOI. When plotting a smoothed spline across backward counted cycle days, all outcomes showed small to moderate mid-cycle increases as depicted in Fig. 3.

3.4. Ovulatory shifts in eating motivation and food intake

To investigate possible ovulatory shifts in eating motivation and food intake, we ran general mixed effects models predicting these outcomes from women's PBFW. The main results are shown in Table 5. Regarding associations of our main predictor, we found a medium-sized significant ovulatory decrease in women's food intake. Although PBFW was negatively associated with appetite and positively associated with satiety and both effects were below a classical significance threshold of 0.05, they did not reach our preregistered alpha rate of 0.01. Considering the interaction of PBFW with hormonal contraceptive use that compares the effect of PBFW between NC and HC women, descriptively, HC women showed effect sizes that were in the opposite direction to NC women for all outcomes. However, this difference in the effect of PBFW between NC and HC women only became significant for food intake. Comparing the effect size of PBFW to the SESOI, all effect sizes were above 0.1 in absolute value. Yet, considering their 90 % confidence intervals, lower limits of appetite (90 % CI [−0.36, −0.08]) and satiety (90 % CI [0.05, 0.31]) fell below the SESOI. Only confidence intervals of PBFW for food intake (90 % CI [−0.43, −0.13]) exceeded the SESOI. When plotting a smoothed spline across backward counted cycle days, appetite and food intake showed small ovulatory decreases and a pronounced luteal increase, whereas satiety showed a small ovulatory increase and a small luteal decrease as depicted in Fig. 4. We restricted our presented results to our preregistered hypotheses, but note our pdf supplement
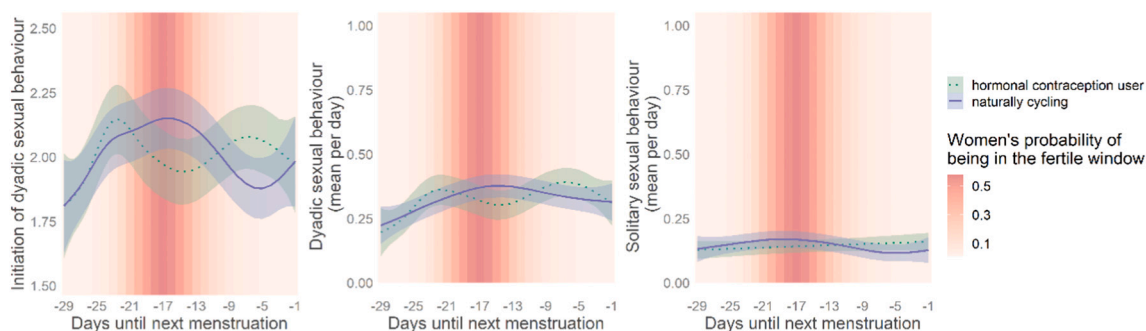

Fig. 3. Women's self-ratings of sexual behaviour across the ovulatory cycle.
Note. Smoothed curves were calculated by generalised additive models. Days until next menstruation are reverse cycle days backward counted from the next observed onset of menstrual bleedings. Bands represent a 99 % confidence interval. For initiation of dyadic sexual behaviour, we displayed a y-axis range of one standard deviation around its mean but for the count variables of dyadic and solitary sexual desire where such a range would go below zero, we displayed a range from zero to one.

Table 5
Overview of preregistered analyses of women's self-reported eating motivation and food intake.

Outcomes	PBFW			HC			PBFW * HC		
	Unstd. Est. (Std. Est.)	99 % CI	p	Unstd. Est. (Std. Est.)	99 % CI	p	Unstd. Est. (Std. Est.),	99 % CI	p
Appetite	−0.22 (−0.21)	−0.45, 0.00	.011	0.15 (0.15)	−0.02, 0.33	.020	0.25 (0.24)	−0.08, 0.59	.050
Satiety	0.18 (0.17)	−0.02, 0.39	.023	−0.00 (−0.00)	−0.17, 0.17	.986	−0.15 (−0.14)	−0.45, 0.16	.208
Food intake	−0.28 (−0.25)	−0.52, −0.04	.003	0.05 (0.05)	−0.12, 0.22	.442	0.38 (0.34)	0.03, 0.73	.006

