Circadian rhythms and decision-making:
a review and new evidence from electroencephalography

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RUNNING HEAD: Circadian rhythms and decision-making
Word count: 9463 words

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Abstract

Since emotions and regulatory control are relevant for decision-making, their circadian fluctuation should influence the outcome of such decisions, but this question has been rarely addressed. A review of the literature suggests that the evidence regarding circadian synchrony effects (better performance at optimal vs. non-optimal times of day according to chronotype) on decision-making is mixed, likely due to the use of different approaches to estimate chronotype. The current experiment studied economic decision-making as a function of both chronotype and the time of day when decisions are made.

The influence of chronotype (Morning-type: N = 28 vs. Evening-type: N = 30) and time of day (8 am vs. 10 pm) on decision-making was measured by the acceptance rate of unfair and fair offers in the Ultimatum Game, and the event-related potentials time-locked to such offers. Subjective affect (PANAS), and appraisal of emotional images (IAPS) were also measured. Chronotype was estimated through questionnaires (MEQ, rMEQ, MCTQ) and the circadian rhythm of wrist temperature.

Synchrony effects were found for both wrist temperature and subjective affect, but not for behavioral performance. Morning-types showed earlier phases of circadian rhythms in temperature, reported better sleep quality, more positive affective balance, accepted more unfair offers, and their frontal P200 potential was attenuated as compared to Evening-types in the Ultimatum Game. Acceptance rate of unfair offers correlated with the chronotype measured by questionnaires (positive correlation with rMEQ and MEQ scores, and negative correlation with Midsleep time in work days -MSWsc from MCTQ) but not with midsleep time estimated through wrist temperature. Finally, participants who accepted more unfair offers later judged positive IAPS stimuli as more pleasant.

We did not observe a synchrony effect in the Ultimatum Game, but morningness was related to rational decision-making as indexed by increased acceptance of unfair offers. Since morning-types show higher emotional regulation and positive mood than evening-types, it is possible that unfair offers did not elicit negative emotions as intense in morning-types as in evening-types, making it easier for them to accept.

Keywords: arousal, chronotype, Ultimatum Game, circadian rhythms, emotion, morningness, eveningness, ERP.

Abbreviations: ACC (anterior cingulate cortex), ANOVA (analysis of variance), BART (Balloon Analogue Risk Task), DLPFC (dorsolateral prefrontal cortex), EEG (electroencephalography), IAPS (International Affective Picture System), ICA (Independent component analysis), KSS (Karolinska Sleepiness Scale), LPP (Late Positive Potential), M (mean), MCTQ (Munich Chronotype Questionnaire), MEQ (Morningness Eveningness Questionnaire), MFN (Medial Frontal Negativity), MSWsc (midsleep time for working days corrected for sleep debt), MSFsc (midsleep time for free days corrected for sleep debt), N (number of participants), PANAS (Positive and Negative Affect Schedule), PSQI (Pittsburgh Sleep Quality Index), PVT (Psychomotor Vigilance Task), rMEQ (reduced Morningness Eveningness Questionnaire), RNA (Ribonucleic acid), RT (reaction time), SAM (Self-Assessment Manikin), SD (standard deviation), UG (Ultimatum Game).

INTRODUCTION

Arousal fluctuates between low levels during sleep and high levels during wakefulness, following a 24-h period known as circadian rhythm. Circadian rhythms are regulated by an endogenous clock composed of a central oscillator located in the Suprachiasmatic Nuclei. The phase of circadian rhythms differs both across species and within the same species, the latter leading to the notion of chronotype (Adan et al. 2012). Humans have been classified into morning, intermediate and evening types according to their natural preferences for waking up and going to sleep, together with the time of day when they show peaks and troughs in arousal (Kleitman 1939).

Individual differences in chronotype can, therefore, circumscribe specific times of day when arousal is at its peak (acrophase), so the performance of physical and cognitive tasks is optimized in relation to other times of day in which the arousal level is less optimal. This interaction between chronotype and time of day is known as the synchrony effect (Horne et al. 1980; May & Hasher 1998). When there is circadian synchrony between internal and external times, the peak in arousal at optimal times of the day can benefit psychological functions, as revealed through subjective, behavioral and physiological measures of alertness. For instance, Morning-type people tested in the morning and Evening-type people tested in the evening (in comparison with mismatches between chronotype and time of day of testing), report less somnolence in the Karolinska Sleepiness Scale (KSS; Akerstedt & Gillberg 1990), respond faster in tasks measuring their reaction time (RT), such as the Psychomotor Vigilance Task (Dinges & Powell 1985) and have higher central temperature (Kerkhof & Van Dongen 1996). Moreover, the synchrony effect has been replicated across multiple psychological domains (Blatter & Cajochen 2007) including emotion and executive control, which we have reviewed as follows.

Kerkhof (1998) first reported a synchrony effect on subjective ratings on mood, leading to more positive affect for times of day matching the chronotype estimated through the circadian rhythm of body temperature. Later research has confirmed this relationship by showing that: 1) the circadian rhythm of self-reports on positive affect had a smaller amplitude and later acrophase (peak) for evening-types than morning-types (Miller et al., 2015); and 2) the acrophase of positive (rather than negative) affect measured by the Positive and Negative Affect Schedule (PANAS) correlated negatively with morningness (Porto et al., 2006), that is, evening-types reported the highest positive affect at later times of day than morning-types. Other studies have further found a main effect of chronotype regardless of time of day, that is, morning-types reported higher positive affect and better mood in general than evening chronotypes (Biss & Hasher, 2012; Díaz-Morales et al, 2015).

Behavioral research with tasks demanding affective processing (emotional face recognition) has reported an attentional bias to negative emotions selective to evening-types, as inferred from their superior accuracy for recognizing sad facial expressions (Berdynaj et al. 2016; Horne et al. 2016). Underlying this effect, there is enhanced activation of the amygdala related to the processing of negative emotions, while the finding of reduced connectivity between amygdala and dorsal anterior cingulate cortex further suggests that the prevalence of negative emotions is not down-regulated effectively in evening-types (Horne & Norbury 2018).

Indeed, a main way to exert emotional regulation requires the contribution of top-down processes related to cognitive control (Gross 1998). Cognitive control is triggered to attain behavioral efficiency in novel or non-routine situations, for example by inhibiting routine responses when they are not appropriate in a specific context (Norman & Shallice 1986). The synchrony effect has been replicated in tasks demanding cognitive control, such as response inhibition (May & Hasher 1998; reviewed by Schmidt et al. 2007). Research further suggests that controlled rather than automatic processes are especially vulnerable to the synchrony effect (May et al. 2005; Lara et al. 2014).

These findings altogether emphasize the role of circadian factors in psychological processes related to arousal, affective state, and the ability to exert cognitive control for emotional regulation. Such processes are relevant for decision-making and have been linked to separate neural substrates (Camerer 2003; Sanfey et al. 2003). Decision-making first triggers an automatic tendency to behave fast and efficiently, which in principle provides an adaptive benefit; but choices in this initial stage may be excessively rigid, driven by automatic processes related to basic emotions or social stereotypes. However, this initial reaction can be regulated by top-down processes related to cognitive control, involving deliberative thinking on different alternatives and inhibition of inappropriate responses, in order to adapt flexibly to uncertain and dynamic contexts like those involving risky decisions, morality and social interaction.

Since emotions and regulatory control are relevant for decision-making, their circadian fluctuation should influence the outcome of such decisions. However, the synchrony effect has been relatively less studied in tasks requiring decision-making. The aim of the current study was to clarify whether decision-making is influenced by individual differences in chronotype and the time of day when decisions are made. Before describing the current experiment, we first review the literature by focusing on tasks typically asking participants to make decisions involving: a) the possibility of cheating others for the own benefit (ethical decision-making), b) uncertainty and risk on the final outcome (risky decision-making), and c) interaction with a partner to share the gains of a limited resource like money (social decision-making).

Review on circadian synchrony and decision-making

This selective review compiled studies measuring the effects of chronotype and time of day on behavior during decision-making tasks. Research based on questionnaires on decision-making, not measuring direct behavior, was beyond our scope and therefore not included in this review. We focused on social decision-making, but ethical and risky decision-making tasks have also been reviewed as they share common processes (e.g., rationality, emotional regulation). Likewise, we included three studies using the same tasks combined with procedures of sleep deprivation, as they provide working hypotheses to ground the effects of circadian manipulations.

Sleep deprivation causes frontal dysfunction, impairing controlled processes of emotional regulation relevant for adaptive behavior in risky decision-making, for instance, in the Iowa Gambling Task (Killgore et al. 2006). Analogously, and in line with the synchrony effects reported in cognitive control (Lara, Madrid, & Correa, 2014; May & Hasher, 1998), this frontal regulatory process would not work most efficiently at non optimal times of day (i.e., morning for evening-types and evening for morning-types), impacting decision making. Although circadian synchrony effects might be rather subtle as compared with the effects of sleep deprivation, it is important to measure them under ecological conditions, not just under severe conditions of sleep deprivation, as people with different chronotypes and normal sleep duration frequently make decisions throughout the day. Table 1 summarizes eight studies on the effects of chronotype and time of day on decision making, two of them also manipulating sleep deprivation (Dickinson & McElroy, 2017; Killgore, 2007), and one additional study on sleep deprivation which used the Ultimatum Game (Anderson & Dickinson 2010), the same task we used in the current experiment, explained below. Studies of Table 1 are ordered and grouped into ethical decision-making, risky decision-making, and social decision-making.

