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Time to decide: Diurnal variations on the speed and quality of human decisions

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ABSTRACT

Human behavior and physiology exhibit diurnal fluctuations. These rhythms are entrained by light and social cues, with vast individual differences in the phase of entrainment - referred as an individual's chronotype - ranging in a continuum between early larks and late owls. Understanding whether decision-making in real-life situations depends on the relation between time of the day and an individual's diurnal preferences has both practical and theoretical implications. However, answering this question has remained elusive because of the difficulty of measuring precisely the quality of a decision in real-life scenarios. Here we investigate diurnal variations in decision-making as a function of an individual's chronotype capitalizing on a vast repository of human decisions: online chess servers. In a chess game, every player has to make around 40 decisions using a finite time budget and both the time and quality of each decision can be accurately determined. We found reliable diurnal rhythms in activity and decision-making policy. During the morning, players adopt a prevention focus policy (slower and more accurate decisions) which is later modified to a promotion focus (faster but less accurate decisions), without daily changes in performance.

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1. Introduction

Living organisms exhibit diurnal fluctuations driven by internal circadian clocks, which persist (with a close to 24 h period) in the absence of external cues (Panda, Hogenesch, & Kay, 2002). As in other species, human circadian rhythms are synchronized by light cycles and social cues (Roenneberg, Kumar, & Merrow, 2007; Wittmann, Dinich, Merrow, & Roenneberg, 2006). Individual differences in entrainment phases (which are defined as the difference between the subject's internal phase and the external time cues), known as "chronotypes", determine the existence of late owls (subjects with Late preferences), early larks (subjects with Early preferences) and intermediate types. Chronotypes can be assessed using standard questionnaires regarding diurnal preferences (MEQ, Morningness–Eveningness Questionnaire (Horne & Ostberg, 1976)), or sleep habits on working and free days (MCTQ, Munich Chronotype Questionnaire (Roenneberg, Wirz-Justice, & Merrow, 2003)). Both scores are highly correlated and also correlate tightly with physiological phase markers (Baehr, Revelle, & Eastman, 2000; Horne & Ostberg, 1976; Kudielka, Federenko, Hellhammer, & Wust, 2006; Zavada, Gordijn, Beersma, Daan, & Roenneberg, 2005).

Circadian variations in physiological and cognitive functions have been demonstrated using constant routine or forced-desynchrony protocols (Schmidt, Collette, Cajochen, & Peigneux, 2007; Wyatt, Ritz-De Cecco, Czeisler, & Dijk, 1999). However, there is a paucity of data on how cognitive function in real life scenarios varies throughout the day and whether this varies according to chronotype. Theories of circadian function postulate that cognitive performance is modulated by both circadian and homeostatic processes (which also control the wake-sleep cycle) (Borbely, 1982; Daan, Beersma, & Borbely, 1984; Goel, Basner, Rao, & Dinges, 2013). One factor that has been postulated to influence cognitive function is sleep pressure. This homeostatic component accumulates sleep drive constantly throughout the wake periods. It then results in a monotonic degradation of cognitive function as a function of the progressive accumulation of time without sleep

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(Schmidt et al., 2007). However, empirical studies find that fluctuations in behavior do not simply change monotonically throughout the day. This is because sleep pressure interacts with the circadian drive; a periodical fluctuation of physiological variables which among other things regulate the threshold needed to trigger sleep, but also might be able to counteract the effects of sleep pressure in cognitive functioning (Goel et al., 2013; Schmidt et al., 2007). These variables interact in a complex way, in fact the phase of circadian performance (the moment of the day in which one achieves maximal performance) varies with the nature and complexity of cognitive tasks (Goel et al., 2013). In simple tasks, performance is normally associated with body temperature rhythms (better performance when temperature is high –during the day-, worse performance when temperature is low –during the night-) reflecting an effect of a daily rhythm in arousal. Instead, higher order cognitive processes exhibit daily modulations but do not systematically reflect arousal rhythms or changes in physiological parameters (Horne, 2012; Schmidt et al., 2007). There are several intrinsic difficulties in these studies. One is that these tasks tend to show more learning modulations than simple tasks. Hence, the non-stationary nature of the task repetitions (in different days and moments of the day) can become problematic. To overcome these difficulties, performance in complex cognitive tasks is normally evaluated using between-subject designs or is assessed only in two times of the day in each subject, usually testing at optimal and non-optimal time of the day (inferred by subjects' chronotypes), showing that participants perform better when tested at their preferred time (synchrony effect) (Hidalgo et al., 2004; May, 1999). In laboratory settings, the influence of sleep pressure and circadian rhythms can be controlled independently. Instead, when cognitive function is measured in real-life conditions, these factors are very difficult to parse out because circadian rhythms and sleep pressure tend to be correlated. For instance, late chronotypes tend to wake up later and hence at night there is a difference both in that it is their preferred time, but also that they have less sleep pressure. In addition, there are several variables such as meal times, the amount of physical activity which interact with the circadian clock and which vary widely and are hard to control in real life settings (Schmidt et al., 2007).