Note. PBFW = probability of being in the fertile window, HC = dummy-coded whether women use hormonal contraceptives or not (0 = false, 1 = true), Unstd. Est. = unstandardised regression coefficient, Std. Est. = standardised regression coefficient, CI = confidence interval. Outcomes are printed in bold if an ovulatory change was significant, its 90 % confidence interval above 0.1 and if it was significantly diminished in women using hormonal contraceptives. For better readability, we do not report results of control variables here but they can be obtained in the pdf supplement (Tables S11–S13).
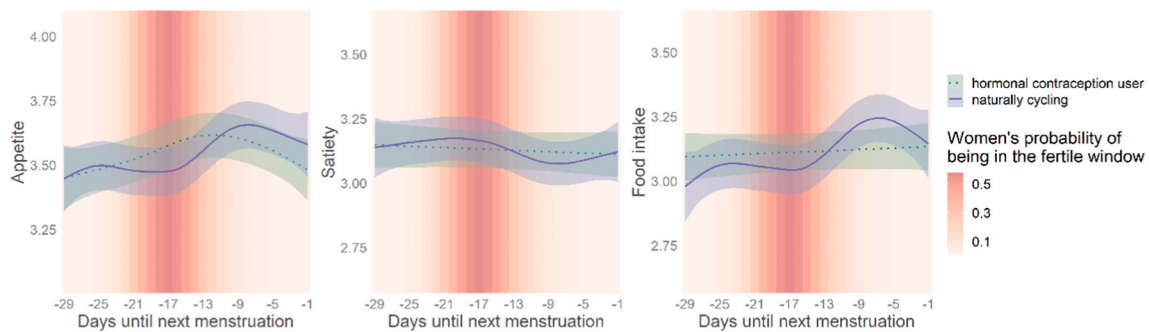

Fig. 4. Women's self-ratings of eating motivation and food intake across the ovulatory cycle.
Note. Smoothed curves were calculated by generalised additive models. Days until next menstruation are reverse cycle days backward counted from the next observed onset of menstrual bleedings. Bands represent a 99 % confidence interval. As outcomes had different means, we always display a y-axis range of one standard deviation around respective means.

(Tables S25–S27) for exploratory analyses on the effect of the luteal phase on changing eating motivation and behaviour.

3.5. Robustness analyses

We conducted several preregistered and exploratory analyses to gauge the robustness of the reported ovulatory cycle shifts. First, we investigated how results of PBFW varied depending on analytical decisions. Specifically, we applied different exclusion criteria (e.g. women who were cycle-aware, had average cycle lengths below 25 or above 35 days or guessed study goals), different estimators of fertility (e.g. forward counting, backward counting 13 instead of the established 15 days to estimate the day of ovulation as reported by Bull et al. (2019) or using discrete fertile windows), and different model specifications (e.g. omitting random effects for (pre)-menstruation, using ordinal models for all Likert-scale outcomes and Gaussian models for solitary and dyadic sexual behaviour). Second, we sought to investigate whether ovulatory cycle shifts are robust against a possible menstrual abstinence effect (e.g. Adams et al., 1978), that is that women might experience diminished sexual motivation and behaviour during menstruation that they catch-up on after the end of menstrual bleedings. Such behaviour could alternatively explain post-menstrual, peri-ovulatory changes. For that, we added a dummy-coded variable for days after menstruation to our models (set to 1 for days after end of menstruation and set to zero for all other days). Since there is little research about the duration of such a possible catch-up effect after menstruation, we coded two dummy variables, spanning two days and three days after the end of menstruation, and compared these models to our preregistered analyses. Third, since the COVID-19 pandemic emerged during the end of our data collection, we sought to gauge its impact on our results. By the time of the first nation-wide lockdown in Germany on March 16, 2020, we had collected 76.22 % of women's diary entries. Consequently, we added further robustness analyses where we compared our main analyses using all data to those only using data before the first lockdown.

