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Testing the modulation of self-related automatic and others-related controlled processing by chronotype and time-of-day

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ABSTRACT

We assessed whether self-related automatic and others-related controlled processes are modulated by chronotype and time-of-day. Here, a shape-label matching task composed of three geometrical shapes arbitrarily associated with *you*, *friend*, and *stranger* was used. Twenty Morning-types, and twenty Evening-types performed the task at the optimal and non-optimal times of day (i.e., 8 AM, or 8:30 PM). Morning-types did not exhibit noticeable synchrony effects, thus proving the better adaptation of these participants to non-optimal moments of the day as compared to Evening-types. Contrary to our predictions regarding the absence of automatic-processing modulation and the presence of controlled-processing influences by time-of-day, we found an influence on self-related but not others-related processing only in Evening-type participants. Although brain structures are not directly tackled, we argue that such modulation may be due to the dependence of the activation of the ventromedial prefrontal cortex (VMPFC), an essential component of the self-attention network on circadian rhythms.

1. Introduction

There are numerous studies demonstrating processing advantage when information from the environment is related to oneself. Thus, when we perceive self-related cues, such as hearing our name or seeing our face, our attentional focus is automatically directed to those stimuli, while other information not associated with oneself is processed in a more controlled way. This effect is known as the Self-Prioritization Effect (SPE; for a review, see Cunningham & Turk, 2017). The SPE is purely adaptive in nature, as it leads individuals to not ignore cues that genuinely concern them (Cunningham, 2016; Cunningham et al., 2013; Klein, 2012). This prioritization scheme in processing information relevant to oneself has been robustly evidenced at both behavioral and neural levels.

At the behavioral level, the SPE is described as a performance advantage that is reflected in faster reaction times (RTs) and/or higher rates of accuracy in processing self-related information compared to information related to others. Specifically, this effect has been observed in a variety of cognitive tasks involving various cognitive domains such as attention (Arnell et al., 1999; Dalmaso et al., 2019; Liu et al., 2016; Shapiro et al., 1997; Sui et al., 2009; Sui & Han, 2007; Martínez-Pérez et al., 2024), memory (Conway & Pleydell-Pearce, 2000; Cunningham et al., 2008; Kesebir & Oishi, 2010; Rogers et al., 1977), working memory (Yin et al., 2019), and

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decision-making (Humphreys & Sui, 2015; Keyes & Dlugokencka, 2014; Ma & Han, 2010; Sui & Han, 2007). In addition, the SPE has been related to simpler cognitive operations, such as perceptual matching. In this regard, Sui et al., 2012, developed an unbiased approach to assess the SPE that begins with learning the association between three different geometric shapes (e.g., "circle", "square" and "triangle") with three labels related to the self (you), a close person (friend), or an unknown person (stranger). Subsequently, both the geometric shapes and the labels are presented in pairs to the participants, who have to judge whether or not the current pair is correct based on the associations they have previously learned. Results commonly observed using this shape-label matching task reflect an SPE in both shorter reaction times (RTs) and better accuracy rates for stimuli previously associated with the self (you), compared to friend- and stranger-related associations (Dalmaso et al., 2019; Desebrock et al., 2018; Liang et al., 2022; Martínez-Pérez, Campoy, et al., 2020). Moreover, this task is shielded from other variables potentially linked to SPE, such as the familiarity, concreteness, frequency, or length of the words used (Humphreys & Sui, 2015; Sui et al., 2012).

At the neural level, different studies have addressed the neural circuit related to the self. For example, in the *meta*-analysis conducted by Denny et al., (2012) the results highlighted the role of the medial prefrontal cortex (MPFC) in both self- and others-related judgments. Furthermore, these authors linked the ventromedial prefrontal cortex (VMPFC) to self-related judgments, while the dorsolateral prefrontal cortex (DLPFC) would be activated during judgments related to others. Sui et al., (2013) conducted a functional magnetic resonance imaging (fMRI) study using the aforementioned perceptual matching task and observed that self-associated stimuli involved the activation of the VMPFC, while those related to friend and stranger (others) involved activation of the DLPFC. These areas, together with the left posterior superior temporal sulcus (LpSTS) and the intraparietal sulcus (IPS), were assumed to be part of the self-attention network (SAN; Humphreys & Sui, 2015), forming the VMPFC and the LpSTS the ventral attentional part of the network, and the DLPFC and the IPS its frontoparietal attentional part. The ventral network would activate in self-related stimulus processing, automatically driving one's attention to that type of stimuli. In contrast, the frontoparietal network is typically associated with goal-related task demands, and the network activation should increase with more complex tasks. Importantly, the two networks should be inversely related: as the processing of stimuli requires more control (self → friend → stranger), activation would move from the ventral to the frontoparietal network.