Table 1. Summary of reviewed studies about the behavioral effects of circadian synchrony (and sleep deprivation) on decision-making as measured by ethical, risky and social decision-making tasks (all abbreviations are defined at the beginning of this article).

Study	Hypothesis	Task	Design	Sample (N)	Chronotype	Results	Conclusion
Gunia et al., 2014	Synchrony effects on **ethical decision-making**	Exp. 1: Matrix task (morning session only)	Cheating scores regressed on both MEQ scores and MEQ-category (morning, intermediate and evening)	48 (N = 16 x 3 groups)	Tercile split of MEQ scores	MEQ scores [b=.36, p=.01] and categories [b=.34, p=.02] predicted morning cheating	Sleep and circadian processes influence the ability to exert self-control to avoid temptation (cheating for own benefit), and so unethical behavior
		Exp. 2: Dice task	Time of day (7-8:30 am vs. 12-1:30 am) x Chronotype (morning vs evening), between-subjects	142 (N = [29-40] x 4 groups)	Tercile split of rMEQ scores	Chronotype x Time of day, $F(1,138)=4.3, p=.04, \eta 2=.03$: more cheating at circadian mismatch	
Ingram et al., 2016	Synchrony effects in both **ethical and risky decision-making** tasks	Balloon Analogue Risk Task (BART) and Matrix task	Time of day (7:30-9 am vs. 4:30-10 pm, within-subjects) x Chronotype (morning, evening)	139. A) N = 29 morning vs 42 evening MEQ-groups; B) N = 26 vs 8 RNA-types	A) MEQ; B) RNA (Per3,Nr1d2)	A) No effects of MEQ-type (ps>.1). B) RNA-MTypes riskier in BART, $F(1,20)=18.4, p<.01, \eta 2=.5$. RNA-type x Time of day in Matrix, $F(1,20)=5.24, p=.04, \eta 2=.21$	Three-hour phase differences in the molecular clockwork influence cognitive and self-regulatory processing to affect behavioral decision-making
Castillo et al., 2017	Circadian mismatch will affect **risky decision-making**	Risky choice task	Time of day (7:30 am, 10 pm) x Chronotype (morning, evening), between-subjects, leading to Circadian Matched vs Mismatched conditions	202 (N = [35-61] x 4 groups)	rMEQ with modified cutoffs (15–25: morning; 4-10: evening)	1) Mismatch did not affect choice consistency (ps>.46). 2) Matched subjects choose the safe bundle more (p = .012)	Cognitive resource depletion via circadian mismatch does not affect choice consistency (rationality) but induces preference for risk shift
Gowen et al., 2019	**Risk-taking** differs between chronotypes and genders	BART	1) Chronotype (Morning, Intermediate, Evening) x Gender. 2) Correlation: MEQ & Risk-taking scores	610	MEQ	1) No Chronotype effect on risk-taking, $F(2,572)=2.20, p=.11$; but 2) MEQ & BART scores correlated: $r=-0.11, p<.01$	Circadian desynchrony = mistiming of glucose metabolism, impacting resources for self-control
Killgore, 2007	**Risk-taking** increases with eveningness and sleep deprivation	BART	1) Chronotype x Session (baseline, sleep deprived, postrecovery, within-subjects). 2) Correlation: MEQ & Risk-taking scores	54 (26 Morning Types vs 28 Evening Types)	Median split of MEQ scores (median=54)	1) Session: $F(2,102)=7.85, p<.01$, lowest risk for Sleep-deprived. No effects of Chronotype. 2) MEQ did not correlate with risk (r = -.1)	Decreased risk-taking may represent avoidance of energy-consuming activities when fatigued by sleep deprivation

Study	Hypothesis	Task	Design	Sample (N)	Chronotype	Results	Conclusion
Anderson & Dickinson, 2010	Sleep deprivation will alter **social decision-making**	Ultimatum Game (UG) and Trust Game (TG)	Sleep (Totally Sleep Deprived vs Rested Wakefulness), within-subjects	32	No	UG: Higher MAO (minimum acceptable offer) in TSD vs RW ($p=.05$). TG: No effect of sleep ($p>.1$)	After sleep deprivation (frontal disruption), emotion guides decisions, increasing rejection of unfair offers
Bodenhau-sen, 1990	Synchrony effects on **stereotypic social judgments**	Exp. 1: Probability judgment task	Time of day (9 am, 8 pm) x Chronotype (morning vs. evening), between-subjects	59 (N ≈ 15 x 4 groups)	Median split of MEQ scores	More conjunction fallacies at circadian mismatch (no statistics reported)	Circadian variations in arousal affects social judgment. People show stereotypic judgments when they are not motivated (or less cognitively able) to consider carefully the relevant evidence (at non optimal times of day)
		Exp. 2: Guilt judgments on members of particular social groups	Time of day (9 am, 3 pm, 8 pm) x Chronotype (morning vs. evening) x Stereotype activation (present vs. absent), between-subjects	189 (N ≈ 16 x 12 groups)	Median split of MEQ scores	Stereotype activation x Time of day x Chronotype: $F(2,177) = 3.49$, $p<.05$. Stereotyped targets more guilty judged at circadian mismatch	
Correa et al., 2017	Synchrony effects on emotions and control, optimising **social decision-making**	Ultimatum Game and Continuous performance test (AX-CPT)	Time of day (9 am, 5 pm, within-subjects) x Chronotype (morning, evening)	64 (32 morning-types and 32 evening-types)	rMEQ	Acceptance rate: No effect of Chronotype ($p>.2$). Decision time: Chronotype x Offer, $F(3, 173)=2.74, p=.05, \eta p2=.04$. Morning-types decided slowest on 2/8 offer, $F(1,62)=4.66, p=.04$	Decision-making is robust across circadian phases (with normal sleep). Morning people show more cautious decision-making
Dickinson & McElroy, 2017	Sleep restriction & Circadian mismatch will impair **social decision-making**	Ultimatum, Dictator and Trust Game	Time of day (7:30 am, 10 pm) x Chronotype (morning, evening), between-subjects, leading to Circadian Matched vs Mismatched conditions. Within-subjects: Control (8-9 h) vs Sleep-restricted (5-6 h)	154 (N = [34-39] x 4 groups)	rMEQ modified cutoffs (16–25: morning; 4-9: evening)	1) Circadian Mismatch: no effect on any task (ps>.25). 2) Sleep restriction marginally decreased Dictator and Trust offers ($p=.07$, $p=.1$)	Adverse sleep states reduce prosocial behaviors, mainly in Dictator Game (by reducing deliberative thought)

The column “Hypothesis” in Table 1 states the assumption that people make more “rational” decisions at their optimal (vs. non optimal) time of day according to their chronotype. This synchrony effect is expected across three main domains of decision-making: ethical, risky and social decision-making. By “rational” decisions we generally mean more ethical (less cheating behavior), safer (low risk/benefit ratio) and prosocial (fair/altruistic behavior), which are presumably regulated by cognitive control. In sleep deprivation studies, the hypothesis is that sleep deprivation will impair these decisions.

The column “Task” summarizes the behavioral tasks typically used to study these three domains, respectively: Matrix task (developed by Gino et al. 2009; Gunia et al. 2014), Balloon Analogue Risk Task (BART, developed by Lejuez et al. 2002; Gowen et al. 2019; Ingram et al. 2016; Killgore 2007) and the Ultimatum Game (developed by Güth et al. 1982; Anderson & Dickinson 2010; Correa et al. 2017; Dickinson & McElroy 2017).

The column “Design” shows the typical design, in which chronotype and time of day factors are crossed to study the synchrony effect. Time of day has been manipulated either within or between participants. Although the within-participants manipulation yields higher statistical power, this review does not suggest that this factor could explain the divergent results across studies. In any case, the high variability across studies in the evening session, ranging between 4:30 pm to 1:30 am, makes direct comparisons difficult.

In the column “Sample”, we can note that the sample size of the reviewed studies is relatively low, ranging between 8 and 60 participants per experimental condition (26±8 participants on average), except for Gowen et al. (2019; Total N = 610). Although underpowered sample sizes may contribute to explain the heterogeneity of results across studies, the effects of chronotype observed with the largest sample size (Gowen et al., 2019) were rather modest, or not statistically significant in some cases, as it will be detailed below.

The column “Chronotype” indicates that another source of variability across studies concerns the estimation and manipulation of chronotype. The Morningness-Eveningness Questionnaire (MEQ; Horne & Ostberg 1976) and its reduced versions (rMEQ; Adan & Almirall 1991; Natale 1999) are the only psychometric tool used by the reviewed studies to measure chronotype, except for Ingram et al. (2016), who additionally followed a biological approach based on the Ribonucleic Acid (RNA) analysis of phase differences in the expression of circadian clock genes (Per3, Nr1d2). It is important to emphasize that many studies did not follow the cut off normative scores of the MEQ to assign participants into different chronotype groups. Rather, median (or tercile) split procedures were applied to MEQ scores to obtain morning-types (intermediate-types) and evening-types groups balanced in sample size. Moreover, given the scarcity of morning-types in the young adult population (the only age range sampled here), other studies modified the cut off score into a more lax criterion to consider original intermediate-type participants as morning-type. These practices, while helped maintaining higher sample sizes, may have increased undesired variability in the chronotype manipulation by including intermediate-type participants into morning and evening-type groups. Nevertheless, we will describe below some studies that have used MEQ and rMEQ scores as a continuous variable to compute regressions with behavioral decisions (Killgore 2007; Gunia et al. 2014; Gowen et al. 2019).