In the following, we seek to give a brief summary of these results. We provide a graphical overview of the conducted robustness analyses for general sexual motivation in Fig. 5. A complete overview of all robustness analyses including further robustness analyses of the comparison of HC and NC women can be found in our pdf supplement (Figs. S4–S12). Importantly, in our robustness analyses the effects of PBFW were rarely nullified or reversed, but often differed in magnitude.

First, concerning robustness analyses of researcher degrees of freedom, our results for general and in-pair sexual desire were vastly robust across all models, both regarding statistical significance and effect sizes. For extra-pair sexual desire and solitary desire, while significance of results varied across alternative analytical approaches, effect sizes remained relatively constant. Regarding dyadic sexual behaviour, effects of PBFW mostly remained non-significant but showed a clear descriptive peak when analysing only women above 25 years ($b = 0.70$, 99 % CI [−0.17, 1.58], $p = .039$) and between Mondays and Thursdays ($b = 0.73$, 99 % CI [0.04, 1.41], $p = .006$). The same pattern applied to solitary sexual behaviour but here effects of PBFW peaked in women above 25 years ($b = 0.68$, 99 % CI [−0.93, 2.29], $p = .275$) and between Fridays and Sundays ($b = 1.00$, 99 % CI [−0.30, 2.29], $p = .047$). For initiation of dyadic sexual behaviour, the effect of PBFW became significant for most modelling decisions but significance of effects varied across different exclusion criteria and fertility estimators. Yet, effect sizes remained relatively unaffected. Regarding outcomes of eating motivation, significance of effects of PBFW for both appetite and satiety varied across modelling decisions, but effect sizes remained relatively constant. Regarding food intake, effects of PBFW became non-significant for some modelling decisions and for about half of the alternative fertility estimators, but effect sizes only varied minimally.

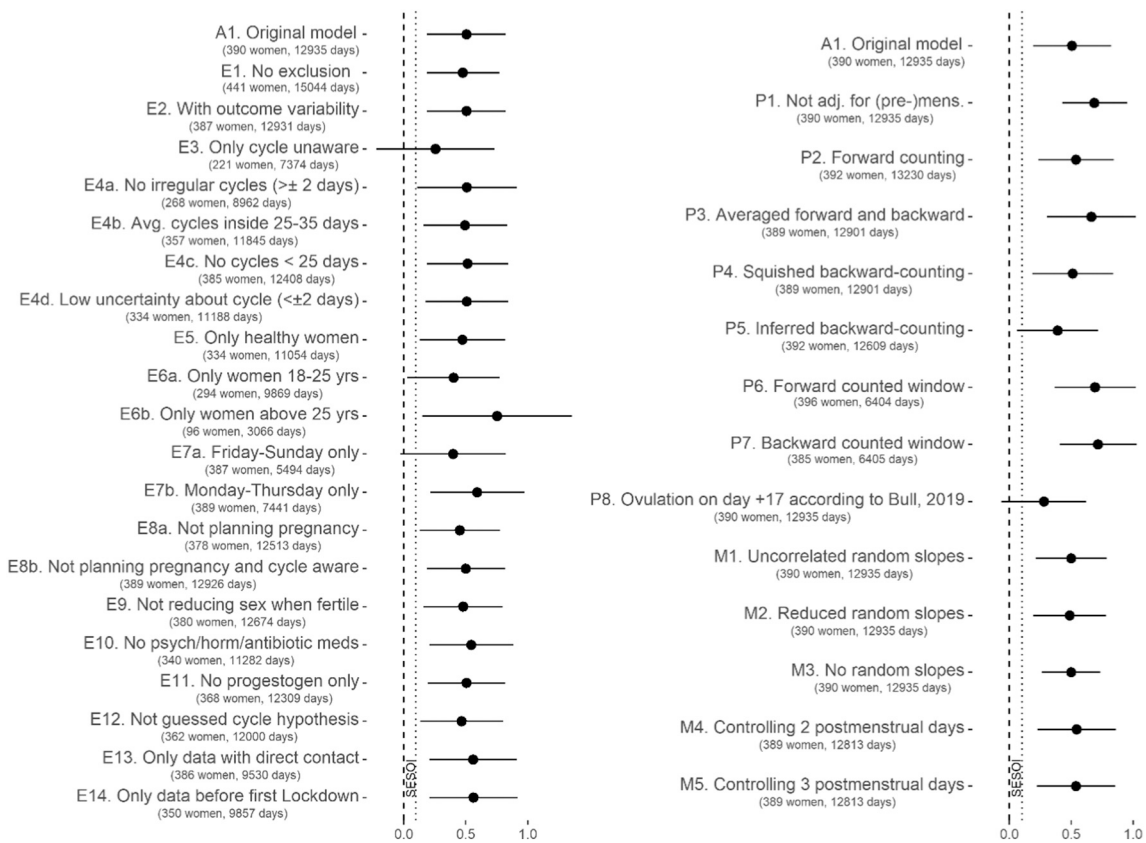Second, concerning a possible menstrual abstinence effect, only