In the present study, we asked whether the processing of stimuli associated with oneself, which is assumed to draw attention in a rather automatic way, and the processing of stimuli related to others, which is assumed to require cognitive control, can be differently modulated by variations in circadian-rhythm patterns. In this regard, we approach an individual-differences circadian trait known as *chronotype* in conjunction with the time of day in which the cognitive assessment takes place. Thus, the chronotype is described as the difference in the preference individuals develop for performing their daily life activities and resting connected to specific time slots throughout the day (Levandovski et al., 2013; Schmidt et al., 2007). The assessment of this trait allows individuals to be classified into different circadian profiles. Individuals who do not develop any circadian preference form the intermediate chronotype, while by extreme chronotypes we mean those individuals who show a clear preference for a time of day for their daily activities. Morning-types prefer to perform their activities in the early morning, while Evening-types prefer to perform their activities late in the day. Thus, it is possible to obtain indices of the cognitive performance of individuals at their optimal and non-optimal times depending on their chronotype. The effect commonly observed using this paradigm is called the *synchrony effect* and refers to the improvement in performance when it occurs at the time of day that coincides with the participants' preference, while deterioration arises when the time of day is the opposite of their chronotype. This synchrony effect has been demonstrated not only at the behavioral level but also at the level of cortical activation. For example, Salehinejad et al., (2021) reported cortical arousal/inhibition balances congruent with optimal and non-optimal times, respectively, for both Morning- and Evening-type chronotypes.

The relevance of looking at chronotype and time-of-day as potential modulators of stimuli associated with self or others is that automatic processes are less vulnerable than controlled processes to the low levels of arousal that characterize non-optimal times-of-day (Lara et al., 2014; Manly, 2002; May et al., 2005; although see (Palmero et al., 2024), for some evidence of chronotype and time of testing modulation of automatic processing). Here, we set out to determine whether automatic processing related to self and controlled processing related to others (friend and stranger), as commonly observed in the perceptual matching task (Sui et al., 2012), can be modulated, on the one hand, by the time of day. In this sense, we are concerned with the study of synchrony effects (i.e., the difference in performance between optimal and non-optimal times of day), which we hypothesize will be more noticeable in the processing of stimuli requiring a larger involvement of control resources. Thus, whereas the processing of self-related stimuli should resist the interference in performance produced by being off-optimal time, as compared to the optimal time of day (i.e., expected lack of synchrony effects), the processing of others-related stimuli (i.e., from friend-, to stranger-related associations), conversely, will be shaped by a time-of-day modulation (i.e., emergence of synchrony effects). Moreover, given the continuum in the development of cognitive-control-based responses, we expect the time-of-day to cause larger impairments of performance when processing stranger-related stimuli than when friend-related stimuli are processed at non-optimal time-of-day. On the other hand, beyond the time-of-day effects, we explored the eventual modulation by the chronotype on the expected synchrony effects. In this line, it is important to highlight that previous research has revealed that Morning-types performance is usually more constant and invariable throughout the day compared with Evening-types performance, nuancing the synchrony effects that are often reported. As such, certain authors have posited that, likely, Morning-types are more sensitive than Evening-types to factors that increase their arousal levels even at their non-optimal time-of-day (Correa et al., 2014; Martínez-Pérez, Palmero, et al., 2020; Mongrain et al., 2008; Palmero et al., 2022). Consistent with this, in a previous study in which we evaluated the time course of the semantic priming effect (Palmero et al., 2024), time-of-day was found to modulate automatic semantic processing only in Evening-types, whereas Morning-types where not affected in any case by time of day. Therefore, it is likely that the expected modulatory effects described before may differ between the two extreme chronotypes, if so, reinforcing the results obtained in this preliminary study. In addition to the above finding, the time-course analysis revealed that Evening-types were significantly poorer than Morning-types in the consistent application of strategies based on cognitive control. Namely, they overused automatic responses far more in control-demanding scenarios, were less accurate, and tended to be slower in initiating control-based responses specifically when tested at their non-optimal times. Such an issue calls directly to the convenience of further exploring not only the overall differences in both modes of processing but also linked to specific RTs that may vary as a function of chronotype and time of day, an aspect that we still approach in the present work. One of the techniques enabling this analysis is the bin-means analysis (Houghton & Grange, 2011). Furthermore, from an individual differences perspective, it is proposed to be even more meaningful to examine the complete distribution of RTs since each individual possesses a unique response manner usually reflected in cognitive assessment (Balota & Yap, 2011), which tends to be rather stable over time (Yap et al., 2012).

We finally envisaged the possibility that chronotype and time-of-day do not produce differential modulatory effects according to the type of processing required (self-related or others-related processing), but rather participants are simply more effective at responding when they perform the task at their optimal moment compared to when they perform it at their non-optimal moment. If that were the case, we should observe an advantage when participants perform the perceptual matching task at their optimal time-of-day (i.e., a standard synchrony effect), irrespective of the kind of shape/label pair they are presented with.

2. Methods

2.1. Participants

Our sample was composed of forty healthy undergraduate volunteers (32 females, $M_{age} = 21.14$; $SD_{age} = 5.45$) selected from a previously elaborated database of 106 participants classified according to the scores obtained in the reduced version of the Horne and Östberg's Morningness- Eveningness Questionnaire (rMEQ) standardized by (Adan & Almirall, 1991) for the Spanish population. The rMEQ consisted of five items to easily evaluate a participant's chronotype, with total scores ranging from 4 (definitively Evening-types) to 25 (definitively Morning-types). Twenty participants who met the criteria of definite Morning- (scores between 17 and 25, M = 18,50, SD = 1.60), and 20 Evening-types (scores between 4 and 11, M = 9.25 SD = 1.68), were summoned to participate. They all received course credits as compensation for taking part in the study. Both Intermediate-types and those with relevant psychological/medical conditions or under any treatment were not part of the experimental sample.