The columns "Results" and "Conclusion" will be presented separately for the three domains mentioned above: ethical, risky and social decision-making.

Chronotype and ethical decision-making

Three experiments have addressed the role of chronotype on ethical decision-making using the Dice task and the Matrix task (Gunia et al., 2014; Ingram et al., 2016). In these tasks, participants are rewarded depending on the outcome they report to the experimenter, so they have the option to cheat and inflate such an outcome to increase their monetary gain. Gunia et al's results showed that eveningness scores in the MEQ correlated positively with the amount of cheating in a morning session (Experiment 1). The synchrony effect found in their Experiment 2 (significant Chronotype x Time of day interaction) confirmed that people cheat more when tested at non-optimal rather than optimal times of day according to their chronotype. However, using the Matrix task as well, Ingram et al's (2016) did not replicate either chronotype or synchrony effects based on the MEQ analysis. They only found the synchrony effect for chronotype groups based on the RNA analysis. In sum, the reviewed studies suggest that the evidence supporting the synchrony effect on ethical decision-making became more evident when the estimation of chronotype did not just rely on a single measurement.

Chronotype and risky decision-making

Behavior during decision-making tasks is expected to be risky at non-optimal times of day, and in evening-types in general. This hypothesis is based on both Killgore's (2006) finding of risky behavior in the Iowa Gambling Task after 49 h of sleep deprivation, and the subjective reports of high impulsivity, risk-taking propensities, novelty and sensation seeking associated with eveningness (Caci et al. 2004; Tonetti et al. 2010; Ponzi et al. 2014),

Three studies used the Balloon Analogue Risk Task, BART (Gowen et al., 2019; Ingram et al., 2016; Killgore, 2007), but they did not find significant effects of MEQ chronotype on behavioral measures of risk (i.e., number of balloon pumps). Nevertheless, further correlational analyses in Gowen et al. (2019) showed a small but significant correlation between MEQ and BART scores (r = - 0.11; i.e., morningness was associated with less risk), whereas Ingram et al. (2016) found the opposite result for RNA-based chronotypes: morning-types took more risks than evening-types. Also unexpected was the Killgore's (2007) finding of decreased risk-taking after sleep deprivation.

Using the risky choice task (Choi et al. 2007), Castillo et al. (2017) were the first to report significant synchrony effects on risky decision-making. Decisions were safer at optimal (vs. non optimal, i.e. "circadian mismatch") times of day according to participants' chronotype as measured by the rMEQ. Additionally, they found that the consistency of choices (an index of rationality) was not altered by chronotype.

To summarize this section, the higher propensity in evening chronotypes for risky decision-making is a solid finding according to self-reports and validated questionnaires. However, this association does not translate easily from the subjective to the behavioral level when subjects actually face risk-taking tasks with real outcomes (i.e., when the possibility of losing money after a risky decision is real). It would be interesting to design experiments directly comparing several risk-taking tasks within the same procedure, in order to clarify whether the lack of robust effects of chronotype on risky behavior are constrained to the use of a particular task to measure this construct.

Chronotype and social decision-making

The first report of synchrony effects on social decision-making was made by Bodenhausen (1990). Using a probability judgment task (Tversky & Kahneman 1983) and guilt judgments on members of particular social groups, Bodenhausen found that people made more stereotypic social judgments at non optimal (vs. optimal) times of day according to their MEQ chronotype. This finding was attributed to reduced resources of cognitive control to trigger deliberative thinking and consider carefully the relevant social information, in order to think beyond stereotypy. However, since later circadian research has not used similar social tasks, in this review we rather focused on economic games such as the Ultimatum Game (Güth et al., 1982).

In the Ultimatum Game, participants have to either accept or reject different offers proposed by another participant (e.g., “1/9”: 1€ for responder / 9€ for proposer). Acceptance involves distribution of gains as proposed, whereas rejection involves no gain for anyone. The predicted results according to economic theory are based on rational behavior to optimize gain, whereby all offers should be accepted regardless of the perceived fairness of the offer, since it is more convenient to accept 1/9 offers to gain 1 euro than rejecting them and gaining zero. Not surprisingly, people usually accept fair offers (5/5 and 4/6). However, when participants face unfair offers (3/7, 2/8 and 1/9) they deviate from rational decision-making and reject about 25% of them on average, a result interesting for Psychology and Behavioral Economics fields.

Neuroimaging research using the Ultimatum Game has shown that unfair offers increase metabolic activity in three main areas: the anterior insula, related to negative emotions like anger and disgust; the anterior cingulate cortex (ACC), related to conflict processing; and the dorsolateral prefrontal cortex (DLPFC), related to cognitive control and emotional regulation (Sanfey et al. 2003). The results were interpreted according to a model by which unfair offers elicit conflict due to opposite responses (“accept” vs. “reject”), involving ACC activation. Unfair offers were accepted if the winner of this competition was the DLPFC (related to rationality) over the insula (related to emotion). In contrast, unfair offers were rejected if the activation of insula won the competition. Optimal performance in this task would therefore involve top-down control by the DLPFC to regulate and inhibit the insula activation (related to negative emotions induced by unfair offers), resulting in high acceptance rate of such offers.

This model underlies our hypothesis regarding synchrony effects on social decision-making. Specifically, at optimal times of day participants would both exert higher inhibitory control over emotion and experience less negative emotions, leading to optimal decision-making as compared to non optimal times of day, when decisions would be dominated by negative emotions (Figure 1).

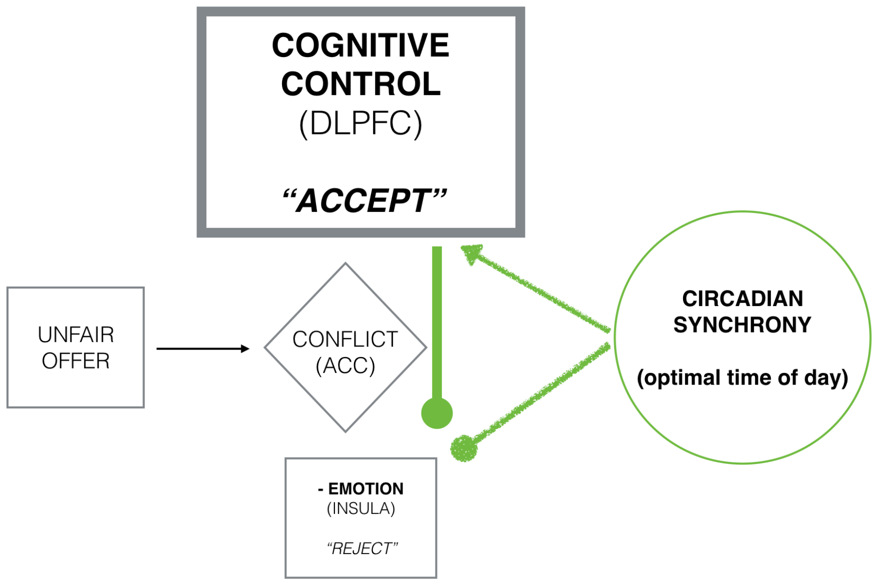

Figure 1. Hypothesis of circadian synchrony effects on decision-making in the Ultimatum Game based on the neural model by Sanfey et al. (2003).

This review has identified three studies addressing the role of sleep (Anderson & Dickinson, 2010) and chronotype (Correa et al., 2017; Dickinson & McElroy, 2017) on decisions during the Ultimatum Game. Anderson and Dickinson (2010) found that, after 36 hours of total sleep deprivation, participants became stricter to accept unfair offers, that is, the "minimum acceptable offer" was higher in relation to a control condition of rested wakefulness. This result was not replicated under less severe conditions of sleep restriction (5–6 h per night during a week), although the authors reported marginally significant effects of reduced prosocial behaviors as measured by Dictator and Trust Games (Dickinson & McElroy, 2017). So far, the synchrony effect has not been reported in the Ultimatum Game. Only a small but significant effect of chronotype was reported in the time taken to decide on unfair offers like 2/8 (or 3/7):

Morning-types decided slower than Evening-types, suggesting more cautious decision-making (Correa et al., 2017).

Conclusions from this review

In general, from the reviewed studies summarized in Table 1 we conclude:

The evidence regarding circadian synchrony effects on decision-making is mixed. Several studies have reported significant interactions between chronotype (all of them using MEQ or rMEQ) and time of day (Bodenhausen 1990; Gunia et al. 2014; Castillo et al. 2017), but not others (Ingram et al. 2016; Correa et al. 2017; Dickinson & McElroy 2017). The comparison between these two sets of studies suggests that the finding of synchrony effects cannot be easily explained by differences in sample size or age, differences in within-participants vs. between-participants experimental designs, instruments and procedures to form chronotype groups, or the times of testing. Naturally, the variability in these procedural features probably added a certain degree of noise and precludes clear-cut comparisons across studies. Therefore, we should aim at further replication studies by designing experimental series that hold constant the main parameters (chronotype manipulation, time of day) across experiments. Indeed, only two of the reviewed published works have followed this strategy (Bodenhausen 1990; Gunia et al. 2014).