Fig. 5. Overview robustness analyses for ovulatory increase in women's general sexual motivation.

Note. Overview of robustness analyses of the fertility predictor PBFW and corresponding 99 % confidence interval. A1 is the main model reported in the results section. Models starting with E are robustness analyses with different exclusion criteria. Models starting with P are robustness analyses with different specifications of the fertility predictor. Models starting with M are robustness analyses with different model specifications. Avg. = average, Adj. = adjusted, HC = hormonal contraception, (pre-)mens = premenstrual and menstrual phase, SESOI = smallest effect size of interest preregistered at 0.1.

general sexual desire and in-pair sexual desire were significantly associated with a higher number of post-menstrual days (effect of coded two post-menstrual days on general sexual desire $b = 0.22$, 99 % CI [0.04, 0.40], $p = .002$, and on in-pair sexual desire $b = 0.17$, 99 % CI [0.03, 0.31], $p = .002$), indicating a possible menstrual catch-up effect for these two outcomes for all women. Supporting distinct ovulatory effects, however, for all models, unstandardised effect sizes of PBFW increased when additionally controlling for post-menstrual days. For example, when controlling for two days after the end of menstruation, unstandardised effect sizes of PBFW for general sexual desire increased descriptively from $b = 0.51$, 99 % CI [0.19, 0.82] to $b = 0.54$, 99 % CI [0.23, 0.86] and for in-pair sexual desire from $b = 0.38$, 99 % CI [0.14, 0.62] to $b = 0.42$, 99 % CI [0.18, 0.67]. Third, the influence of COVID-19 on our data collection seems negligible since effect sizes were nearly identical when comparing all data to only those collected before the first lockdown in Germany. Taken together, robustness analyses indicate that effect sizes of PBFW were largely robust against different exclusion criteria, menstrual abstinence effects or influences of COVID-19 measures. Regarding statistical significance, results varied considerably when choosing other, presumably less valid methods of estimating women's fertility, although effects of PBFW for general and in-pair sexual desire held across nearly all researcher degrees of freedom.

4. Discussion

Using almost 13,000 diary entries of NC and HC women, the aim of this preregistered diary study was to investigate adaptive cycle shifts in sexual and eating motivation and corresponding behaviours across women's ovulatory cycles. In general, our findings were in line with the

MPSH: We found evidence for ovulatory increases in general sexual desire, in-pair sexual desire and initiation of dyadic sexual behaviour with women's male romantic partners. Additionally, we found evidence for concurrent ovulatory decreases in food intake. Findings for the remaining motivational (i.e., extra-pair sexual desire, solitary sexual desire, appetite, and satiety) and behavioural (i.e., number of dyadic and solitary sexual behaviour) outcomes, however, remain less conclusive. Below, we discuss our findings in detail and consider their theoretical implications.