2.2. Apparatus, stimuli, and procedure

Participants completed two sessions separated by approximately one week. The sessions were scheduled at 8:00 AM (morning session) and at 8:30 PM (evening session). The order of the sessions was balanced across participants within each chronotype group such that half of the Morning-types came to the lab in the first session at their optimal time of day and the other half at their non-optimal time of day, and the same for the Evening-type participants. Participants were previously requested not to take any stimulant substance such as caffeine or theine in the 2 h before the beginning of their sessions. Each experimental session had the same structure and duration (1 h approximately). Participants were asked about the hours of sleep the night before the experimental session to ensure that they were not sleep deprived (all of them reported having slept at least five hours as instructed), and then began with the Psychomotor Vigilance Task (PVT, Lim & Dinges, 2008), which was used for the sole purpose of ensuring the correct selection of our sample through rMEQ. The PVT has proven to be a fairly sensitive task to the oscillation of vigilance produced by variations in circadian rhythms as those produced by the chronotype (Blatter & Cajochen, 2007; Schmidt et al., 2007). Participants ended up performing the shape-label matching task (Sui et al., 2012). In between, participants performed another cognitive task described in a separated study. In the PVT (10 min duration), each trial started with a blank screen during a random interval between 2 and 10 s. Then, a red circle of 50 pixels in diameter popped up at the center of the screen. Participants had to press the central button of the Chronos device with the index finger of their dominant hand as quickly as they detected the red circle. After responding, the screen became black, and a new trial began. The shape-label matching task (14 min approximately) was equivalent to that used by Sui et al., (2012) (Experiment 1) and (Martínez-Pérez et al., 2020) and was composed of two phases. Participants first were verbally asked to remember for 1 min the associations between three geometric shapes (triangle, circle, and square) and three verbal labels (*you*, *friend*, or *stranger*). The six plausible shape-label associations were counterbalanced across participants and equally represented in each chronotype group. Also, it is important to note that participants completed the task in the same counterbalanced group in both sessions (i.e., the specific shape-label combination remained unchanged in both their optimal and non-optimal times of day according to their chronotype). In the second phase, participants performed a matching task in which they had to judge whether the different shape-label pairs matched or not the previously given associations. Each trial started with the presentation of a 500-ms central fixation cross. Suddenly, a shape and a label were simultaneously presented above and below the fixation cross for 100 ms, followed by a blank-1100 ms screen in which participants must give a response. In this line, participants had to indicate whether the shape-label pairs matched or mismatched by pressing as quickly and accurately as possible one of two response buttons (the rightmost button or the leftmost button of the response box, respectively). Then, a feedback message ("correct" or "incorrect") appeared during 500 ms and a new trial began. Each participant completed five blocks of 48 trials. Each block was composed of 8 trials for each shape-label combination (you-matched, you-nonmatched, friend-matched, friend-nonmatched, stranger-matched, and stranger-nonmatched) presented in random order. Participants completed a practice block of 48 trials with the same distribution as the experimental ones. With a view distance of 60 cm, the three geometrical shapes subtended visual angles of 4° × 4° approximately and were presented above a fixation cross (1° × 1°). The Spanish words *TU* (*you*), *AMIGO* (*friend*), and *EXTRAÑO* (*stranger*) were displayed below the fixation cross (1.7° high × 1.4°, 4°, or 4.2° width, respectively). The distances between the fixation cross and the center of the shape and the center of the label were 4° and 3°, respectively. The background color of the screen was gray, and stimuli were presented in white. The two experimental tasks were programed in E-Prime 3.0 software (Schneider, Eschman, & Zuccolotto, 2012) and presented on a 22-in. TFT monitor (resolution = 1920 × 1080 pixels). Responses were recorded by using a Chronos device (Psychology Software Tools).

3. Results

Data were processed using R software (R Core Team, 2022) and analyzed with JASP 0.16.3 (JASP Team, 2022).

The PVT data was the same as in (Palmero et al., 2024), as the shape-label matching task was part of the same experimental session and was performed by the same participants. Mean RTs were subjected to a mixed ANOVA with time-of-day (optimal and non-optimal) as the within-participants factor, and chronotype (Morning-types and Evening-types) as the between-participants factor. The main effect of time-of-day was statistically significant, $F(1, 38) = 5.61$; $p = .02$; $\eta_p^2 = 0.13$, which indicated that, in general, performance at the optimal time produced shorter RTs (M = 319 ms) than at the non-optimal time (M = 341 ms). The difference in performance between the optimal and non-optimal time-of-day according to the different chronotypes is referred to as the synchrony effect and the current results replicate those obtained in other experiments using the same task (Correa et al., 2014; Lara et al., 2014; Martínez-Pérez et al., 2022). Accordingly, the current synchrony effect confirms the appropriate selection of our sample of extreme chronotypes. No other effects or interactions were significant (all $ps > 0.31$).