Estimations of chronotype were limited to one measure and instrument in all cases except for Ingram et al. (2016). Note that Adan and Almirall (1991) reported that a 22% of their sample (N = 202 out of 908) changed chronotype group as measured by the MEQ and rMEQ (e.g., an intermediate-type who was classified as a morning-type). Moreover, the MEQ does not consider the influence of different work schedules to estimate chronotype. However, it is known that sleep timing can differ greatly between work-days and free days (Levandovski et al. 2013). The Munich Chronotype Questionnaire (MCTQ) provides a quantitative estimation of the person's sleep phase, separately for free days and work days, which can be used to define chronotype (Roenneberg et al. 2003; Kühnle 2006). This approach seems closer to the biological estimation of circadian profiles based on markers like body temperature or expression of clock genes (Ingram et al., 2016). Hence, the estimation of chronotype via measurement of multiple dimensions of this complex construct by considering both temporal preferences (MEQ) and actual timing schedules (MCTQ) could provide more comprehensive information regarding the circadian synchrony effects on decision-making.

Finally, we note that decision-making has been investigated through subjective and behavioral measures in most reports; however, there is a surprising lack of physiological data in this field. Since it is possible that circadian synchrony effects on decision-making are not evident at the behavioral but at the neural level, the recording of physiological correlates of decision-making can provide complementary and rich information to our main research question. The current experiment was conducted incorporating some of the issues raised in this review.

The current experiment

The current experiment studied circadian synchrony effects on social decision-making as measured by behavioral performance and electrophysiological correlates of choices in the Ultimatum Game. We expected regulatory control of negative emotions to be most effective at optimal times of day, such that the acceptance rate of unfair offers should be higher at optimal vs. non optimal times of day according to participants' chronotype (see Figure 1). Time of day for testing was scheduled at 8 am and 10 pm, so the evening session was considerably later than in Correa et al.'s study (2017), 5 pm, in order to increase the circadian mismatch of morning-types performing in the evening.

Chronotype was estimated subjectively, through three questionnaires (MEQ, rMEQ, MCTQ), and objectively, through the circadian rhythm of wrist temperature during a week of recording. Chronotype grouping was therefore more strict and aimed to include stable chronotypes across different measurements. The MCTQ and wrist temperature were used to provide further confirmation of actual sleeping schedules, and to study the relationship between these estimations of chronotype with behavioral performance in the Ultimatum Game.

Electroencephalographic (EEG) activity was measured during the performance of behavioral tasks. Event-related potentials tested with high temporal resolution whether the perception of fair and unfair offers can be modulated by circadian factors at the physiological level. We focused on the Medial Frontal Negativity (MFN), since the presentation of unfair offers in the Ultimatum Game triggers higher MFN amplitudes compared to the presentation of fair offers (Boksem & De Cremer 2010; Moser et al. 2014). The neural source of the Medial

Frontal Negativity has been located in the anterior cingulate cortex (Gehring & Willoughby 2002), a region associated with conflict processing and negative emotional states (Sanfey et al., 2003).

The current experiment further explored the link between emotional state and decision-making. The question of whether cognitive control would mediate decisions in the Ultimatum Game was already addressed in our previous study (Correa et al., 2017), so here we rather focused on the affective aspects of these decisions by using an appraisal task of stimuli from the International Affective Picture System (IAPS; Lang et al. 1999). Yoo et al. (2007) found a larger amygdala response to aversive IAPS stimuli and a decreased functional connectivity between the amygdala and the medial prefrontal cortex in a group of total sleep deprivation versus well rested participants, suggesting that negative emotion may dominate decision-making under sleep deprivation. Moreover, Liu et al. (2012) found that the Late Positive Potential (LPP) correlated with activity in the insula (processing of negative emotions) for unpleasant IAPS stimuli.

The following hypotheses were tested:

1. In the Ultimatum Game, there will be lower acceptance rates and larger MFN amplitude for unfair versus fair offers.

2. Unfair offers will be more accepted and the MFN amplitude will be attenuated at optimal vs. non-optimal times of day, that is, we will observe a synchrony effect.

3. According to Ingram et al. (2016), we expect differential effects on behavior as a function of chronotype measures, being wrist temperature more sensitive to the synchrony effect than chronotyping based on the questionnaire.

4. In the IAPS task, we expect more positive valence evaluations for positive than for negative pictures, and a synchrony effect where pictures in general will be rated as more positive in the morning by morning-types and in the evening by evening-types than at their respective suboptimal times of day.

5. Morning-types will rate, in general, IAPS images as more positive than evening-types.

6. If emotional appraisal mediates decision-making in the Ultimatum Game, appraisal

will correlate with higher acceptance rates of unfair offers.

MATERIALS AND METHODS

Participants

Sample size was calculated by power analysis (PANGEA, http://jakewestfall.org/pangea/) with .80 power at .05 alpha error probability to detect most relevant effect sizes (between .25 and 1.9) reported in related studies (Bodenhausen 1990; Gunia et al. 2014; Ponzi et al. 2014; Ingram et al. 2016; Correa et al. 2017), which estimated a minimum of 30 participants per group.

Sixty-three healthy volunteers were recruited through announcements and from a database of students from the University of Granada. All of them had normal or corrected-to-normal vision. The study was conducted at Granada, Spain (coordinates: 37°11′33″N, 03°35′58″W; UT+02:00) between March and October 2017. Only participants with extreme morning or extreme evening chronotypes were selected: the morning-type group included participants with rMEQ scores between 17 and 24, whereas in the evening-type group scores were between 4 and 11 (Correa et al. 2013; Correa et al. 2014; Correa et al. 2014; Lara et al. 2014). This initial classification of chronotype had to be confirmed by the MEQ completed at the experimental session, according to previous research (Lara et al. 2014). This criterion discarded two morning-types according to rMEQ, who changed to evening-types according to MEQ (Subjects 11 and 41), and one evening-type that was later categorized as morning-type (Subject 44). This procedure warranted a strict selection of extreme and stable chronotypes. Further exclusion criteria were pregnancy, major medical conditions, circadian or sleep disorders, night or shift work, and transmeridional travels within three months prior to the experiment. Data from two morning-type participants who felt slept during the evening session were rejected (Subjects 2 and 45).

The final sample included 58 participants (28 Morning-types and 30 Evening-types) with ages ranging between 18 and 36 years (M = 21.55, SD = 3.49; 15 men). This study was approved by the Ethics Committee of the University of Granada (n.34/CEIH/2015). All experimental protocols conform to international ethical standards (Portaluppi et al. 2010). All participants gave prior written informed consent and they were rewarded economically (30 EURO) at the end of the experiment.

Apparatus and stimuli

Questionnaires

The Pittsburgh Sleep Quality Index (PSQI) evaluated sleep quality (Buysse et al. 1989). The PSQI assesses usual sleep habits during the last month and is composed of 19 items grouped in 7 dimensions: subjective sleep quality, sleep latency, duration, efficiency and disturbances, use of sleep medication and performance during the daytime. Scores can range from 0 to 21, with higher values indicating poorer sleep quality.

The Spanish version of the reduced Morningness–Eveningness Questionnaire (rMEQ; Adan & Almirall, 1991) was administered online to assess participants' chronotype. The standard version of MEQ (Horne and Östberg, 1976) was later applied during the experiment (definitely evening type: score 16–30, moderately evening type: 31–41, neither type: 42–58, moderately morning type: 59–69 and definitely morning type: 70–86).

The Munich Chronotype Questionnaire (MCTQ; Roenneberg et al. 2003) assessed midsleep time for free days (MSF) and workdays (MSW) separately, by computing the midpoint between actual sleep onset and wake up times. We applied the correction to MSF by sleep debt (MSFsc) proposed by Roenneberg et al. (2004), who considered that people usually sleep more during free days to recover the sleep debt accumulated during work days. According to these authors, MSFsc, measured at free days, is a reliable marker of chronotype, because it is free of the influence of social demands from workdays. We likewise applied this same correction for sleep debt in work days (MSWsc), as recommended by Jankowski (2017). The following formulae were therefore used:

MSFsc = sleep onset on free days + half of the average weekly sleep duration.

MSWsc = sleep onset on workdays + half of the average weekly sleep duration.

The Positive and Negative Affect Schedule (PANAS; Watson et al. 1988), has twenty 5-

level Likert items that measure both positive and negative affect. The affective balance index is computed by subtracting positive minus negative affect scores, with higher scores above zero representing a positive affective balance.

Ultimatum Game

Participants played a modified version of the Ultimatum Game in which they had to either accept or reject economic offers made by a partner, who was a different person on each trial. Participants were told that in each trial their partner, the proposer, received an initial amount of fictional money (10 Euros) and split it into two parts, one for each of them. The participant then had to either accept or reject the offer. If she/he accepted it they would both earn their share, whereas if she/he decided to reject the offer, none would add money for that trial. To every participant, the same set of splits including two kinds of fair offers (5/5, 4/6) and three different unfair offers (1/9, 2/8, 3/7) were presented.

The participant was told that offers used in the experiment were made by other participants in previous experiments from a foreign university. They were also informed that they were playing with actual money and their decisions would impact in both theirs and their partners' final payment.

