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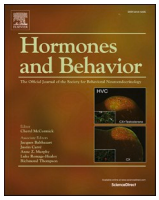

The influence of time of day on memory recognition for faces

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ABSTRACT

Time of day can alter memory performance in general. Its influence on memory recognition performance for faces, which is important for daily encounters with new persons or testimonies, has not been investigated yet. Importantly, high levels of the stress hormone cortisol impair memory recognition, in particular for emotional material. However, some studies also reported high cortisol levels to enhance memory recognition. Since cortisol levels in the morning are usually higher than in the evening, time of day might also influence recognition performance. In this pre-registered study with a two-day design, 51 healthy men encoded pictures of male and female faces with distinct emotional expressions on day one around noon. Memory for the faces was retrieved two days later at two consecutive testing times either in the morning (high and moderately increased endogenous cortisol levels) or in the evening (low endogenous cortisol levels). Additionally, alertness as well as salivary cortisol levels at the different timepoints was assessed. Cortisol levels were significantly higher in the morning compared to the evening group as expected, while both groups did not differ in alertness. Familiarity ratings for female stimuli were significantly better when participants were tested during moderately increased endogenous cortisol levels in the morning than during low endogenous cortisol levels in the evening, a pattern which was previously also observed for stressed versus non-stressed participants. In addition, cortisol levels during that time in the morning were positively correlated with the recollection of face stimuli in general. Thus, recognition memory performance may depend on the time of day and as well as on stimulus type, such as the difference of male and female faces. Most importantly, the results suggest that cortisol may be meaningful and worth investigating when studying the effects of time of day on memory performance. This research offers both, insights into daily encounters as well as legally relevant domains as for instance testimonies.

1. Introduction

Two important mechanisms govern physiological and cognitive processes of the human body: first, homeostasis protects the body against external influences and keeps it in balance through internal regulatory processes (Cannon, 1934). Part of this mechanism is the hypothalamic-pituitary-adrenal axis (HPA axis), which helps the organism to react to potential threats and likewise to adapt under the influence of stress (de Kloet et al., 2005). Second, the circadian rhythm optimally adjusts internal body processes to the respective time of day, dependent on environmental cues (zeitgeber) such as light or food intake (Gamble et al., 2014). These zeitgeber provide input for the central circadian clock, the hypothalamic suprachiasmic nucleus (SCN), which in turn relays information to peripheral clocks throughout the body (Dumbell et al., 2016). These time-of-day dependent light pulses activate not only the vegetative nerve system, but also the HPA axis in a regular 24-hour cycle. The retinohypothalamic tract from the eye forwards light information to the SCN which projects to the paraventricular nucleus (PVN) of the hypothalamus and thus ensures a cyclic release of corticotrophin-releasing hormone (CRH) and arginine vasopressin. Both peptide hormones in turn trigger the release of adrenocorticotrophic hormone from the anterior pituitary gland into the peripheral circulation, consequently resulting in the release of glucocorticoids such as cortisol from the adrenal cortex (Androulakis, 2021; Koch et al., 2017). The circadian rhythm governs cortisol level to peak usually within 1 h after awakening with a gradual decline throughout the day, while there is usually an additional small peak after lunch time (Pruessner et al., 1997; Weitzman et al., 1971; Wüst et al., 2000). The same HPA axis response can be observed in response to a stressor, induced via signals from the limbic forebrain and the brainstem through the PVN (Buckley and Schatzberg, 2005; Dumbell et al., 2016; Gamble et al., 2014).

Previous studies showed that the stress hormone cortisol exerts a

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strong impact on memory retrieval. In most cases, high cortisol levels impair memory retrieval (Het et al., 2005; Shields et al., 2017; Wolf, 2017), with emotional material being especially impacted (Shields et al., 2017; Wolf, 2017), but there are also studies revealing high cortisol levels to improve memory recognition (Hupbach and Fieman, 2012; Pötzl et al., 2023; Schwabe et al., 2009). The origin of these high cortisol levels varied widely across these studies. Some of them used a psychosocial (Kuhlmann et al., 2005; Li et al., 2013) or a psychophysiological stress induction (Pötzl et al., 2023; Schwabe and Wolf, 2014), while others administered glucocorticoid-receptor agonists such as hydrocortisone (Schilling et al., 2013). One study investigated the impact of endogenous cortisol levels on recognition performance (Ackermann et al., 2013) showing that high cortisol levels correlated with impaired memory retrieval. Thus, not only pharmacologically manipulated or stress-induced, but also endogenous high cortisol levels reduce recognition performance. It therefore seems feasible that cortisol fluctuations throughout the circadian rhythm could trigger similar effects. Certainly, time of day dependent effects on cognitive processes are influenced by many factors such as sleep and light, we assume cortisol levels to represent a crucial one (Schmidt et al., 2007).

Indeed, time of day and related cortisol levels can have an influence on different aspects of memory performance (Gerstner and Yin, 2010; Smarr et al., 2014), as well as episodic memory retrieval in particular (Folkard et al., 1977). However, the exact mechanisms as well as the impact of the hormone cortisol are not entirely clear, although there are indications that cortisol might be meaningful in this context. First, stress impaired memory encoding if participants were tested in the morning, but not in the evening (Maheu et al., 2005). Second, memory retrieval was impaired by stress independently of time of day (morning vs. evening; Smeets, 2011). Third, pharmacological suppression of the morning cortisol rise resulted in an impaired free recall of pictures and words (but not memory recognition), whereas the authors note that a lower dose might have even improved memory performance (Rimmele et al., 2010). These results hint to the fact that time of day and especially cortisol levels in this context might also modulate recognition performance. Furthermore, the specific type of used stimuli should be considered, since most of the studies used words (Buchanan et al., 2006; Schwabe and Wolf, 2014; Smeets, 2011) or pictures of scenes (Hidalgo et al., 2015; Schönfeld et al., 2014), while face stimuli relying on additional brain areas such as the fusiform face area (Kanwisher and Yovel, 2006) are highly social (Bruce and Young, 1986; Young et al., 2008) and relevant for our daily lives, but were rarely investigated so far.