4.1. Ovulatory changes in sexual motivation

In line with studies showing increases in broader sexual motivation (Arslan, Schilling, et al., 2021; Bullivant et al., 2004; Jones et al., 2018a; Marcinkowska et al., 2022; Roney and Simmons, 2016; Shirazi, Self, et al., 2019), we found ovulatory increases in general sexual desire and in-pair sexual desire for naturally cycling women. Importantly, we found no corresponding effects in HC women who do not experience ovarian hormonal fluctuations. These medium-sized effects clearly exceeded our preregistered SESOI and were robust to multiple researcher degrees of freedom in analytical decisions. Hence, our results support the MPSH by providing clear evidence for the existence of ovulatory increases in general sexual desire and in-pair sexual desire. With regards to the other components of sexual motivation, findings require a more detailed discussion.

As expected, extra-pair sexual desire of NC women showed a mid-cycle increase, yet the overall pattern and the theoretical implications of this finding are less clear: Although effects run in opposing directions for HC women descriptively, NC and HC women did not differ in their

extra-pair sexual desire across their ovulatory cycle at a statistically significant level. Thus, we cannot rule out that observed increases in extra-pair sexual desire follow other mid-cycle changes unrelated to approaching ovulation, such as an absence of pre-, peri- and/or post-menstrual symptoms. Yet, since comparing NC and HC women by testing interaction effects takes even higher statistical power than testing main effects (Rohrer and Arslan, 2021), it is possible that the interaction effect exists but was still too small to be detected, despite the large sample size of this study.

Although we found no significant associations of PBFW with solitary sexual desire, considering the high robustness of its effect size, we still expect solitary desire to be affected by PBFW. Yet, it might be that solitary sexual desire rather follows other ovulatory increases such as those in general sexual desire. For example, it might be that women resort to solitary sexual desire if no sexual partner is available (Carvalheira and Leal, 2013). In support for this idea, effect sizes on days where women had contact with their romantic partners were lower than effect sizes on all days. Unfortunately, the number of diary days without direct contact of the couple was too low (~3000 days) to yield any reliable results. In order to explain the current heterogeneity in studies, more research is needed to investigate whether partner contact or partner availability might be a possible moderator of ovulatory increases in solitary sexual desire.

4.1.1. Comparing in-pair and extra-pair sexual desire

Regarding our results of in-pair and extra-pair sexual desire, it was striking that standardised and unstandardised effect sizes of the association of women's PBFW with their extra-pair sexual desire were descriptively lower than with their intra-pair sexual desire. These findings are in contrast to the predictions made by the GGOSH assuming larger fertile-window increases in extra-pair, as compared to in-pair sexual desire, and to previous studies supporting these predictions (Gangestad et al., 2002, 2005; Pillsworth and Haselton, 2006). We identified three reasons that might explain this difference. First, in a study with women in romantic relationships, it makes sense that ovulatory increases in general sexual motivation as predicted by the MPSH largely translated into increased in-pair sexual desire. Second, ovulatory shifts in in-pair sexual desire might have further increased by self-selection of couples: Since the cover story was framed as a couple's quiz to investigate needs and emotions of one's romantic partner, it is possible that mostly couples participated who were highly satisfied and committed to each other (Park et al., 2021). This might explain the lower variance we find in extra-pair sexual desire compared to in-pair sexual desire, which in turn might have resulted in lower effect sizes. Supporting this explanation, as one of few dyadic diary studies that analysed data of possibly highly committed couples as well, Righetti et al. (2020) reported no associations of estradiol (the steroid hormone that dominates the follicular and fertile window) with extra-pair sexual desire. However, they also found negative associations of estradiol with in-pair sexual desire that contradict our findings. As Righetti et al. (2020) discuss themselves, their results are likely limited by low statistical power since they only investigated 33 women across 15 diary days, thereby making comparisons to our findings difficult. Third, it is also possible that effects of extra-pair sexual desire were small because women who participate in a study together with their romantic partners are reluctant to report on their extra-pair sexual desire. Yet, this effect is likely mitigated by the high anonymity we ensured in this online study and by excluding participants who reported to have answered dishonestly.