Each trial started with a fixation cross ("+"; 0.4° of visual angle) lasting 1750 ms on average (random 1500-2000 ms) in the center of the screen (Figure 2). Subsequently, a picture of a proposer's face (7.15°) was displayed for 200 ms, and then, the fixation point was presented for another 750 ms on average (random 500-1000 ms). Finally, the offer, consisting of two numbers separated by a slash symbol (1.5°), appeared at the center of the screen lasting 1500 ms. The first number corresponded to the amount for the responder, i.e., the participant. The whole experiment consisted of 300 trials and had an approximate duration of 30 min. A different set of non-affective faces was used for each experimental session (for a total of 600 different images).

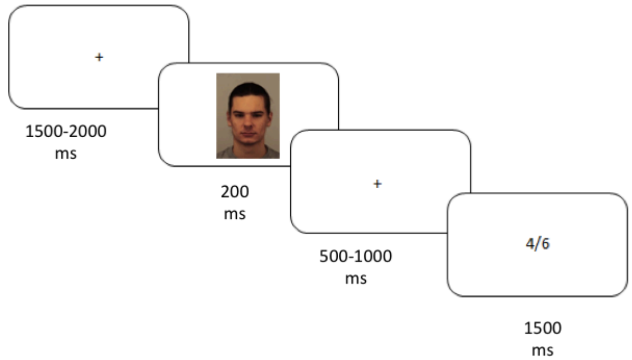

Figure 2. Schematic display of a trial sequence in the Ultimatum Game.

International Affective Picture System (IAPS)

Participants were required to appraise a set of IAPS pictures (Lang et al., 1997). These images were selected to target positive (M = 7. 20, SD = 0.60) and negative (M = 2.77, SD = 0.92; $p <$ .001) emotions. The IAPS was complemented with the Self-Assessment Manikin (SAM; Bradley & Lang 1994), a non-verbal pictorial assessment tool by which participants rated both valence and arousal of the IAPS pictures.

Each trial started with a fixation cross ("+"; 0.4° of visual angle, in gray font color) lasting 1750 ms on average (random 1500-2000 ms) and appearing at the center of the screen, over a black background (Figure 3). Then, a picture from the IAPS dataset (24 x 42°) was displayed for 200 ms. The picture was followed by another fixation point during 700 ms on average (random 600-800 ms). Finally, in two consecutive displays, lasting 3000 ms each one, participants were required to rate (from 1 to 9 in a Likert-type scale) the IAPS image according to the SAM regarding affective valence and arousal level. Pictures form the IAPS were different for each session (240 images in total were selected from the IAPS dataset). The 120 emotional pictures were presented on a trial-by-trial basis in each session. Positive and negative pictures were presented in different blocks (positive or negative) with the same order of presentation across morning and evening sessions, but counterbalanced across participants.

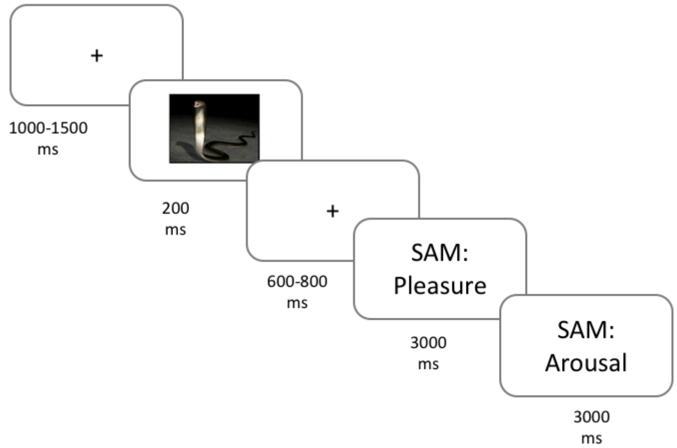

Figure 3. Sequence of events in a trial of the appraisal task on stimuli from the International Affective Picture System (IAPS).

Physiological Data Collection

Skin temperature recordings

Body temperature was measured using a temperature sensor (iButton-DS1921H; Maxim, Dallas), which has a temperature range from +15°C to +46°C and 1°C of accuracy with a precision of 0.125°C. The sensor was placed, at the beginning of the first experimental session, at the palmar side of the wrist of the non-dominant hand (attached to a sport band) and was removed after the end of the last session. The sensor was programmed to sample every ten minutes along the whole study period (9 days).

EEG recording and pre-processing

Continuous EEG data were derived from 32 active Ag/AgCl electrodes attached on the subjects' head (Acticap, Brain Products, Munich, Germany), according to the "10–20 International System". The sampling rate was set at 1000 Hz (Brain Vision Recorder, Brain Products, Munich, Germany). Electrode impedance was reduced to less than 5 kΩ throughout the recording. The cap was adapted to individual head size, and each electrode was filled with Signa Electro-Gel (Parker Laboratories, Fairfield, NJ) to optimize signal transduction. Participants were instructed to avoid postural movements as much as possible and to keep their gaze on the center of the screen during the task. EEG data pre-processing was conducted using custom MATLAB scripts and the EEGLAB (Delorme & Makeig, 2004) MATLAB toolbox. Data were band-pass filtered offline from 0.1 and 40 Hz to remove signal drifts and line noise, and re-referenced to a common average reference. Horizontal electro-oculograms were recorded by bipolar external electrodes for the offline detection of ocular artifacts. The EEG was then segmented 200 ms before and 1000 ms after target onset. Independent component analysis (ICA) was used to remove artifacts such as eye movements and muscle noise (Onton et al. 2006). A minimum of 30 trials per condition will be established to consider participants' data as valid for EEG data. The Greenhouse-Geisser correction was applied when sphericity was violated (Jennings & Wood 1976), and corrected probability values and degrees of freedom are reported. Data from bad channels were later replaced using a spherical interpolation algorithm (Perrin, Pernier, Bertrand, & Echallier, 1989). Finally, trials containing electro-oculogram differences greater than 70 μV were excluded. A 200-ms pre-stimulus interval was used as baseline.

For target analyses (offer in UG and affective picture in IAPS tasks, respectively), amplitudes were calculated as the mean voltage in temporal windows and electrodes chosen on the basis of visual inspection of the grand average waveforms and on the topographical distribution of the scalp activity. Specifically, the MFN potential was represented at frontal and central sites (Fz, FC1, FC2 and Cz) as the mean amplitude between 320 and 380 ms after offer onset in the UG task. Exploratory analyses included the P200 potential after visual inspection of data and later reading of the literature (Potts et al. 2006, see Discussion for details; Dong & Yang 2008). The P200 potential was located at frontal sites (FC1, FC2 and Fz) as the mean amplitude between 180 and 210 ms after the offer onset. Finally, the LPP was analyzed at central and parietal sites (CP1, CP2, Cz and Pz) as the mean amplitude between 500 and 800 ms after picture onset in 'the IAPS.

Procedure

Participants completed an online version of the rMEQ before the laboratory sessions. They carried out a first screening session of one hour, and two 1.5-hour experimental sessions in different days. The screening session and first experimental session were separated by one week, in which participants were instructed to follow their habitual schedule. During the screening session, the temperature sensor was placed at the armpit. Then, participants completed the MCTQ, PSQI and PANAS.

In the experimental sessions (separated by at least 48 h), morning-type and evening-type participants were tested at two different times of day (8:00 and 22:00 h). The order of these two experimental sessions was counterbalanced across participants within each experimental group. Participants were seated in front of a computer, connected to a 21-inch monitor, in a sound-attenuated Faraday dim-light room and were prepared for EEG measurements. Then, the Ultimatum Game was administered, for 30 minutes approximately. Finally, they carried out the IAPS appraisal task, which lasted about 12 minutes. The order between these two tasks was not counterbalanced to facilitate comparison with our previous research (Correa et al., 2017), in which the Ultimatum Game was the main and first administered task.

Design and data analysis

The general design was a mixed factorial analysis of variance (ANOVA) with Chronotype (Morning-type, Evening-type) manipulated between participants, and Time of day (Morning: 8 am, Evening: 10 pm) manipulated within participants.

Separate ANOVAs with Chronotype as factor were conducted on age, chronotype scores (MEQ, MSWsc, MSFsc, midsleep point of wrist temperature), sleep quality (PSQI) and affective balance (PANAS) registered in the screening session.

The analysis of PANAS questionnaire also included Pre-post testing (Pre-task, Post-task) as within-participant factor, with affective balance (positive affect minus negative affect) as the dependent variable.

The Ultimatum Game task further included Offer (Fair: 4/6 and 5/5, Unfair: 1/9, 2/8, 3/7) as within-participant factor. Dependent variables were acceptance rate and decision time in the behavioral analyses. In the electrophysiological analyses, the mean amplitudes of both MFN and P200 were analyzed (see below for further details on EEG analysis). Only trials with a valid response, with reaction time between 100 and 1500 ms (0.33% rejected), were included.

The IAPS task included Valence of the pictures (Negative, Positive) as a within-participant factor. The dependent variables in the behavioral analyses were the evaluation of both arousal and valence (9 point Likert-type scales). In the electrophysiological analyses, the mean amplitude of the LPP was analyzed.

Pearson correlation analyses tested: 1) the relationship between different estimations of chronotypes, 2) whether acceptance rate of unfair offers was related to our different measures of chronotype, and 3) whether such economic decisions were related to emotion as measured by the appraisal of IAPS stimuli.