Another important factor, when investigating memory performance is the distinction between recollection and familiarity. Recollection is primarily based on hippocampal activity, which is influenced by cortisol on a large scale (de Kloet et al., 1998; Joëls et al., 2012). Familiarity on the other hand primarily relies on perirhinal regions (Eichenbaum et al., 2007; Sauvage et al., 2008), which are not influenced by cortisol to such a large extent. Therefore, hippocampal-based recollection processes might be especially prone to time-of-day dependent cortisol effects.

Moreover, more basic cognitive processes like alertness might be differentially influenced by time of day as well as the underlying cortisol levels. Alertness is a subcomponent of attention, which describes a state of achieving and maintaining high responsiveness to environmental stimuli (Posner and Petersen, 1990). The general capacity to respond to environmental stimuli is defined as tonic alertness. The maintenance of this alertness state throughout a longer time window is labeled as intrinsic alertness. The capacity to increase responsiveness to an environmental stimulus after a warning signal as phasic alertness (Posner, 2008; Valdez, 2019). Attention in general seems to be influenced by the circadian rhythm (Hartsock and Spencer, 2020; Schmidt et al., 2007; Snider et al., 2018), while alertness as the most basic form of each attention process seems not to be sufficiently investigated. Previous research on the influence of the circadian rhythm on alertness is not conclusive (Clarisse et al., 2010; Matchock and Mordkoff, 2009; Valdez, 2019; Xu et al., 2021): alertness should be low in the morning, showing a peak level around noon, followed by a rapid decrease after lunch time (Valdez, 2019; Xu et al., 2021). Based on these results, alertness should be slightly higher in the morning compared to the evening.

Taken together, many questions remain unanswered when investigating the impact of time of day on memory retrieval. To our knowledge, the effect of the time of day on the recognition of images (of faces), in the absence of any stress or cortisol induction, has not yet been investigated in any prior study. In this context, we are trying to investigate the role of the hormone cortisol by considering various influencing factors, such as the influence of attention and the accuracy of memory content. Therefore, in the current study, we focus on time of day related changes in cortisol (Ackermann et al., 2013; Li et al., 2013; Pötzl et al., 2023; Schilling et al., 2013) and alertness levels (Cabeza et al., 2003) on memory recognition. Participants learned stimuli of faces on day one at noon. Two days later they were asked to distinguish those stimuli from additional face stimuli either in the morning or in the evening. Before each memory task, participants were subjected to an alertness task.

Based on previous literature we expected cortisol levels to be higher in the morning in comparison to the evening group. Further, we assumed recognition performance to differ significantly between both groups, with the strongest effects expected for recollection. Based on the previous mixed findings, we did not make a directional prediction of the effects. Concerning the alertness task, we expected a significantly better performance in the morning group (vs. the evening group), based on previous literature (Valdez, 2019; Xu et al., 2021). In case of impaired memory recognition in the morning compared to the evening group, we assumed that memory performance should be negatively correlated with high cortisol levels. Otherwise, if memory recognition is enhanced in the morning compared to the evening group, we presumed that memory performance should be positively associated with alertness levels.

2. Material and methods

The present study was preregistered on the Open Science Framework (OSF): https://osf.io/78563/?view_only=bd78897ec65e435389bf435b3b798efa

2.1. Participants

Based on a preceding power analysis using G*power 3.1.9.4 (Faul et al., 2009) with a 1-$\beta \geq 0.85$ power to detect a medium effect size of $f = -0.245$ or $d = -0.49$ (see meta-analysis by Het et al., 2005) at $\alpha \leq 0.05$ and a correlation of $r = 0.30$ and a non-sphericity correction of $\mathcal{E} = 0.80$ we aimed at a sample of 52 participants to detect a group × valence interaction.

Since only a limited number of participants could be tested, the sample only consisted of men, thus restricting sex hormone effects to a minimum (Jentsch et al., 2022; Merz and Wolf, 2017). Participants were recruited at the campus as well as via online platforms of the Ruhr University Bochum. As part of the recruitment process, participants were randomly assigned to a morning or evening group. One participant had to be excluded due to arbitrary rating behavior (rating over 94 % of the face as "new" in both recognition phases, predominantly using the same rating in a row) which resulted in a final data set of 51 participants. All participants were healthy men between 19 and 33 ($M = 23{,}49$, $SD = 3.65$) years with a BMI between 18 and 29 ($M = 22.67$; $SD = 2.40$) kg/m^2. Additional exclusion criteria were sleep problems, night or shift work (Strahler et al., 2017), as well as a regular consumption of alcohol (more than one glass of wine/beer on 5 days a week; Seitz and Bühringer, 2008) and drugs (more than once a month). Participants were also excluded if they were regularly smoking cigarettes, taking any kind of medication or were in current psychotherapy. Also, extraordinary psychological (e.g. exam phase) or physical stress (e.g. preparing for an exhausting sport competition) served as exclusion criteria. If participants had donated blood, appointments were always scheduled at least four weeks afterwards or in case of a vaccination or being abroad with a

time lag of >5 h the examination date was set at least two weeks later (Strahler et al., 2017). To minimize possible influences on cortisol levels participants were instructed to abstain from demanding exercise as well as any kind of food and beverages (except for water) 3 h before the testing session on day one (starting around 12.30–2.00 pm). On day two, the waiver period lasted for the entire morning before the testing session for the morning group (starting around 8.00–10.00 am) and for 4 h before the testing session for the evening group (starting around 4.00–6.00 pm). Furthermore, before the testing session on day one, participants had to be awake for not less than 3 h. On day two, participants in the evening group were instructed to be awake for 6 h at minimum, while participants in the morning group should be awake for no more than 1 h before the beginning of the session. Participants received either 30,- € or course credits for their participation. The ethics committee of the Faculty of Psychology of the Ruhr University Bochum approved data collection (registration number: 18-6448), it follows the guidelines of the Declaration of Helsinki.

2.2. Memory paradigm

The process of the memory paradigm was identical to the one described in our previous study (see Fig. 1; Pötzl et al., 2023), thus consisting of an encoding phase on day one, as well as two recognition phases on day two. The paradigm was conducted using MATLAB (version 2018b) as well as the Psychophysics Toolbox (Kleiner et al., 2007) and OTBR Toolbox (Rose et al., 2008). The encoding as well as each of the two recognition phases lasted about 16 min and was preceded by a training session (consisting of four additional images) in every phase.