As for the shape-label matching task, three different analyses were performed. First of all, we addressed accuracy data. Secondly, we presented the analysis of the inverse efficiency score (IES). This index is defined as the mean energy consumed by the system throughout the trials (Townsend & Ashby, 1983), and was used to verify the absence of speed-accuracy trade-offs among RT and accuracy data. IES rates were obtained per participant in each of the experimental conditions by the division of the mean RT correct-response trials by the mean accuracy proportions. As RTs, IESs are expressed in ms. Finally, data from RTs was approached.

Practice trials and non-response trials (2.55 %) were removed from all analyses. In addition, trials with incorrect responses (10.76 %) were also excluded from the RT analysis. The remaining RTs were transformed into natural logarithms (Ln) to reduce skewness in the distribution. Visual inspection of individual RT distributions for each participant in each condition did not reveal the presence of extreme outliers, and thus no trimming procedure was applied (note that, moreover, there was a response window of 1100 ms, which limited the possibility of extreme RTs). To further deepen the analysis of RTs, they were partitioned into five rank-ordered RT bins thus enabling the consideration of the additional information that might arise from the RT distributions. Specifically, data from each participant in each session was sorted from the lowest RT to the highest and buffered into five bins as equally sized as possible. Subsequently, the mean Ln-RTs across each bin was obtained. The latter data was submitted to the conducted mixed ANOVAs.

We adopted a statistical significance level of $\alpha = 0.05$ for all statistical analyses. In addition, we present effect size values for our contrasts using partial eta squared (η_p^2) in ANOVAs, and the mean difference (MD) and 95 % CI for Student's t-tests. In addition, since different hypotheses are considered in this study and, to minimize the possibility of committing family-wise error rates (FWER), the Holm-Bonferroni correction is applied to all the post hoc *t*-test analyses.

3.1. Accuracy

Percentages of correct responses were introduced into a 2 × 3 × 2 × 2 mixed ANOVA with match (matching, non-matching), label (*you*, *friend*, *stranger*), and time-of-day (optimal, non-optimal) as within-participants factors, and chronotype (Morning-types, Evening-types) as the between-participants factor.

The main effect of label was significant, $F(2,76) = 16.03$; $p < .001$; $\eta_p^2 = 0.30$, indicating that responses for the condition *you* were significantly more accurate (M = 92 %) than those for conditions *friend* (M = 88 %), and *stranger* (M = 87 %). The difference between condition *friend* and condition *stranger* was not significant ($p_{\mathrm{Holm}} = 0.28$). The label × match interaction was also significant, $F(2,76) = 11.60$; $p < .001$; $\eta_p^2 = 0.23$.

In the matching trials, conditions *you* and *friend*, *you* and *stranger*, and *friend* and *stranger* differed significantly, $t(39) = 3.5$, $p_{\mathrm{Holm}} = 0.006$, MD = 0.05, 95 % CI [0.008, 0.91]; $t(39) = 6.97$, $p_{\mathrm{Holm}} < 0.001$, MD = 0.09, 95 % CI [0.05, 0.14]; and $t(39) = 3.44$, $p_{\mathrm{Holm}} = 0.008$, MD = 0.05, 95 % CI [0.006, 0.09], respectively. In the non-matching trials, none of the above three comparisons were statistically significant (all $ps_{Holm} > 0.12$). Neither the main effect of time-of-day nor that of chronotype reached statistical significance ($ps > 0.18$). The label × match × time-of-day interaction did not reach statistical significance either, $F(2,76) = 0.50$; $p = .61$; $\eta_p^2 = 0.01$.

3.2. Inverse efficiency scores (IESs)

Mean IESs were subjected to a 2 × 3 × 2 × 2 mixed ANOVA with match (matching, non-matching), label (*you*, *friend*, *stranger*), and time-of-day (optimal, non-optimal) as within-participants factors, and chronotype (Morning-types, Evening-types) as the between-participants factor. The main effect of label was statistically significant, $F(2,76) = 15.08$; $p < .001$; $\eta_p^2 = 0.28$, indicating lower IESs (i.e., lower RTs) in condition *you* than in conditions *friend* and *stranger* ($ps_{\mathrm{holm}} < 0.001$). The difference between conditions *friend* and *stranger* was not statistically significant ($p_{\mathrm{Holm}} = 0.25$). Also, the main effect of match proved to be statistically significant, $F(1,38) = 6.90$; $p = .01$; $\eta_p^2 = 0.15$, showing faster IESs in matching than in non-matching conditions. Finally, the interaction between label and match was found to be statistically significant, $F(2,76) = 8.39$; $p < .001$; $\eta_p^2 = 0.18$. In the matching trials, conditions *you* and *friend*, *you* and *stranger*, and *friend* and *stranger* differed significantly, $t(39) = 3.2$, $p_{\mathrm{Holm}} = 0.02$, MD = 0.51, 95 % CI [0.04, 0.98]; $t(39) = 6.35$, $p_{\mathrm{Holm}} < 0.001$, MD = 1.01, 95 % CI [0.54, 1.48]; and $t(39) = 3.14$, $p_{\mathrm{Holm}} = 0.02$, MD = 0.05, 95 % CI [0.03, 0.16], respectively. In the non-matching trials, none of the above three comparisons were statistically significant (all $ps_{Holm} > 0.16$).