4.1.2. Implications for the theoretical debate on ovulatory cycle shifts

Although the reported increase in extra-pair desire was small, we cannot rule out an effect or show that is smaller than the SESOI. Nonetheless, our findings of robust and medium-sized ovulatory increases in both general and in-pair sexual desire but inconclusive evidence for extra-pair sexual desire contradict previous studies reporting

no ovulatory increases in in-pair sexual desire but only a target-specific ovulatory increase in extra-pair sexual desire (Gangestad et al., 2002; Gangestad et al., 2005; Grebe et al., 2016; Pillsworth and Haselton, 2006). As exploratory analyses revealed that extra-pair sexual desire was mostly characterised by attraction to, as opposed to wanting sexual contact with, other men, it seems unlikely that ovulatory shifts in extra-pair sexual desire in this sample function to obtain high sire genetic quality from men other than women's primary partners as predicted by the GGOSH. These results further speak against the assumption that the pre-ovulatory nadir in food-intake functions to spend more time on "shopping" alternative mates (Fessler, 2003). A recent study by Schön et al. (2023) showing that cyclical changes in serum levels of estradiol and progesterone do not seem to affect women's self-rated sexual attraction to (extra-pair) visual sexual stimuli further question mechanisms by which ovulatory increases in extra-pair sexual desire could ensue. Instead, as women's in-pair sexual desire was mostly characterised by seeking sexual contact with their primary partners, any resulting offspring would carry genes of women's primary partners. Rather than considering in-pair sexual desire and extra-pair sexual desire as opposing effects, it is possible to conceptualise them as different facets of the same ovulatory increase in general sexual motivation that translate into target-specificity depending on women's pre-existing preferences or situational factors.

4.2. Ovulatory changes in sexual behaviour

Providing further support for the MPSH, naturally cycling women initiated more sexual behaviour with their romantic partners when fertile. The effect exceeded the SESOI and was significantly diminished among HC users, thereby fully supporting the existence of ovulatory increases in sexual initiation, as also demonstrated in previous research (Adams et al., 1978; Bullivant et al., 2004; Harvey, 1987; Marcinkowska et al., 2022). Despite this increase in sexual initiation, or proceptivity in evolutionary terminology, women neither reported more frequent sexual behaviour with their romantic partners, nor more frequent solitary sexual activity. In the case of dyadic sexual behaviour, this lack of findings might be explained by the fact that partnered sexual behaviour is not only influenced by sexual initiation of one partner. Instead, it is also strongly affected by the other person's motivational states, their possibly biased perceptions of these sexual advances (Dobson et al., 2018) as well as external factors such as time constraints, relationship dynamics and partner availability (Arslan, Schilling, et al., 2021). In support for the relevance of such external factors, effect sizes for dyadic sexual behaviour increased when only analysing days with direct contact of the romantic couple. Hence, ovulatory increases in sexual initiation might more strongly reflect endogenous shifts in sexual motivation, as proposed by the MPSH, that does not necessarily lead to dyadic sexual behaviour but rather increases its possibility (Caruso et al., 2014; Roney, 2016). Future research is needed to better understand the interplay of sexual initiation and dyadic sexual behaviour, particularly by considering the perceptions and motivational states of both romantic partners.

In the case of solitary sexual behaviour, it might be that – as with solitary sexual desire – women resort to solitary sexual behaviour when they experience ovulatory increases in sexual motivation but have no sexual partner available (Burleson et al., 2002; Caruso et al., 2014). Unfortunately, the number of observed diary days where romantic couples had no direct contact were too few to analyse such moderating effects of partner availability.