The instruction to the memory paradigm was presented orally and in writing through a cover story. During encoding, participants should imagine being at a party where they will encounter several other guests (faces on a screen). They were also told that they had been invited to another party on the second testing day (approximately 48 h later). Therefore, they should try to memorize the presented faces, so that if they are encountering additional faces on the second day, they will be able to differentiate them from previously seen faces. To evaluate the perceived valence of the faces, participants further had to answer a 7-point Likert scale ranging from 1 (very negative) to 7 (very positive).

On day two, participants had to retrieve their memory for the observed faces in two separate recognition phases. In both recognition phases, participants had to rate each face based on having seen it before as well as confidence about their decision on a 6-point Likert scale (1 - very sure new, 2 - fairly sure new, 3 - slightly sure new, 4 - slightly sure old, 5 - fairly sure old, 6 - very sure old). Ratings during each of the three phases (encoding, recognition one and recognition two) were achieved using the arrow keys on the keyboard. The two recognition phases were used to allow for a better comparability to the design of a previous study (see Pötzl et al., 2023), whereby no major differences between both recognition time points were expected for the present study. The two recognition time points were also not compared with each other since the statistical requirements for this additional comparison were not met.

2.3. Stimuli and randomization

Stimuli for the memory recognition were the same as used previously (Pötzl et al., 2023). Altogether 120 frontal view face images from the Radboud Face Database (Langner et al., 2010) and Chicago Face Database (Ma et al., 2015) showing happy, angry, or neutral facial expressions were harmonized in brightness, quality and alignment using the image editing program GIMP (GNU Image Manipulation Program 2.10.8.) and the shine toolbox (Willenbockel et al., 2010). A pre-evaluation of the images by 24 participants as well as valence ratings of our previous study (Pötzl et al., 2023) indicated that happy facial expressions were on average rated as positive, angry as negative and neutral as neutral. Based on their valence, images were split into equal stimulus sets (A and B) consisting of 60 stimuli each.

For the encoding session, one of the two stimulus sets (A or B) was randomly presented to the participants. Using block randomization, presented stimuli were split into two blocks of 30 faces each, which were again divided into 10 angry, 10 happy and 10 neutral faces as well as equally divided for stimulus sex (5 pictures of male faces and 5 pictures of female faces for each valence). During each recognition phase, one half of the remaining set (30 “new” stimuli) was additionally presented to one half of the encoding set (30 “old” stimuli). Thus, each recognition phase consisted of a different stimulus set and used the same

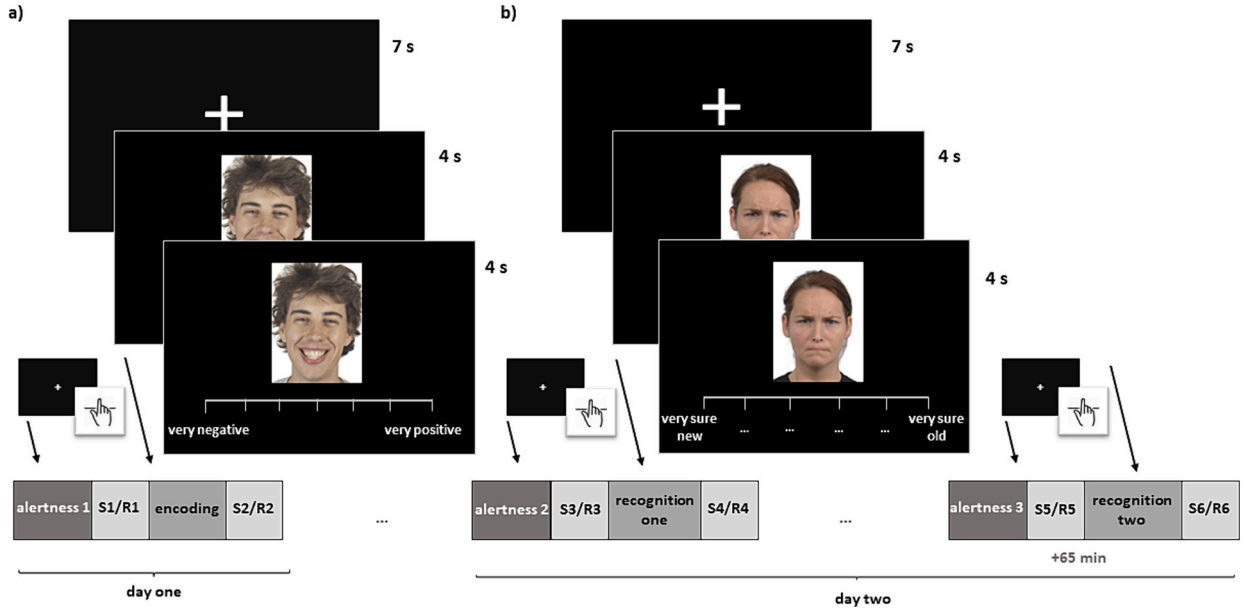

Fig. 1. Illustrated are the course of the memory paradigm (encoding, recognition one and recognition two), the alertness test as well as the time points of saliva samples (S) and affect ratings (R) for day one (A) and two (B). For the encoding and both recognition phases, the stimulus was presented for 4 s, followed by the additional presentation of the rating scale (4 s) and a light-matched, jittered fixation cross (7 s, jittered in 0.192 s steps within 2.5 s). Importantly, in the paradigm all levels of the recognition rating scale are formulated in words while it is simplified for this illustration (see Section 2.4. Memory Paradigm).

randomization in terms of stimulus valence and sex as the corresponding encoding phase. The same stimulus valence or sex was never presented more than twice in a row.

2.4. Salivary cortisol and affect ratings

To investigate the influence of endogenous cortisol levels on memory recognition performance for both groups, saliva samples were taken at six time points (day one: before vs. after encoding; day two: before recognition one, after recognition one, before recognition two, after recognition two) using Salivette collection devices with a synthetic swap (Sarstedt, Nuembrecht, Germany). The collected samples were stored at −20 °C and analyzed in the local biochemical laboratory using a Synergy2 plate reader (Biotek, USA) as well as a commercial enzyme-linked immunosorbent assay (ELISA; IBL International GmbH, Hamburg, Germany) compliant with the manufacturer's instructions. Intra- and inter-assay variability was below 7 %.