Data from circadian rhythms of wrist temperature were submitted to non-parametric analyses (Refinetti 1992) to estimate the Midsleep time: the central time of M5 phase, where M5 is defined as five consecutive hours when skin temperature is maximal. We computed midsleep time for both working days (MSwrist-Work) and free days (MSwrist-Free). Temperature data from one morning-type (Subject 39) and from one evening-type (Subject 42) could not be analyzed due to technical problems during the recording. Preliminary analyses showed that MSwrist-Free was not reliable, as four additional subjects did not wear the sensor on the weekend, and other subjects wore it only partially, leading to noisy recordings, so this measure was not included in correlational analyses.

RESULTS

Demographic and circadian rhythms

Morning-type and evening-type groups were matched in gender (10% vs. 16% of males, respectively), $\chi^2(1) = .55$, $p = .46$, and age, $F\ (1, 56) = 3.27$, $p = .08$. Chronotype classification based on the rMEQ scores was confirmed by significant differences between groups in both the long version (MEQ), $F\ (1, 56) = 137.41$, $p < .01$, $\eta p^2 = .71$, and the Munich questionnaire (MCTQ) indices of midsleep times, on working days (MSWsc), $F\ (1, 56) = 51.99$, $p < .01$, $\eta p^2 = .48$, and on free days (MSFsc), $F\ (1, 56) = 36.26$, $p < .01$, $\eta p^2 = .39$ (Table 2).

Table 2. Demographic and questionnaires data. Mean scores (standard error of the mean between brackets) for Morning-type and evening-type groups. MEQ: Morningness-Eveningness Questionnaire; MSWsc: Midsleep point for working days corrected for sleep debt; MSFsc: Midsleep point for free days corrected for sleep debt; MSwrist-Work: Midsleep point for working days estimated by wrist temperature; MSwrist-Free: Midsleep point for free days estimated by wrist temperature; PSQI: Pittsburgh Sleep Quality Index; MCQT: Munich

Chronotype Questionnaire; PANAS: Positive and Negative Affect Schedule (affective balance score from the screening session). Midsleep points and sleep durations are expressed as hours in the centesimal system.

	Morning-Type	**Evening-Type**	**Chronotype effect**
Age	22.39 (.65)	20.77 (.66)	F (1, 56) = 3.27, p = .08
MEQ	56.68 (1.32)	35.20 (1.27)	F (1, 56) = 137.41, p < .01, ηp^2 = .71
MSWsc	4.01 (.16)	5.66 (.16)	F (1, 56) = 51.99, p < .01, ηp^2 = .48
MSFsc	4.88 (.21)	6.61 (.20)	F (1, 56) = 36.26, p < .01, ηp^2 = .39
MSwrist-Work	3.86 (.64)	6.29 (.61)	F (1, 54) = 7.59, p < .01, ηp^2 = .12
MSwrist-Free	7.02 (.78)	7.71 (.82)	F (1, 50) = .37, p = .55
PSQI	5.11 (.54)	8.33 (.52)	F (1, 56) = 18.62, p < .01, ηp^2 = .25
Sleep Duration Work (MCTQ)	7.99 (.21)	7.03 (.20)	F (1, 56) = 11.28, p < .01, ηp^2 = .17
Sleep Duration Free (MCTQ)	8.62 (.28)	8.78 (.27)	F (1, 56) = .17, p = .68
PANAS	13.61 (1.68)	7.87 (1.62)	F (1, 56) = 6.03, p = .02, ηp^2 = .10

In the screening session, Morning-type, as compared to Evening-type participants, reported having better sleep quality (PSQI), F (1, 56) = 18.62, p < .01, ηp^2 = .25, longer sleep duration in working days (MCTQ), F (1, 56) = 11.28, p < .01, ηp^2 = .17 (but not in free days: F (1, 56) = .17, p = .68), and reported more positive affective balance (PANAS), F (1, 56) = 6.03, p = .02, ηp^2 = .10. Since all these variables (PSQI, sleep duration and PANAS) did not correlate with our variable of interest, acceptance rate of unfair offers (r = -.04, p = .78; r = -.01, p = .92 and r = .01, p = .95, respectively), they were not analysed further as covariates.

The analysis of wrist temperature further provided objective confirmation of the different circadian rhythms as a function of our chronotype manipulation. Note that distal wrist temperature normally follows the inverse pattern as central temperature (Sarabia et al. 2008; Ortiz-Tudela et al. 2010). Figure 4 shows an evening rise of distal temperature in anticipation of sleeping, which occurred earlier in morning-types than in evening-types. The figure also shows phase differences between chronotypes regarding the point of maximal distal temperature (lowest arousal), leading to differential temperatures at the times of testing: wrist temperature was lowest (high arousal) both for Morning-types in the morning and for Evening-types in the evening session (shaded rectangles, Figure 4).

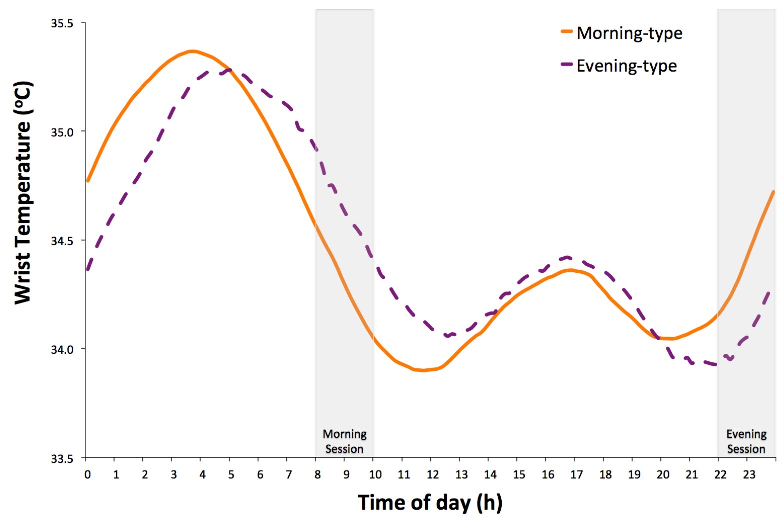

Figure 4. Circadian rhythm of wrist temperature averaged across working days for Morning-type (orange solid line) and Evening-type (purple dashed line) groups. Shaded bars mark the timing of morning and evening sessions.

These visual impressions were confirmed by a significant effect of chronotype on the midsleep time during working days (MSwrist-Work), F (1, 54) = 7.59, p < .01, ηp^2 = .12, peaking around 2.5 hours earlier for morning-types (3:51 am) than evening-types (6:17 am). This difference however vanished during the weekends (F (1, 50) = .37, p = .55), as morning-types delayed their midsleep point (7:01 am) nearly as much as evening-types (7:43 am).

Results of experimental sessions

The chronotype x time of day ANOVA on wrist temperature during the experiment showed a main effect of time of day (Morning: 34.40 ºC vs. Evening: 34.92 ºC, F (1, 56) = 8.16, p < .01, ηp^2 = .13, which was qualified by an interaction with chronotype (i.e., the synchrony effect, Figure 5, left), F (1, 56) = 7.76, p < .01, ηp^2 = .12. Temperature differences between chronotypes were significant in the evening, F (1, 56) = 5.37, p = .02 (higher temperature for Morning-types vs. Evening-types), but not in the morning session, F (1, 56) = .79, p = .38.

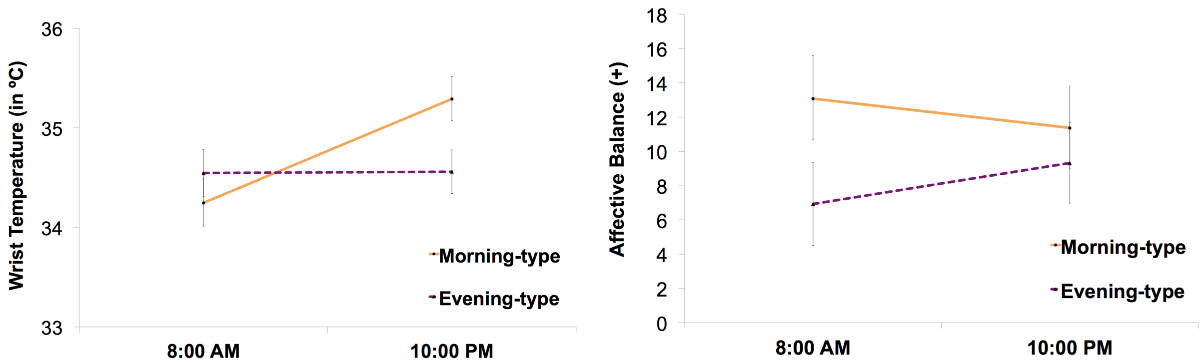

Figure 5. Synchrony effects on both wrist temperature (left panel) and affective balance in the PANAS (right panel), as a function of Chronotype (Morning-type -orange solid line-, Evening-type -purple dashed line) and Time of Day (8 am, 10 pm) of testing sessions.

The chronotype x time of day x pre-post testing (pre-task, post-task) ANOVA on affective balance (PANAS) showed a significant synchrony effect, Chronotype x Time of day: F (1, 56) = 9.93, p < .01, ηp^2 = .15, with Morning-types reporting more positive affect than Evening-types in the morning, F (1, 56) = 6.27, p = .02, but not in the evening, F (1, 56) = .73, p = .40 (Figure 5, right). The chronotype x pre-post testing interaction was also significant, F (1, 56) = 8.95, p < .01, ηp^2 = .14, indicating that positive affect decreased along the session in Morning-types (Pre score: 13.70 vs. Post: 10.77, F (1, 56) = 11.09, p < .01), but not in Evening-types, who reported having already lower positive affect since the beginning (Pre: 7.76 vs. Post: 8.49, F (1, 56) = .74, p = .39).