4.3. Ovulatory changes in eating motivation and food intake

In line with the MPSH, concurrent to ovulatory increases in sexual motivation and sexual initiation, women showed an ovulatory decrease in food intake that fully met all our criteria of evidential support. Thus, this study adds convincing evidence, based on self-reported food intake,

to previous studies reporting an ovulatory nadir in both self-reported and weighed food intake (Fleischman and Fessler, 2007; Gorczyca et al., 2016; Roney and Simmons, 2017). However, we could not convincingly support ovulatory changes in appetite and satiety as possible motivational mechanisms behind the reduction in food intake. To our knowledge, this is the first study that sought to expand our understanding of ovulatory changes in eating motivation by assessing self-reported appetite and satiety. As appetite in particular showed the expected result pattern on a classical, liberal level of significance and there is neuroscientific evidence that appetite is modulated by estradiol in rats (Asarian and Geary, 2006), we hope to encourage future empirical studies and theoretical debates about which motivational and physiological processes translate into the observed reduction in food intake. However, as Fessler (2003) argued that women might simply lack the time to eat because of their prioritisation of mating efforts when fertile (although our results suggest that mating motivation in general, not solely extra-pair mating, is prioritised), it is also possible that ovulatory decreases in eating motivation are not needed to explain the observed reduction in food intake. We chose not to report a test of difference scores, as in Roney and Simmons (2017), since we believe it adds little new information while making the results section more convoluted because our multiple outcomes would have implied nine potential difference scores (also see Edwards, 2001, for a critique on the use of difference scores). Ideally, future studies should directly investigate a trade-off between eating and sexual motivation. To do so, studies should measure eating and sexual motivation in a convertible currency (e.g. time or energy spent) and also assess other confounding energetic demands. If these can be held constant, future work could test whether the trade-off between eating and sexual motivation is specific to the fertile phase by examining residual correlations across the cycle. Additionally, replications of our study are needed that assess further aspects of eating motivation such as food craving (Gorczyca et al., 2016) or cost-intensive foraging, and address current incongruities in the types of food consumed across the ovulatory cycle (Fleischman and Fessler, 2007; Gorczyca et al., 2016).

4.4. Limitations and future directions

Despite having multiple strengths, this study has some limitations. To begin with limitations regarding our design, a number of measures could be improved in future studies. First, we based our results only on women's self-reports. Therefore, biases such as measurement reactivity, desirability bias and recall error might affect our findings (e.g. Meston et al., 1998). Although these biases cannot be ruled out, we expect they are diminished by using an anonymous online diary design, randomising the item order and by restricting daily recall to the previous 24 h.

Second, we used backward counting from the next onset of menstrual bleedings to determine the day of ovulation. Because the luteal phase is less variable in length than the follicular phase, backward counting is more accurate than forward counting (Fehring et al., 2006). Additionally, many women use forward counting methods as a form of contraception method and cycle-awareness. Hence, fertile days based on backward counting might be less affected by demand characteristics on days when women expect to be fertile based on their own forward counting. Moreover, counting methods have been shown to exceed validity of commonly used salivary immunoassay assessments of estradiol and progesterone to infer the fertility peak within the cycle (Arslan et al., 2023). Yet, while backward counting is the best practice for counting methods, it is still outperformed by ultrasound or luteinising hormone tests (Gangestad et al., 2016). However, high costs, low feasibility and reduced anonymity of these measurements often result in low sample sizes that in turn restrict informational value of studies. Moreover, using direct measurements of ovulation often reveal a study's focus on ovulation, which might introduce response biases. Thus, backward counting of observed menstrual onsets balanced the need of high statistical power and high validity of measurements. Future

research might benefit from studies that combine biological markers of ovulation and large sample sizes.

Third, the complexity of our diary study as well as the high number of daily items did not allow for multi-item assessments of most variables. Although multilevel reliabilities were satisfying and using mostly single-items probably resulted in a higher sample size and reduced nonresponse bias, we had to use less established measurements. While the discussion of the practical use of single-items is ongoing (Arslan, Brümmer, et al., 2020; Fisher et al., 2018), we hope future research validates our findings with more established scales.