Questionnaires surveying affect ratings were collected at the same time points via the German version of the Positive and Negative Affect Schedule (PANAS; Breyer and Bluemke, 2016).

2.5. Alertness

Alertness was assessed using the Test of Attentional Performance (TAP; version 2.3.1. – PSYTEST; Zimmermann and Fimm, 2007) at three time points during the experiment: before encoding, before recognition one and before recognition two. It was used to measure two different aspects of alertness. On the one hand, the intrinsic alertness was examined by having the participants to react to a visual stimulus (cross on a screen) as quickly as possible via a button press. On the other hand, phasic alertness was measured by preceding the visual stimulus with a cue (a warning tone, see Fig. 1).

Each alertness test lasted about 5 min in total and was split into two blocks without (A) and two blocks with (B) an additional warning tone in the context of an experimental ABBA-design. In every case, the participants were instructed about the subsequent type of block. Before each block at least two test trials (in case of omissions up to five additional test trials) were displayed, but not analyzed. During each block 20 trials (in case of omissions up to 25 trials) were presented and are thus available for analyses. The visual cues were presented until the participants reacted via button press, but for 2000 ms at maximum. They were always shown between 1800 and 2700 ms after a previous reaction. In case of a warning-tone-block, the warning tone was always presented for 400 ms and the duration between the warning tone and the presentation of the visual cue varied between 500 and 1400 ms.

2.6. Chronotype

Chronotype was assessed using the German version of the Morningness-Eveningness Questionnaire (MEQ; Horne and Ostberg, 1976) and the Munich Chronotype Questionnaire (MCTQ; Roenneberg et al., 2003). The MEQ assesses participants' active and alert phases at particular times of day via Likert-scales as well as timescales comprising a time frame of 7 h (divided into blocks of 15 min). For this questionnaire global scores are calculated, which divide the participants into morning types, evening types or neutral types. However, only a few participants could be allocated to the morning (morning group: $n = 2$, evening group: $n = 5$) or evening chronotype (morning group: $n = 8$, evening group: $n = 3$), while most of them were allocated to the neutral chronotype (morning: $n = 15$, evening: $n = 18$), not making it possible to adequately analyze the influence of chronotype categories on memory recognition. Therefore, we conducted correlative analyses with the help of the raw scores.

With the help of the MCTQ phases of participants' entrainment (synchronization of the internal clock with regularly recurring environmental factors), focused on sleep-timing, are assessed separately for workdays and work-free days. For this questionnaire the sleep-time corrected midpoint of sleep on work-free days (MSF_{sc}) was used for correlation analyses since it represents the most meaningful value regarding the chronotype. The MSF_{sc} describes the midpoint between sleep onset and wake up on work-free days, corrected for sleep time on workdays (Roenneberg et al., 2003).

2.7. Procedure

Participants came to the invariably illuminated laboratory on two different days. On the first day, the sessions started between 12.30 and 2.30 pm. At the beginning of the session, participants obtained detailed information about the study, signed their informed consent, and provided their personal data. Afterwards they underwent the first alertness test, which was preceded by a pre-test to ensure that the participants understood the task. Thereafter, they were instructed about the subsequent memory task (encoding), went through a training run, filled out the first affect rating (R1) and provided their first saliva sample (S1). Next participants went through the encoding task, filled out the affect rating again (R2), provided a second saliva sample (S2) and answered a final questionnaire (Flow Short Scale – FKS; (Rheinberg et al., 2019); not analyzed here).

For the second testing session, participants came back to the identical laboratory 48 h later. Testing sessions in the morning group started between 8.00 and 10.00 am, while sessions in the evening group started between 4.00 and 6.00 pm. Again, in a first step, participants' personal data was surveyed, followed by a first alertness test, the instruction for the memory paradigm (recognition) and a training run. Thereafter, the first affect rating (R3) as well as the first saliva sample (S3) of the day were provided, participants underwent the first recognition task and handed in a second affect rating (R4) as well as a second saliva sample (S4). The participants then had to fill out a series of questionnaires: surveying daytime sleepiness (Epworth Sleepiness Scale - ESS; Johns, 1994), chronotype (MCTQ: Roenneberg et al., 2003; MEQ: Horne and Ostberg, 1976) as well as trait anxiety (the State-Trait Anxiety Inventory – Trait (STAI-T); Spielberger et al., 1983), symptoms of depression, anxiety and somatization (Brief Symptom Inventory (BSI); Derogatis and Melisaratos, 1983). To bridge the time before the next memory task, participants then watched the same neutral videos we used previously (see Pötzl et al., 2023) before conducting the second alertness test, going through a second training run of the recognition task and providing a third affect rating (R5) and saliva sample (S5). Afterwards participants conducted the second recognition task, provided a last affect rating (R6) and saliva sample (S6) for a last time.

2.8. Data analysis

The statistic software R version 4.1.3 (2022–03–10) and MATLAB R2020b (Natick, Massachusetts: The MathWorks Inc.) were used to analyze the data. In case of non-normally distributed data, the packages WRS (Wilcox, 2012) and WRS2 (Mair and Wilcox, 2020) were applied to conduct robust analyses, based on sample trimmed means as before (Pötzl et al., 2023). Both packages allow for analyses discarding a defined percentage of data (20 %) at both ends of the distribution, preventing a high degree of variability obscuring statistics. Most of the analyses were conducted using the latest WRS package (WRS2; 2-way ANOVA, ANCOVA, regression analyses and Yuen-Welch tests; Mair and Wilcox, 2020). As the previous version (WRS package; Wilcox, 2012) additionally provides the possibility to conduct 3-way ANOVA, the valence*sex*group interactions were conducted using this package.

For significance testing we used the standard $p < .05$ criterion. For analyses of variance (ANOVA) we calculated effect sizes using partial Eta Squared (η_p^2), while for comparisons between independent samples we used Hedges g (g_s; Lakens, 2013).

Influence of time of day on cortisol release and subjective affect was investigated via a robust mixed ANOVA for salivary cortisol levels and

affect ratings (positive and negative affect) separately for day one and two, using the within-subjects factor Time (day one: before vs. after encoding; day two: before recognition one, after recognition one, before recognition two, after recognition two) and the between-subjects factor group (morning vs. evening).