3.3. Reaction times (RTs)

Mean ln-RTs were submitted to a 2 × 3 × 2 × 5 × 2 mixed ANOVA with match (matching, non-matching), label (*you*, *friend*, *stranger*), time-of-day (optimal, non-optimal), and bin (1–5) as within-participants factors, and chronotype (Morning-types, Evening-types) as the between-participants factor.

The main effects of match and label were statistically significant, $F(1,38) = 393.86$; $p < .001$; $\eta_p^2 = 0.91$, and $F(2,76) = 68.96$; $p < .001$; $\eta_p^2 = 0.65$, respectively. RTs were faster in matching than in non-matching trials, and faster in the condition *you* than in conditions *friend* and *stranger* ($ps_{holm} < 0.001$). The difference between conditions *friend* and *stranger* did not reach the statistical significance level ($p_{holm} = 0.26$). The lack of a significant label × match interaction indicates that the SPE was similar in matching and non-matching trials. Neither the main effect of time-of-day nor that of chronotype reached the statistical significance level (all $ps > 0.14$).

However, the main finding was the significant label × time-of-day × chronotype × bin interaction, $F(8,304) = 2.65$; $p = .008$; $\eta_p^2 = 0.06$. To further analyze the interaction, and in line with previous studies that have consistently shown different patterns of results between Morning- and Evening-types (Lara et al., 2014; Martínez-Pérez et al., 2020; Palmero et al., 2022), we conducted separate analysis for each chronotype.

3.3.1. Morning-types

Mean ln-RTs were submitted to a 3 × 2 × 5 repeated-measures ANOVA with label (*you*, *friend*, *stranger*), time-of-day (optimal, non-

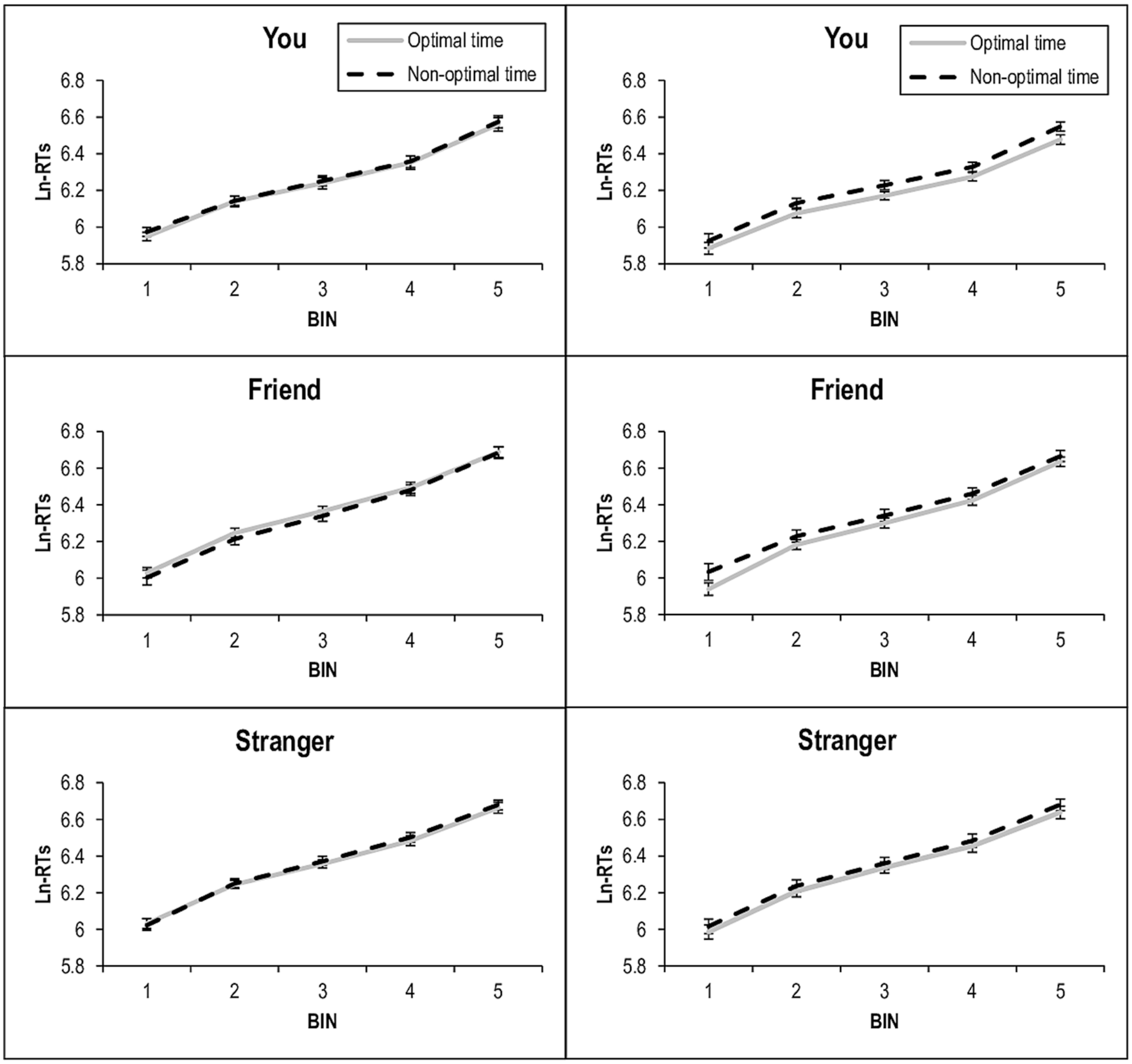

Fig. 1. Time-of-day modulation of performance of Morning-types (left panel), and Evening-types (right panel) in each label condition: *you*, *friend*, *stranger*, as a function of response speed.