Ultimatum Game results

The chronotype x time of day x offer ANOVA on acceptance rates confirmed that participants accepted more frequently fair offers than unfair offers, F (1, 56) = 293.56, $p < .01$, $\eta p^2 = .84$ (Hypothesis 1). Most relevant, this behaviour differed between chronotypes (chronotype x offer: F (1, 56) = 4.25, $p = .04$, $\eta p^2 = .07$), as morning-types tended to accept more unfair offers than evening types, F (1, 56) = 3.28, $p = .08$ (Figure 6). The synchrony effect was not significant (chronotype x time of day: F (1, 56) = 1.07, $p = .30$; chronotype x time of day x offer: $F < 1$).

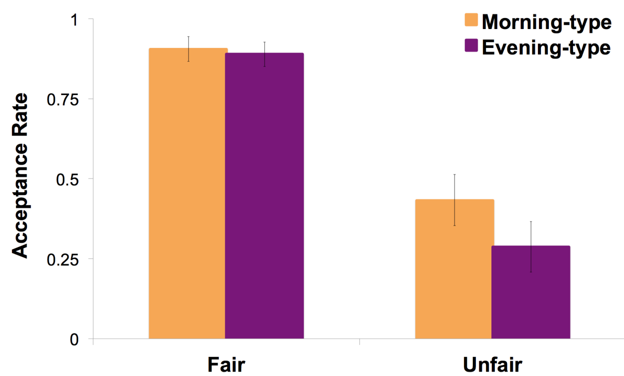

Figure 6. Mean acceptance rate in the Ultimatum Game as a function of Chronotype (Morning-type: orange bars, Evening-type: purple bars) and Offer (fair: 5/5 and 4/5, unfair: 3/7, 2/8, 1/9).

The chronotype x time of day x offer ANOVA on decision times confirmed that participants were faster in accepting fair than unfair offers, F (1, 56) = 23.65, $p < .01$, $\eta p^2 = .30$ (M = 541 ms vs. M = 579 ms, respectively). A main effect of time of day, F (1, 56) = 6.65, $p = .01$, $\eta p^2 = .1$, revealed faster decisions in the evening than in the morning (M = 544 vs 576 ms). The synchrony effect was far from significant (chronotype x time of day and chronotype x time of day x offer: $Fs < 1$).

The chronotype x time of day x offer ANOVA on the mean amplitudes of MFN replicated a main effect of offer, F (1, 56) = 6.14, $p = .02$, $\eta p^2 = .10$, with a larger amplitude for unfair offers as compared to fair offers (M = -0.58 vs. M = -0.33 μV). No other effects were significant (all $ps > .1$).

The chronotype x time of day x offer ANOVA on the mean amplitudes of P200 revealed a main effect of time of day, F (1, 56) = 43.73, p < .01, ηp^2 = .44, with a smaller amplitude at evening as compared to morning sessions (M = 1.52 vs. 2.26 μV). The main effect of offer was also significant, F (1, 56) = 10.82, p < .01, ηp^2 = .16, with a smaller amplitude for unfair offers as compared to fair offers (M = 1.78 vs. 1.99 μV). Most relevant, the chronotype x offer interaction, F (1, 56) = 4.45, p = .04, ηp^2 = .07 (Figure 7), showed that the offer effect was significantly reduced for unfair vs. fair offers by Morning-types, F (1, 56) = 14.08, p < .01, but not by Evening-types. (F < 1). The synchrony effect was far from significant (chronotype x time of day and chronotype x time of day x offer: Fs < 1).

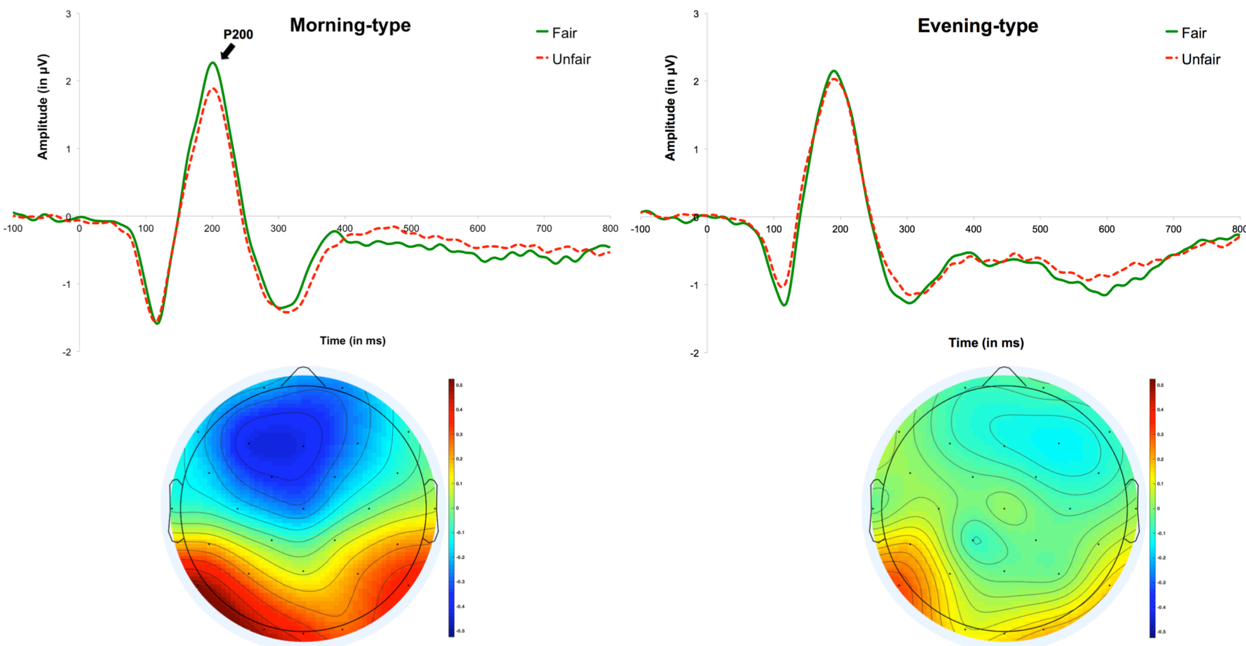

Figure 7. Grand average waveforms at frontal electrodes (FC1, FC2 and Fz collapsed) time-locked to offer onset as a function of Offer (fair: green, solid line; unfair: red, dashed line) and Chronotype (Morning-type: left panel, Evening-type: right panel) in the Ultimatum Game. The topographies, below each chronotype group, represent the difference wave of the P200 potential (between 180 and 210 ms) for unfair minus fair offers; they show attenuation of the P200 at frontal sites that is selective to morning-types.

International Affective Picture System (IAPS) Task

The chronotype x time of day x valence (negative, positive) analyses showed that negative vs. positive pictures were judged as more arousing (M = 6.32 vs. 5.42, F (1, 56) =

40.40, $p < .01$, $\eta p^2 = .42$) and less pleasant (M = 2.73 vs. 6.94, F (1, 56) = 702.66, $p < .01$, $\eta p^2 = .93$). No other effects were significant (all *ps* > .16). The mean amplitude of the LPP also replicated a main effect of valence, F (1, 56) = 17.99, $p < .01$, $\eta p^2 = .24$, with positive pictures inducing a larger LPP than negative ones (M = 1.25 vs. 0.95 μV). The LPP was also larger at evening vs. morning sessions (M = 1.26 vs. 0.95 μV, F (1, 56) = 6.38, $p = .01$, $\eta p^2 = .10$). No other effects were significant (all *ps* > .2).

Correlation analyses

Table 3 details the Pearson correlations between our different estimations of chronotype. All chronotype measures showed significant correlations, with the strongest relationship between the MEQ and its reduced version (rMEQ), whereas the weakest (yet significant) correlations (r coefficient about 0.3) involved the objective estimation of chronotype based on wrist temperature (MSwrist-Work).

Table 3. Matrix of Pearson Correlation Coefficients between chronotype measures. P-values for all correlations were < .01 (otherwise indicated between brackets). rMEQ: reduced Morningness-Eveningness Questionnaire; MEQ: Morningness-Eveningness Questionnaire; MSFsc: Midsleep point for free days corrected for sleep debt; MSWsc: Midsleep point for working days corrected for sleep debt; MSwrist-Work: Midsleep point for working days estimated by wrist temperature.

	MEQ	**MSFsc**	**MSWsc**	**MSwrist-Work**
rMEQ	.87	-.62	-.71	-.35
MEQ		-.64	-.75	-.31 (*p*=.02)
MSFsc			.51	.32 (*p*=.02)
MSWsc				.33 (*p*=.01)

Most relevant, the acceptance rates of unfair offers correlated with chronotype as measured by the rMEQ ($r = .33$, $p = .01$), MEQ ($r = .26$, $p = .05$), and the MSWsc ($r = -.30$, $p = .02$; Figure 8). As Figure 8 shows, participants with later midsleep times during working days in the Munich questionnaire (MSWsc) accepted less unfair offers than participants with earlier midsleep points. It has been proposed that higher social jet lag in evening-types results in sleep loss and emotional distress (Wittmann et al. 2006). To test this possibility, ad hoc analyses were performed on Social Jet Lag corrected for sleep debt (SJLsc) as recommended by Jankowsky (2017), but they did not reveal any difference between evening-types (M: 54 min, SEM: 14 min) and morning-types (M: 46 min, SEM: 14 min; $F < 1$).