For encoding on day one, we used a robust two-way mixed ANOVA to investigate differences in valence ratings of the stimuli between groups. Recognition performance was assessed based on the signal detection model (Snodgrass and Corwin, 1988) using the sensitivity index (d-prime: d′), which depicts the ability to discriminate between old and new stimuli, and the bias index (C), which is an indicator of the participants bias to rate an item as old. Additionally, recollection (r0) and familiarity (dF) were calculated based on the dual-process signal detection model (Yonelinas, 2002) by means of the receiver operating characteristics (ROC) - Toolbox (Koen et al., 2017). Memory performance was assessed using robust mixed ANOVA separately for recognition one and two including the within-subjects factors valence and sex as well as the between-subjects factor group.

Alertness on day one was analyzed separately for mean and median reaction time of intrinsic and phasic alertness as well as for the parameter of phasic alertness between groups using separate Yuen-Welch tests. The parameter of phasic alertness represents the difference between the mean (or median respectively) of reaction times of intrinsic (block without auditory cue) and phasic alertness (block with auditory cue) providing information about the positive influence of the auditory cue. This parameter describes the corrected measure of phasic alertness. Since all participants reacted correctly to the stimuli (ceiling effect), differences for correct reactions could not be analyzed. For day two, robust mixed ANOVA with the within-subjects factor time (before recognition one vs. before recognition two) and the between-subjects factor group was conducted for all alertness variables.

We further investigated the area under the curve with respect to ground (AUC_g) to incorporate all saliva measurements on day two in one measure (Pruessner et al., 2003). The AUC_g is used as a salivary cortisol measure in correlations with significant memory variables. Further variables associated with significant memory variables were alertness as well as affect scores, chronotype (MEQ), hours of sleep and daytime sleepiness (ESS). Furthermore, chronotype and average sleeping behavior (ESS & MCTQ) as well as hours of sleep before the testing were exploratively analyzed and compared between groups using Yuen-Welch tests.

As we found pre-existing group differences in the hours of sleep on day two and general daytime sleepiness ratings, additional explorative (non-pre-registered) analyses were performed on these two variables. Both ANCOVA with inclusion of these variables as covariates in previously significant analyses and the inclusion of these variables in the significant regression can be found in Sections 3.7 and 3.9.

3. Results

3.1. Participant characteristics

The morning and the evening group did not differ in age ($Y_{t(27.61)} = 0.69$, $p = .495$) and BMI ($Y_{t(28.72)} = 0.06$, $p = .95$). Additionally, both groups did not differ in psychological symptoms according to the BSI (all $p > .05$) or STAI-T (trait anxiety; $p > .05$).

3.1.1. Sleep

On average, participants in the morning group had been awake for 1.15 h ($SD = 0.42$) before the start of testing, while the evening group had been awake for 7.92 h ($SD = 1.05$). For day two (but not for day one; $p = .45$), groups differed significantly for hours of sleep ($Y_{t(26.24)} = 4.76$, $p < .001$, $g_s = 1.15$, 95 % CI [−1.80, −0.60]), such that the evening ($M = 8.15$; $SD = 1.20$) group slept significantly longer than the morning group ($M = 6.96$; $SD = 0.80$). However, robust regression analyses revealed that significant memory effects (see Section 3.6) did not correlate with sleeping hours (all $p > .05$). We also controlled for the general likelihood of daytime sleepiness by means of the ESS. Groups differed significantly for the ESS scores ($Y_{t(24.15)} = 3.02$, $p < .05$, $g_s = 0.74$, 95 % CI [−5.16, −0.64]): the morning group ($M = 5.23$; $SD = 3.32$) showed lower levels of daytime sleepiness in comparison to the evening group ($M = 8.08$; $SD = 4.27$). Overall, daytime sleepiness was quite low and ordinary (Johns, 1991). Also, for this measure a robust regression analyses demonstrated that significant memory effects (see Section 3.6) did not correlate with ESS ratings (all $p > .05$).

3.1.2. Chronotype

Based on insufficient and unequally distributed data for the morning or evening chronotype in each group, we could not conduct multivariate analyses for the chronotype measures MEQ and MCTQ. Therefore, for the MEQ, we conducted robust correlation analyses based on the continuous ratings of the chronotype measure. For all significant memory measures (see Section 3.6) we did not find any correlation with the chronotype ratings overall or within each group (all $p > .05$). With the help of the MCTQ we additionally analyzed if typical sleeping behavior for workdays and for non-working days differed between both groups. Results revealed that groups differed neither for average sleep onset, sleep duration, mid sleep or sleep loss of workdays and non-working days, nor for the MSF_{sc} used as a measure of chronotype (all $p > .05$; see Section 2.6).

3.2. Endogenous cortisol levels

For day one, a robust mixed ANOVA resulted in a significant main effect of time ($F_{(1,22.76)} = 13.55$, $p < .005$, $\eta_p^2 = 0.18$) reflecting higher cortisol levels for the first saliva sample ($M = 5.05$; $SD = 3.09$) in comparison to the second sample ($M = 4.30$; $SD = 2.80$) across groups according to the circadian rhythm. For day two, there was a main effect of time ($F_{(3,13.68)} = 14.32$, $p < .001$, $\eta_p^2 = 0.24$), group ($F_{(1,16.83)} = 88.72$, $p < .001$, $\eta_p^2 = 0.28$) as well as a time*group interaction ($F_{(3,13.68)} = 7.47$, $p < .005$, $\eta_p^2 = 0.06$) revealing significantly higher saliva cortisol measures for the morning versus the evening group at all time points, as well steeper decrease in the morning, versus the evening group (see Fig. 2). Putting the saliva samples together in the AUC_g revealed identical results, thus, higher cortisol output in the morning ($M = 524.55$; $SD = 236.76$) compared to the evening group ($M = 191.11$; $SD = 236.23$) only for day two ($Y_{t(16.56)} = 8.46$, $p < .001$, $g_s = 1.38$, 95 % CI [200.31,466.57]).