optimal), and bin (1–5) as within-participants factors. The main effect of label was significant, $F(2,38) = 28.77$; $p < .001$; $\eta^2_p = 0.60$, indicating faster RTs in the condition *you* than in conditions *friend* and *stranger*, but the difference between the conditions *friend* and *stranger* did not reach the statistical significance level ($p = .09$). The three-ways label × time-of-day × bin interaction was not statistically significant, $F(8,152) = 0.88$; $p = .53$; $\eta^2_p = 0.04$. Neither was any other interaction involving the time-of-day factor (all $ps > 0.11$). The results of these analyses are illustrated in Fig. 1 (left panel).

3.3.2. Evening-types

Mean ln-RTs were submitted to a 3 × 2 × 5 repeated-measures ANOVA with label (*you*, *friend*, *stranger*), time-of-day (optimal, non-optimal), and bin (1–5) as within-participants factors. The main effects of label and time-of-day were significant, $F(2,38) = 40.58$; $p < .001$; $\eta^2_p = 0.68$, and $F(1,19) = 5.05$; $p = .04$; $\eta^2_p = 0.21$, respectively. RTs were faster in the condition *you* than in conditions *friend* ($p_{\mathrm{Holm}} < 0.001$), and *stranger* ($p_{\mathrm{Holm}} < 0.001$), but we did not find any significant difference between conditions *friend* and *stranger* ($p_{\mathrm{Holm}} = 0.25$). RTs were also faster in the optimal than in the non-optimal time-of-day. Importantly, the label × time-of-day × bin interaction was statistically significant, $F(4,76) = 3.25$; $p = .002$; $\eta^2_p = 0.15$. According to our previous hypotheses, we were interested in assessing whether RTs differed between the optimal and non-optimal time-of-day in each label condition and if that potential time-of-day modulation of self- and others-related associations differed as a function of response speed.

In condition *you*, we found a significant effect of time-of-day, $F(1,19) = 5.75$; $p = .02$; $\eta^2_p = 0.23$. RTs were faster in the optimal than in the non-optimal time-of-day. However, the time-of-day × bin interaction did not reach the statistically significant level, $F(4,76) = 1.87$; $p = .12$; $\eta^2_p = 0.09$. In condition *friend*, we found a significant effect of time-of-day, $F(1,19) = 4.34$; $p = .05$; $\eta^2_p = 0.19$. Again, RTs were faster in the optimal than in the non-optimal time-of-day. The time-of-day × bin interaction was also significant $F(4,76) = 4.37$; $p = .003$; $\eta^2_p = 0.19$. The interaction analysis revealed that the advantage of the optimal time-of-day in performance occurred only in the first bin. In bin 1, $t(39) = 3.57$; $p_{\mathrm{Holm}} = 0.01$; MD = 0.09, 95 % CI [-0.002, 0.19]; in bin 2, $t(39) = 1.80$; $p_{\mathrm{Holm}} = 0.33$; MD = 0.04, 95 % CI [0.04, 0.14]; in bin 3, $t(39) = 1.57$; $p_{\mathrm{Holm}} = 0.38$; MD = 0.05, 95 % CI [0.04, 0.14]; in bin 4, $t(39) = 1.39$; $p_{\mathrm{Holm}} = 0.38$; MD = 0.04, 95 % CI[0.03, 0.13]; and in bin 5, $t(39) = 1.18$; $p_{\mathrm{Holm}} = 0.38$; MD = 0.03, 95 % CI [0.06, 0.13]. In condition *stranger*, neither the time-of-day nor the time-of-day × bin interaction reached the statistically significant level, $F(1,19) = 1.99$; $p = .17$; $\eta^2_p = 0.09$, and $F(4,76) = 0.27$; $p = .90$; $\eta^2_p = 0.01$, respectively. The results of these analyses are illustrated in Fig. 1 (right panel).

4. Discussion

In the present study, we aimed to link the SPE to a trait related to circadian rhythms known as chronotype and to the time of day at which the task is performed. The SPE was assessed using an unbiased task designed by Sui et al. (2012), in which participants associated three different geometric shapes with verbal labels related to themselves, a friend, or a stranger, and then judged whether the presented label-shape pairings were correct based on what they had previously learned. We found a significant SPE in the three studied outputs (i.e., accuracy rates, IES, and RTs), demonstrating the robustness of the effects as well as the absence of trade-offs in participants' performance. Moreover, in RTs the SPE appeared specifically on both matching and non-matching trials, whereas in accuracy the SPE only appeared on matching trials. Our results replicate previous studies on the existence of the SPE in the perceptual domain using the shape-label matching task (Dalmaso et al., 2019; Desebrock et al., 2018; Martínez-Pérez, Campoy, et al., 2020; Sui et al., 2012; Martínez-Pérez et al., 2024). Likewise, the nuance of effects that we found as a function of response speed in RTs (i.e., five-ranked binning procedure) reinforces the need to consider the complete distribution of RTs to explore potential effects that might be covered up by using only a single global parametric value.