Fourth, our study was not able to capture all constructs that might be relevant to ovulatory cycle shifts in sexual behaviour. Specifically, as a limitation caused by the dyadic diary design we did not assess extra-dyadic sexual behaviour, in order not to cause adverse effects on women's relationships or put them at risk of partner violence. As a result, we cannot compare ovulatory effects on the target of dyadic sexual behaviour that might have informed theoretical debates. However, in previous research (Arslan, Schilling, et al., 2021) rates of extra-pair sexual behaviour were too low for proper statistical analyses. In the future, diary studies that only assess data from one partner may put a special focus on cycle shifts in extra-pair sexual behaviour. In addition, as a limitation of our research focus, we did not assess pre-existing preferences in targets of sexual motivation in women that might have advanced a discussion of how increases in general sexual motivation might translate differently into sexual motivation aimed at primary partners or other men. Future studies might directly assess pre-existing preferences and investigate their influences. Such studies should preferably implement Open Science practices, use cover stories to reduce self-selection bias, and aim to achieve diverse samples. As another limitation of our research focus, we only investigated ovulatory changes. Since the MPSH predicts an alternating pattern of sexual and eating motivation across the whole cycle, we would also expect decreased sexual but increased eating motivation in the luteal phase. Only few studies have reported such a mid-luteal increase in food intake, appetite and food cravings so far (Gorczyca et al., 2016; McNeil et al., 2013). Graphically, the effects we find are consistent with a luteal increase in appetite and food intake, but since this preregistered study aimed at uncovering ovulatory changes, we restricted our statistical analyses to the preregistered examination of the fertile window. To inform future research, we added exploratory analyses of luteal changes in appetite, satiety and food intake that support luteal increases in eating motivation and behaviour (although not statistically different in HC and NC women) to our pdf supplement (Tables S25–S27). As these exploratory analyses were not preregistered, they should only be cautiously interpreted pending further research.

Finally, regarding external validity of our findings, to investigate possible reproductive functions, we only assessed heterosexual couples. Moreover, our sample, although more diverse than an undergraduate student sample, predominantly consisted of young, educated participants from a developed Western country that fulfils all aspects of a WEIRD sample (Henrich et al., 2010). Consequently, the generalisability of our results may be limited although we expect functional hormonal mechanisms to be universal among humans. Particularly because of the relevance of nutritional status and food availability on possible motivational trade-offs in sexual and eating motivation (Fessler, 2003; Loucks and Thuma, 2003; Roney and Simmons, 2017), more research with higher diversity in sample characteristics, cultural backgrounds and health is called for.

5. Conclusion

In this preregistered and highly powered online diary study, we observed ovulatory increases in partnered, naturally cycling women for general sexual desire, in-pair sexual desire and initiation of dyadic sexual behaviour, as well as ovulatory decreases in food intake. Extra-pair sexual desire showed a significant mid-cycle increase, but we

could not rule out non-ovulatory confounders using our quasi-control group design. Ovulatory changes for solitary sexual desire, solitary and dyadic sexual behaviour, appetite and satiety were not significant but not clearly negligible either. We therefore encourage further replication. The overall result pattern in our study fits the Motivational Priority Shifts Hypothesis better than the Good Genes Ovulatory Shift Hypothesis.

Transparency and openness

All materials including preregistration (of study design, hypotheses, data collection process and sample size, data analyses), survey files, data cleaning, analysis scripts, codebook as well as code used for data anonymisation are accessible on the Open Science Framework: https://osf.io/v98t2/.

Anonymised data are accessible as scientific use files under doi: https://doi.org/10.7802/2330.

Ethical standards

The authors assert that all procedures contributing to this work comply with the APA Ethical Principles.

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Lara Schleifenbaum: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Software, Visualization, Writing – original draft. **Julia Stern:** Conceptualization, Investigation, Writing – review & editing. **Julie C. Driebe:** Conceptualization, Validation, Writing – review & editing. **Larissa L. Wieczorek:** Software, Writing – review & editing. **Tanja M. Gerlach:** Conceptualization, Writing – review & editing. **Ruben C. Arslach:** Conceptualization, Methodology, Software, Validation, Writing – review & editing. **Lars Penke:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no conflicts of interest.

Data availability

A link is shared by which one can access anonymised data for scientific use.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.yhbeh.2024.105542.

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