3.3. Affect ratings

For positive affect, robust mixed ANOVA revealed no significant

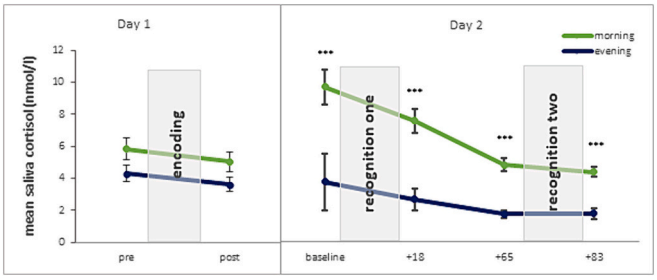

Fig. 2. Mean salivary cortisol concentrations depicted at distinct time points at day one and two. Memory encoding and both recognition phases are depicted in gray. Endogenous cortisol levels were significantly higher for the morning (versus the evening) group during both recognition phases. Please note that the analyses were conducted with trimmed mean values (according to: Mair and Wilcox, 2020; Wilcox, 2012), thus excluding extreme values. The figures may therefore deviate slightly from the data in the final analyses. Error bars represent standard errors of the mean. ** $p < .001$.

differences on day one (all $p > .05$), but a main effect of time on day two ($F_{(3,23.30)} = 4.83$, $p < .05$, $\eta_p^2 = 0.10$), depicting a decrease of positive affect over time independent of group assignment. For negative affect, a main effect of time on day one was determined ($F_{(1,29.65)} = 5.27$, $p < .05$, $\eta_p^2 = 0.10$), reflecting a decline of negative affect across both groups. On day two, a significant main effect of group was observed ($F_{(1,27.31)} = 4.90$, $p < .05$, $\eta_p^2 = 0.09$), indicating significantly higher negative affect ratings for the evening in comparison to the morning group.

3.4. Alertness

Robust mixed ANOVA revealed no effects for reaction times of intrinsic alertness as well as phasic alertness (all $p > .05$ for mean and median reaction times for the three time points between both groups). For the parameter of phasic alertness there was a group*time interaction effect ($F_{(2,28.06)} = 3.48$, $p < .05$, $\eta_p^2 = 0.06$), such that for time point 1 (alertness before encoding) only, the evening group benefited more from the auditory cue than the morning group ($Y_{t(26.72)} = 3.10$, $p = .005$, $g_s = 0.49$, 95 % CI [−0.065, 0.004]). No other than the reported main effects were observed.

3.5. Encoding

For the valence ratings during encoding, a robust mixed ANOVA revealed a main effect of group ($F_{(1,25.14)} = 6.09$, $p < .05$, $\eta_p^2 = 0.12$) as well as a main effect of valence ($F_{(1,21.64)} = 227.73$, $p < .001$, $\eta_p^2 = 0.88$). Overall, faces were rated more positively in the evening compared to the morning group. Irrespective of group allocation, positive stimuli were rated significantly different in comparison to negative and neutral stimuli (all $p < .001$), ratings for negative stimuli were significantly different from neutral stimulus ratings ($p < .001$). Happy faces were rated most positively ($M = 5.78$, $SD = 0.75$), while angry faces were rated most negatively ($M = 2.19$, $SD = 0.67$) and neutral faces were averaged between those two ratings ($M = 3.94$, $SD = 0.30$).

3.6. Memory recognition

3.6.1. D-prime

For d-prime, a robust mixed measures 3-way-ANOVA (valence*-sex*group) revealed a trend significant valence*group interaction ($p = .08$) for recognition one An exploratory narrowed two-way ANOVA resulted in a significant valence*group interaction ($F_{(2,57.33)} = 3.33$, $p < .05$, $\eta_p^2 = 0.15$; see Fig. 3) providing an indication that positive faces tended to be better remembered in the morning vs. the evening group during recognition one ($Y_{t(53.93)} = 2.23$, $p < .05$, $g_s = 0.61$, 95 % CI [0.20, 0.90]). For recognition two, no significant effects were observed.

3.6.2. Bias index (C)

For the bias index, a robust mixed measures ANOVA depicted a main effect of sex ($F_{(1,86.30)} = 6.61$, $p < .05$, $\eta_p^2 = 0.16$) for recognition one. Male faces were processed via a lower bias level than female faces independently of group assignment, indicating that male faces were more likely to be rated as old in comparison to female faces. For recognition two, no significant effects were found.

3.6.3. Familiarity

For recognition one, a robust mixed measures ANOVA revealed no significant effects. For recognition two, a significant stimulus sex*group interaction emerged ($F_{(1,89.96)} = 4.86$, $p < .05$, $\eta_p^2 = 0.07$) revealing that female faces (but not male) were more often recognized via familiarity in the morning group in comparison to the evening group ($p < .05$; see Fig. 3).

3.6.4. Recollection

For recognition one, no significant effects for recollection measures occurred (all $p > .05$). For recognition two, a trend significant ($p = .084$) main effect of group was observed for the three-way ANOVA (valence*sex*group). According to this, faces showed a tendency of being generally better recognized via recollection in the morning vs. the evening group in the second recognition phase (see Fig. 3).

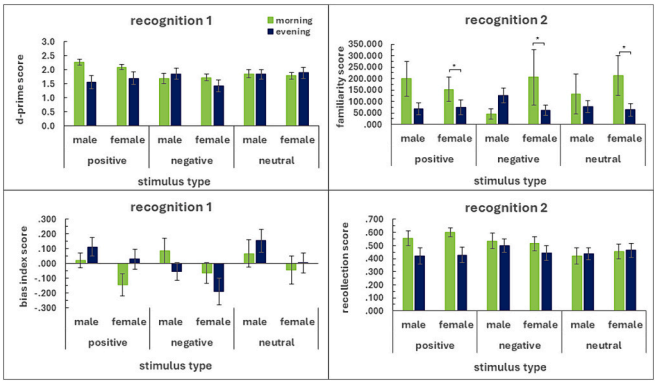

Fig. 3. Mean performance scores for the memory measures d-prime d′ (A), familiarity dF (B), bias index (C) and recollection r0 (D). All raw memory scores are depicted separately for stimulus valence and sex as well as both recognition phases. Since applied analyses are based on trimmed sample means, diagrams might slightly differ from the mentioned results. D-prime (A) as well as recollection (C) ratings only revealed trend significant effects, such that the morning group showed higher d-prime ratings for positive faces during recognition one, while the same group exhibited overall better recollection ratings during recognition two. The most prominent effect was observed for familiarity ratings, which were significantly higher in the morning (versus the evening) group during recognition two. Please note that the analyses were conducted with trimmed mean values (according to: Mair and Wilcox, 2020; Wilcox, 2012), thus excluding extreme values. The figures may therefore deviate slightly from the data in the final analyses. Individual data points can be derived from the Supplemental Fig. 1. Error bars are standard errors of the mean. * $p < .05$.