In addition to studying the SPE, our main interest focused on the distinction between the processing styles of stimuli related to oneself (you) and those related to others (friend and stranger). In the former case, the processing mode seems to occur rather automatically, whereas the latter requires a higher degree of cognitive control. In the present study and based on previous studies concerned with the modulation of automatic and controlled cognitive processing as a function of chronotype and time-of-day, we hypothesized that such circadian modulation would mainly affect controlled processes, that is, processing of friend-related and mainly stranger-related stimuli. However, contrary to our initial predictions, our results showed a significant modulation of chronotype and time-of-day on automatic processing, and it occurred only in the Evening-type participants. That is, we found differences between optimal and non-optimal time-of-day only when participants processed self-related stimuli, and partially when they processed friend-related stimuli. When participants processed stranger-related stimuli, we found no evidence of such modulation.

These results contradict those of previous studies that have observed an absence of chronotype and time-of-day modulation in automatic processing (Lara et al., 2014; Manly, 2002; May et al., 2005). However, in a recent study (Palmero et al., 2024) observed a modulation of automatic semantic processing only in Evening-type participants. Participants performed a category semantic priming task at both their optimal and non-optimal time-of-day and were able to suppress the automatic activation of the prime category only when the task was performed at their optimal time, producing a synchrony effect. Importantly, the synchrony effect was not observed neither in the Intermediate-type nor in the Morning-type groups of participants. These results reveal that under certain circumstances, automatic processes are prone to modulatory effects of both chronotype and moment of testing.

An explanation of the specific modulatory effect of time-of-day on self-related automatic processing observed in the current study may lie in the relationship between the main areas involved in the SAN and their close relationship with circadian rhythms. Humphreys and Sui (2015) pointed to the VMPFC and DLPFC regions as the core areas for the processing of self- and others-related stimuli, respectively. However, despite some studies have supported the SAN's proposal, contradictory results regarding the explicit role of each network-related area have also been reported.

Regarding the role of the VMPFC in self-related processing, Martínez-Pérez et al. (2020) attempted to modulate the SPE by applying excitatory and inhibitory high-definition transcranial direct current stimulation (HD-tDCS) over the VMPFC. The authors reported null results in terms of SPE modulation. Liang et al. (2022) conducted a study using transcranial magnetic stimulation (TMS) and showed that it was the LpSTS instead of the VMPFC which causally affected self-related processing. However, Liang et al. (2022) argued that because both areas are functionally connected, any damage to either the VMPFC or the LpSTS should decrease the SPE. Given that during the non-optimal time-of-day according to the chronotype, occurs a decrease in cortical excitability balance and an increase in inhibition levels (Salehinejad et al., 2021), our results may suggest that VMPFC activation would be compromised when Evening-type participants performed the task at the non-optimal time-of-day, affecting negatively self-related automatic processing.

Regarding the role of the DLPFC, recent studies have shown its association with cognitive functions closely linked to circadian rhythms, such as vigilant attention (Martínez-Pérez et al., 2022; Sturm & Willmes, 2001), and that area is recruited in tasks requiring a high degree of executive control (Duncan & Owen, 2000; see Friedman & Robbins, 2022 for a recent review), although its activation is severely altered under conditions of sleep deprivation (Bratzke, Steinborn, Rolke, & Ulrich, 2012). However, both Liang et al. (2022) and Martínez-Pérez et al. (2020) failed to find any involvement of the DLPFC in the SPE. These results put into question any causal relationship of the DLPFC in others-related processing, probably due to the involvement of other attention-related brain regions such as the temporoparietal junction (TPJ), which is crucial in the distinction between self and others (Brass, Ruby, & Spengler, 2009; Fuentes-Claramonte et al., 2020; Spengler, Yves von Cramon, & Brass, 2009). Thus, our failure to find any time-of-day modulation on the others-related processing suggests that the brain areas involved may not be so prone to changes in excitation/inhibition balance due to circadian rhythms.

Also related to the brain regions proposed from the SAN's model, a complementary explanation must be noted. In this vein, an account for the modulation occurring on the processing of self-related labels (involving the VMPFC), paralleled by the absence of others-related labels modulation requiring greater cognitive control and implying the DLPFC, would stem from studies that have delved less into the particular role of each of these regions and rather into the interaction between both of them. Thus, it is worth pointing out that the DLPFC and the VMPFC cooperate to support higher-level human behaviors such as emotional processing (Nejati et al., 2021), as well as both areas alternate in their activation levels in healthy individuals when performing attention-demanding tasks (Fox et al., 2005), indicating its interconnected operating mode within the network. Indeed, the desynchronization between both areas leads to attentional failures such as the so-called mind-wandering phenomena (Nejati et al., 2023). Consequently, an impairment in VMPFC functioning is likely to be caused by the fact of being off-optimal time according to the chronotype, thus compromising the processing of self-related labels as well as the aforementioned ability to exert attentional awareness. In contrast, the DLPFC, which is presumably less affected by circadian oscillations, may compensate for this deficit and maintain the successful processing of others-related labels in both optimal and non-optimal times of day.