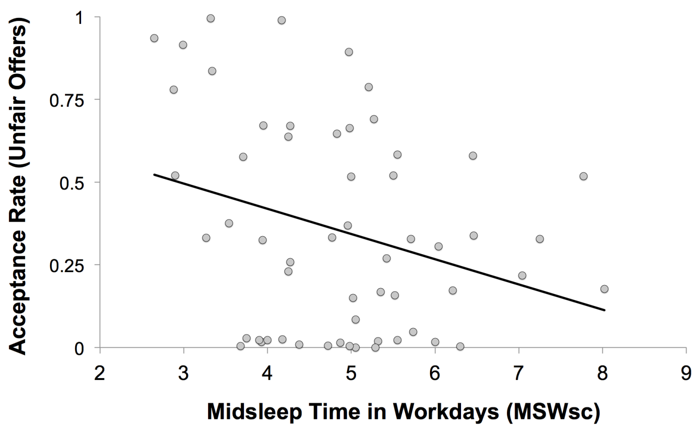

Figure 8. Linear negative correlation between acceptance rates of unfair offers and chronotype as quantified by the Midsleep point for working days corrected for sleep debt (MSWsc).

Finally, midsleep times during free days (MSFsc) and the biological measurement of chronotypes (MSwrist-Work) did not correlate with the acceptance of unfair offers ($r = -.19$, $p = .15$; $r = .01$, $p = .94$, respectively). The correlation between acceptance rates to unfair offers and appraisal was significant only for positive images ($r = .28$, $p = .04$; for negative images: $r = .11$, $p = .42$), such that participants that accepted more unfair offers later judged positive IAPS stimuli as more pleasant.

DISCUSSION

The current study tested whether people make better economic decisions at optimal times of day according to their chronotype. Three main contributions of this work can be summarized as follows: 1) Human chronotype was characterized following a multidimensional approach, based on the estimation through subjective (rMEQ, MEQ and MCTQ) and objective (circadian rhythm of wrist temperature) measures. We tested which estimations of chronotype were most closely associated with behavioral decision-making; 2) electroencephalographic recordings informed, for the first time, on the neural dynamics underlying circadian effects on decision-making; and 3) the role of affective factors in decision-making was tested both explicitly, by self-report measures (PANAS), and implicitly, by the participants' appraisal of affective images.

The influence of chronotype (Morning-type vs. Evening-type) and time of day (8 am vs. 10 pm) on decision-making was measured by the acceptance rate of unfair and fair offers, and the event-related potentials time-locked to such offers, in the Ultimatum Game. Circadian rhythms of wrist temperature, subjective affect (PANAS), and appraisal of IAPS images were also measured.

The results confirmed the effectiveness of the chronotype manipulation, showing that Morning-types vs. Evening-types, classified according to the rMEQ score and confirmed by late administration of the MEQ, had more than 1.5 hours earlier midsleep times as indexed by both the Munich questionnaire and the wrist circadian rhythm. Chronotype interacted with time of day, leading to synchrony effects, both in wrist temperature recorded during the experimental session and in subjective affect: Morning-types had lower distal temperature (indicating higher arousal) and reported more positive affective balance in the morning than in the evening, while Evening-types tended to show the inverse pattern. This synchrony effect, however, was not reflected on the behavioral performance of the Ultimatum Game or IAPS appraisal tasks.

The lack of synchrony effects on performance in the Ultimatum Game did not confirm our Hypothesis 2, but replicated previous research using this same task (Correa et al. 2017; Dickinson & McElroy 2017). In fact, chronotype rather than time of day was the factor producing the strongest behavioral effects. Specifically, Morning-types reported better sleep quality and more positive affective balance, and most relevant to the current research, they accepted more unfair offers than Evening-types in the Ultimatum Game.

Our effect of morningness on economic decision-making was further replicated by significant correlations between different estimations of chronotype (rMEQ, MEQ and MSWsc) and the acceptance rates of unfair offers. However, in contrast to both Hypothesis 3 and Ingram et al. (2016), the chronotype effect was not stronger when estimated objectively through the circadian rhythm of wrist temperature. Indeed, MSwrist-Work was not predictive of the acceptance of unfair offers, and showed the weakest correlations with chronotype measures based on questionnaires. This dissociation between subjective and objective estimations of chronotype justifies the importance of multidimensional approaches to understand human chronotype, as they inform of different aspects: individual preferences related to a trait-like feature vs. actual sleep/wake schedules (Levandovski et al. 2013). In other words, our results suggest that chronotype, as measured by questionnaires in relation to an ideal preference, cannot be completely estimated by an objective monitoring tool. It is, however, possible that our measure of wrist temperature was not sensitive enough, so other circadian markers (actigraphy, expression of clock genes) should be tested in future research.

Our main finding is also in line with Anderson and Dickinson (2010), who reported reduced acceptance of unfair offers after 36 h of total sleep deprivation. Although our evening-types were not sleep deprived, they indeed reported shorter sleep duration in working days (MCTQ) and poorer sleep quality (PSQI) than morning-types. Since we did not record sleep diaries or actigraphy, it is difficult to conclude that evening-types showed less optimal decisions because they slept less or were partially sleep deprived as compared with morning-types. However, even if we assumed that evening-types could have a mild form of sleep restriction in the 8 am session, the lack of synchrony effects in our study, and the null effect of sleep restriction (5-6 h per night during a week) on acceptance rates reported by another study (Dickinson & McElroy, 2017) does not support convincingly this explanation. Note also that sleep quality (PSQI scores) and duration did not correlate with acceptance rates of unfair offers. Therefore, differences in sleep quality or duration between chronotypes may not be the main explanatory factor.

Electroencephalographic results provide a plausible explanation to our main finding. Event-related potentials time-locked to the presentation of the offer replicated the expected result (Hypothesis 1) of larger MFN for unfair than fair offers. However, this marker was not sensitive to circadian factors. Interestingly, the frontal P200 amplitude to unfair (vs. fair) offers was attenuated only in morning-types but not in evening-types. Dong and Yang (2008) used an emotional flanker task where a central face was flanked by other faces portraying either positive or negative emotions, and found that the P200 was larger when the flanking faces were negative rather than positive. This result points to the P200 as a marker of emotional conflict, being increased when the distracting negative emotion has to be inhibited. Analogously, since optimal decisions in the Ultimatum Game involve regulation of negative emotions induced by unfair offers to accept them, the reduced P200 to unfair offers in morning-types may represent a brain correlate of more efficient emotional regulation in this group. In other words, the larger P200 in evening-types would signal the dominance of negative emotion over cognitive control underlying the rejection of unfair offers. In fact, the P200 seems to share a common neural source to the MFN (Potts et al. 2006), with the ACC involved in the processing of conflict and negative emotions (Sanfey et al. 2003).

The subjective reports of more positive affective balance (PANAS) by morning-types vs. evening-types tested in the screening session, and the finding of a synchrony effect during the experimental sessions, supported the relevance of chronotype and time of day in the affective state of individuals, replicating previous research (Kerkhof 1998; Porto et al. 2006; Biss & Hasher 2012; Díaz-Morales et al. 2015; Miller et al. 2015; Berdynaj et al. 2016; Horne et al. 2016). In contrast, the implicit measurement of the affective state through the appraisal task of emotional stimuli (IAPS) showed a different pattern, and the effects of chronotype predicted by Hypothesis 4 (synchrony effect) and Hypothesis 5 (more positive appraisal for morning-types) were not confirmed. Nevertheless, the correlational results revealed that participants who accepted more unfair offers also judged positive IAPS stimuli as more pleasant (Hypothesis 6). This finding further supported the influence of affective factors in our social decision-making task, providing a link between overall positive emotions and the optimal decision to accept unfair offers (Sanfey et al. 2003; Yoo et al. 2007).

Conclusions

Behavioral performance in social decision-making depends on individual differences in circadian rhythmicity, rather than on time of day; it did not depend, either, on the interaction between chronotype and time of day. Morningness, as measured by different chronotype questionnaires, was related to rational decision-making, that is, an increased acceptance of unfair offers in the Ultimatum Game. The neural model by Sanfey et al. (2003) can explain this result, since morning chronotypes have shown higher performance in cognitive control tasks relevant for emotional regulation (Horne & Norbury 2018), and they usually report more positive mood than evening-types. It is possible that unfair offers do not elicit negative emotions in morning-types as intense as in evening-types, as the former probably exerted higher emotional regulation, making easier for them to accept such offers.

Declaration of interest statement

The authors report no conflicts of interest.

Acknowledgements

This work was supported by the Spanish Ministerio de Economía y Competitividad (PLAN NACIONAL de I+D+i, grant number: PSI2014-58041-P. www.mineco.gob.es) to AC and by the Junta de Andalucía (SEJ-3054, http://www.juntadeandalucia.es) to AC and MR. Preliminary data were presented as a poster communication during the European Workshop on Cognitive Neuropsychology, held in Bressanone from 21 to 26 January 2018, and as a conference during the 30th Conference of the International Society for Chronobiology, held in Warsaw from 2 to 5 July 2019. The materials are available at http://doi.org/10.5281/zenodo.3347405.

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