3.7. Influence of hours of sleep and daytime sleepiness on significant memory results

To control for the presumable influence of the pre-existing differences in hours of sleep (on day two) and daytime sleepiness ratings (ESS), we conducted ANCOVA using the car package in R. ANCOVA were only conducted for the significant or trend significant results (i.e.: interaction of recognition of positive faces via d-prime (recognition 1) and group (morning vs. evening); interaction of recognition of female faces via familiarity (recognition two) and group (morning vs. evening)).

The results can be derived from Tables 1 and 2 in the supplements. Overall, previously significant memory recognition performance effects between groups persisted when controlling for hours of sleep on day two (see Supplemental Table 1). For ESS ratings significant group effects persisted for d-prime ratings of positive faces during recognition 1 and familiarity ratings of female faces during recognition 2, but not for overall recollection ratings during recognition 2 (see Supplemental Table 2). Since it was not possible to conduct robust analyses for this approach, these exploratory results should be interpreted with caution, pre-existing effects cannot be completely ruled out.

3.8. Interaction of cortisol or alertness and memory performance

To get a deeper insight into interrelations of relevant constructs observed here, we conducted robust regression analyses for significant and trend significant memory measures (see Section 3.6), temporally matching alertness (plus the parameter of phasic alertness before encoding) as well as mean or median reaction times of intrinsic and phasic alertness and cortisol measures (AUC_g cortisol level on day two (AUC_{g2})). We used z-transformed variables to determine which of the

two predictors (cortisol or alertness) had a greater influence on the outcome variable memory performance. Both predictors were always included together in each model. Only significant regressions will be reported.

Significant results were only found for the outcome variable overall recollection performance during recognition two. Here, both mean and median reaction times of phasic alertness before recognition two as well as AUC_{g2} predicted memory performance. Indeed, especially higher cortisol levels but also to a lesser degree shorter mean reaction times of phasic alertness predicted higher memory performance (mean: $R^2 = 0.126$, $F_{(2,\ 47)} = 7.29$, $p < .05$; median: $R^2 = 0.137$, $F_{(2,\ 47)} = 8.07$, $p < .05$). When including the predictor intrinsic alertness, slightly different results occurred: shorter mean reaction times of intrinsic alertness predicted memory performance to a higher degree than higher cortisol levels ($R^2 = 0.181$, $F_{(2,\ 47)} = 11.02$, $p < .01$), while for median reaction times the influence of alertness was lower in comparison to cortisol ($R^2 = 0.153$, $F_{(2,\ 47)} = 8.95$, $p < .05$).

Thus, especially cortisol, but also alertness predicted recollection performance for recognition two. No further significant regressions were observed.

3.9. Interaction of sleep, cortisol and memory

Including the variables hours of sleep on day two as well as the measure of daytime sleepiness (ESS ratings) into the regression analysis of AUCg cortisol and the overall recollection ratings during recognition 2 resulted in a persistent significant effect for AUCg cortisol throughout the groups (both $p < .05$). Thus, the significant correlation between cortisol and memory recognition via recollection ratings on day two does not appear to be influenced by the differences in the hours of sleep or presumed daytime sleepiness across the morning and the evening group.

3.10. Interaction of affect and memory performance

Finally, we conducted robust regression analyses for significant memory measures (see Section 3.6) and negative as well as positive affect ratings before respective memory tests between groups. However, we found no significant correlation between negative or positive affect and memory performance (all $p > .05$).

4. Discussion

In this study, we assumed and confirmed that time of day can have an impact on recognition performance for faces. During recognition one, especially positive faces (via d-prime ratings) and during recognition two, all types of faces (via recollection ratings) showed a tendency of being better recognized by the morning group in comparison to the evening group. However, as these trends were not significant, the results must be interpreted with caution. Most prominently, during recognition two, especially female faces were significantly better identified via familiarity ratings in the morning.

Salivary cortisol levels in the current study were on the one hand significantly higher in the morning in comparison to the evening as described in the literature stating a cyclic release of glucocorticoids like cortisol following a circadian rhythm (Dickmeis, 2009; Koch et al., 2017; Oster et al., 2017). On the other hand, salivary cortisol levels during recognition two also correlated with the recollection of face stimuli at that time point, even when controlling for sleep time and general sleepiness, although pre-existing effects cannot be completely ruled out.

Still, the results hint to our initial hypothesis suggesting that recollection ratings in particular could be related to the cortisol secretion throughout the day. Yet, further investigations are necessary to draw more detailed conclusions. However, contrary to our hypothesis is the fact that the differences in memory performance between the two groups were generally most pronounced in the assessment of familiarity. Still, previous studies have also shown that increased cortisol levels can be associated with memory in the context of familiarity (McCullough et al., 2015; van Ast et al., 2014; Wiemers et al., 2019; Yonelinas et al., 2011). The extent to which memory processes are subject to recollection or familiarity, and the extent to which valence- or sex-specific information is processed differently as a result, must be investigated in future research. It is conceivable that in the context of high cortisol levels during recognition one, emotional processes are more strongly affected by increased amygdala activity (Gagnon and Wagner, 2016; which in turn could reflect the tendency of better processing of positive stimuli) than in the context of moderately increased cortisol levels (cf. Fig. 2) during recognition two (better processing of female faces). Ultimately, however, it is not possible to conclusively explain the effects without over-interpreting the results.

Interestingly, the effect of improved memory retrieval for female faces in the context of enhanced cortisol levels replicates the results of a prior study using the same paradigm, albeit not including different times of day, but a psychophysiological stressor to approach differentially increased saliva cortisol levels before retrieval (Pötzl et al., 2023). In both studies, higher cortisol levels were correlated with significantly better recognition of female faces. Since the circadian rhythm is influenced by many additional factors, the results cannot be extrapolated one-to-one. Nevertheless, this pattern could indicate that cortisol might be of great importance in both cases.