To end, a third explanation should also be taken into consideration. It is possible that performing the task at the non-optimal time-of-day affects participants' performance in those conditions where fast responding is promoted, as it happens in self-related processing. Fast responses have room to slow down under certain adverse circumstances, such as performing the task at a non-optimal time when the arousal level is low. In the case of slower responses, such as the processing of others-related stimuli, there might be less room for worsening performance, perhaps because performance is close to a ceiling effect. In favor of this explanation is the fact that the time-of-day modulation effect occurs in those conditions in which faster responses are observed, i.e., in condition *you* and in the range of faster responses (first bin) in condition *friend*. However, the fact that time-of-day modulation effects occur in both matching (faster responses) and non-matching trials (slower responses) in conditions *you* and *friend*, would argue against this explanation. Therefore, the findings of the present study lead us to reconsider the modulation of automatic processing by chronotype and time-of-day. In this sense, we cannot maintain the claim that there is no circadian influence on those processes that do not require cognitive control (i.e., automatic processing), but that there are other factors that are potentially influential in such modulation. One of those factors is the specific chronotype of the individuals, mainly Evening-types, who are particularly vulnerable to such influences, but also the type of task used as well as the brain areas involved. Thus, we conclude that the modulation we observed in self-related automatic processing as a function of time-of-day can be due to the association between activation levels of self-related brain areas involved in the SAN (e.g., the VMPFC) and circadian rhythms.

A final issue concerns the absence of time-of-day modulation effects in Morning-type participants. The pattern of results observed here in these participants is in line with the results of previous studies suggesting greater flexibility and adaptation of Morning-types when performing tasks at their non-optimal time-of-day (Adan et al., 2012; Lara et al., 2014; Martínez-Pérez et al., 2022; Mongrain et al., 2008; Palmero et al., 2022; Schmidt et al., 2015). At the behavioral level, the Evening-type chronotype has been linked to certain personality traits such as impulsivity, greater sensation seeking, less vigilance, and less conscientiousness (Finomore et al., 2009; Oginska et al., 2010). In addition, it has been suggested that changes in sleep dynamics could explain the differences between Morning- and Evening-types (Lara et al., 2014). Indeed, some research associates poor sleep habits and a greater need for sleep with Evening-types, while sleep hygiene would be more associated with Morning-types (Lehnkering & Siegmund, 2007; Taillard et al., 2002). At the physiological level, interactions have been described between the activation of certain hormones such as cortisol or other female sex hormones such as estrogen and progesterone and circadian rhythms, which would also explain the better performance of Morning-type women in sustained attention tasks (Palmero et al., 2022). However, more research is needed on linking specific physiological patterns in terms of cortical excitability, with specific chronotype profiles.

5. Limitations and future directions

The present study has some limitations that should be taken into account. First, the reasons given to explain the findings obtained based on interactions between neuroanatomical structures and their proper functions must be treated cautiously, given that our study has not included the direct measurement of neuroanatomical functioning, but exclusively of the behavioral output. In this sense, the interpretation of the results observed here would benefit from measuring cortical excitability levels of the brain areas involved (Salehinejad et al., 2021). In addition, further study of both DLPFC and VMPFC in parallel through non-invasive brain stimulation techniques may shed light on new results related to the specific roles exerted by the brain regions of interest in the SPE, given earlier results proving their close linkage (see Nejati et al., 2023). Besides, more information on the sleep quality of our participants as well as the total hours of sleep the night before the experiment would have allowed for a more detailed explanation of the main differences observed between the two chronotypes. Addressing the proposed limitations would contribute to improving knowledge about the cognitive and physiological functioning of the Morning- and Evening- chronotypes and understanding the specific influences that certain circadian variables exert on automatic and controlled processes.

6. Conclusion

The results of the present study call for a reconsideration of the modulation of automatic processing by chronotype and time-of-day. In this sense, we cannot assert that there is no circadian influence on those processes that do not require any degree of cognitive control (i.e., automatic processing), but that there are other potentially influential variables in this modulation. One of the most important of these is the specific chronotype of individuals, especially the Evening-type chronotype, which has been found to be particularly vulnerable to such influences. Others refer to the type of tasks used, which may vary in the demands of cognitive control, as well as to the brain areas involved in them, specifically the VMPFC, involved in cognitive operations that seem to be especially influenced by circadian variations.

Ethical approval

The present study is part of a research project approved by the ethics committee of the University of Murcia and adjusted to the standards set forth in the Declaration of Helsinki in 1964.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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CRediT authorship contribution statement

Lucía B. Palmero: Conceptualization, Data curation, Formal analysis, Methodology, Software, Visualization, Writing – original draft. **Víctor Martínez-Pérez:** Conceptualization, Methodology, Software, Writing – original draft. **Miriam Tortajada:** Conceptualization, Methodology, Writing – original draft. **Guillermo Campoy:** Methodology, Software, Data curation, Writing – review & editing. **Luis J. Fuentes:** Conceptualization, Funding acquisition, Supervision, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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