In addition, we examined the influence of attention on time-of-day dependent memory recognition performance. Admittedly, neither intrinsic nor phasic alertness differed between groups at any time point. The fact that recognition performance was affected by time of day, while alertness was not, could be explained by the assumption that simple cognitive processes might be less influenced by the circadian rhythm than more complex processes (Gessner et al., 2022). Nonetheless, mean reaction times of intrinsic alertness seemed to be associated with recollection performance during recognition two. Therefore, it is still likely that not only cortisol, but also the level of attention might have an influence on memory performance.

Considering our prior study (Pötzl et al., 2023), the question arises as to how the same pattern of results can be explained. With focus on overlapping factors, the most apparent similarity between both studies is the cortisol level before memory retrieval in the respective groups. In the prior study, the stress group, which revealed significantly better memory performance for female faces (d-prime and familiarity), displayed a delta mean cortisol level of 5.08 nmol/l before retrieval. In the present study, the cortisol level before retrieval was comparable (5.16 nmol/l). It is striking that these effects were not seen for the other respective time points when cortisol levels were either higher (first recognition phase in the present study) or lower (second recognition phase in the prior study). This reinforces the assumption that the amount of cortisol release is crucial for the activation of mineralocorticoid (MR) and glucocorticoid (GR) receptors and the subsequent effects on respective brain areas (Oster et al., 2017). In line, presumably mainly the activation of MR receptors resulted in improved memory retrieval in both studies, leading to enhancement of behavioral reactivity and response selection as well as maintenance of hippocampal excitability (de Kloet et al., 2000). Furthermore, several studies revealed that the hippocampus, especially the CA2 area of the hippocampus, is crucial for social memory and novelty processing (Kogan et al., 2000; Tzakis and Holahan, 2019). Since MR receptor expression is highest in this hippocampal subfield (McCann et al., 2021), it is plausible that especially highly social stimuli (as for instance faces) are influenced by mildly elevated cortisol levels. Additionally, effects were specifically observed for stimulus sex (in comparison to stimulus valence), which can be explained by the assumption that not only valence and arousal, but also motivational relevance of a stimulus supposedly has a strong impact on memory performance (Larson and Steuer, 2009). Triggered by the social (party) context in which memory tests took place, it is conceivable that sex of the stimulus had a greater semantic relevance than the

emotionality of the facial expression. Since we did not ask the participants for sexual orientation or evaluation of attraction for the face stimuli, this assumption remains to be confirmed in future studies. However, investigating only the valence of the stimulus in this context might not be enough to disentangle these effects. If the sex of a face stimulus specifically is governing these effects remains to be investigated in the future. Another explanation for these results might be found in the distinctiveness of prosocial behavior, already shown in previous stress studies (Taylor et al., 2011; von Dawans et al., 2012). Can the pattern of searching for social support, which has been shown in some stress studies, also be applied to endogenous cortisol levels during the circadian rhythm? Certainly, both contexts are not entirely comparable, still there are studies hinting to prosocial behavior being more pronounced in the morning in comparison to the evening (Francis et al., 2021; Kouchaki and Smith, 2014), leading to the suggestion that also here cortisol might be relevant. Accordingly, within the party context in which the memory paradigm is embedded, the enhanced memory for faces would constitute a social advantage, evoked by enhanced cortisol levels.

Furthermore, our data revealed some results which might raise the assumption of additional impact factors on recognition results. For instance, the ability to increase the general level of attention on a short-term (measure of phasic alertness) during encoding was significantly higher for the morning in comparison to the evening group. Nevertheless, this measure did not correlate with any of the observed memory effects and no further effects of intrinsic or phasic alertness during encoding or recognition emerged. The general probability of daytime sleepiness was significantly increased for the evening in comparison to the morning group, however, this probability did not relate to the specific situation, but to recent everyday situations. Further, no other measures (alertness, affect, chronotype questionnaires or information of sleep timing) hint to a higher sleepiness during memory recognition in the evening in comparison to the morning group. Importantly, measures of daytime sleepiness did not correlate with memory recognition performance. However, when controlling for sleepiness ratings in the context of group comparisons, the influence of daytime sleepiness could not be completely ruled out. It is therefore possible that participants' sleepiness as well as the sleep times had an influence on memory performance. Future studies should investigate these variables in more detail, e.g. by experimentally manipulating them. Needless to say, it is possible that other factors besides cortisol and attention additionally influenced memory performance. Yet we tried to keep as many variables as possible, such as lighting conditions in the testing room, sleeping quality and nutrition, comparable between groups.

Eventually, conclusions about the underlying causes require further investigations in the future. In addition, future studies should consider sex hormones as a fundamental influencing factor (Jentsch et al., 2022; Merz and Wolf, 2017) as well as other hormones which are essential for the circadian rhythm, such as melatonin (Rawashdeh and Maronde, 2012). Also, the cortisol awakening response and cortisol daytime profiles, which have not been investigated here, could give more detailed insights into the circadian response (Ennis et al., 2016). Finally, neuronal correlates of relevant brain areas such as the hippocampus should shed light on underlying neural processes (Eckel-Mahan and Storm, 2009; Li et al., 2015, 2014; Tsukiura, 2012).

5. Conclusion

Overall, time of day seems to have an impact on memory recognition of faces. The similarity to the results of a study using the same design in a stress context, hint to the fact that cortisol might be a relevant player when investigating those effects. However, since the circadian rhythm is very complex as well as mediated by many factors, further investigation is necessary to draw conclusions about underlying mechanisms. We further advocate a distinguished examination of stimulus types, especially regarding social stimuli, as well as the consideration of the extent of cortisol release and the influence of sex hormones. The results could provide important implications for all kinds of daily social encounters as well as eyewitness interviews.

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CRediT authorship contribution statement

Lisa Pötzl: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Oliver T. Wolf:** Writing – review & editing, Methodology, Conceptualization. **Christian J. Merz:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

None.

Data availability

The data that were used in this study are openly available on the homepage of the OSF and can be accessed via the following link: https://osf.io/sbymu/?view_only=039172b82ba94d3992aae88fbf7b2a88.

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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.2024.105633.

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