In summary, there is substantial evidence and theoretical support for daily variations in several aspects of human performance including very low-level tasks (such as psychomotor vigilance task), memory tasks, complex tasks, sports (Blatter, Opwis, Munch, Wirz-Justice, & Cajochen, 2005; Facer-Childs & Brandstaetter, 2015; Johnson et al., 1992; May & Hasher, 1998; Wright, Hull, & Czeisler, 2002). These changes result from a complex interaction between two governing factors: sleep pressure and circadian rhythms. However, one aspect which remains unknown is whether decision-making changes throughout the day. One exception is a study of judges showing that the percentage of favorable rulings abruptly change along the day in relation to food breaks (Danziger, Levav, & Avnaim-Pesso, 2011).

Here we set out to investigate diurnal fluctuations in human decision-making, capitalizing on online rapid chess servers. Indeed, these public repositories offer a huge amount of data of human decision-making in natural conditions and without the problems associated to the repeated testing (a main problem when evaluating diurnal profiles in higher order functioning).

Chess has been widely used in psychology and cognitive neuroscience as a model for studying complex human thinking and decision-making in a controlled but natural way (Charness, 1992; Connors, Burns, & Campitelli, 2011; de Groot, 1978; F. Gobet & H. A. Simon, 1996; Leone, Petroni, Fernandez Slezak, & Sigman, 2012; Sigman, Etchemendy, Slezak, & Cecchi, 2010; Slezak & Sigman, 2012). Chess is a voluntary activity, players choose when to play and when to stop, and they have to make around 40 moves or decisions by game on a finite time budget. One of the main advantages of chess, compared to other decision-making domains, is that the quality of a player can be accurately determined through a rating system (Elo, 1978). Finally, a fundamental advantage of this setup is that a measure of the outcome of each decision can be determined accurately (Sigman et al., 2010).

Hence, analyses of chess playing allow us to precisely determine diurnal fluctuations not only in activity but also in the speed and accuracy of the decision-making process and how these fluctuations interact with individual chronotypes.

Based on previous evidence about diurnal fluctuations which we described above, we expect that individual diurnal preferences or chronotypes determine the daily changes in chess playing, with individuals being more active and effective in their optimal time (when time of day is in synchrony with their preferred time). In particular, we hypothesized that players would exhibit circadian fluctuations in speed and accuracy of the decisions revealing diurnal variations which depend on specific chronotypes. These may lead to two alternative hypotheses which here we seek to investigate: (H1) the entire efficiency of the decision-making system, revealed in more accurate and faster decisions varies with time of day according to chronotypes, or (H2) alternatively, circadian fluctuations affect regulatory aspects of decision-making such as the speed/accuracy trade-off (SAT). Hypothesis 1 seems plausible from current knowledge of circadian modulations of behavior reviewed above, revealing changes in performance. Instead, from a neurophysiological perspective, it is more natural to postulate that circadian modulation should affect and govern the SAT. This is because changing the SAT simply requires to change baseline neural activity in decision-related areas, with higher baseline responses when speed is given precedence over accuracy (Forstmann et al., 2008; Ivanoff, Branning, & Marois, 2008; Shadlen & Newsome, 2001). Circadian rhythms regulate the concentration of several hormones, including steroids and other molecules which in turn control basal levels of neural activity. Specifically, the decision threshold is mainly set by a circuit in the basal ganglia (Lo & Wang, 2006) and the basal ganglia is a brain region whose activity is modulated by circadian rhythms (Bussi, Levin, Golombek, & Agostino, 2014; Mendoza & Challet, 2014). Moreover, the SAT is related to stress (Rastegary & Landy, 1993) and the concentration of cortisol (which is a hormone which indexes stress) varies with a circadian rhythm (Krieger, Allen, Rizzo, & Krieger, 1971).

In addition, as described above, homeostatic daily fluctuations interact with circadian rhythms which are idiosyncratic for each individual. Hence, we expect that daily fluctuations should interact with an individual's diurnal preference. As described above this interaction is highly complex but overall we expect (based on the studies reviewed here) that the efficacy of decision-making should increase during the preferred time. Last, reflecting the interaction between homeostatic sleep pressure and circadian rhythms, the differences in phase between chronotypes should be smaller when testing time is referred relative to the phase of individuals' wake-sleep cycle.

We tested these hypotheses with international open-access databases of chess players playing games of different time budgets, which allowed us to evaluate the robustness of diurnal variations in rapid and slow decision-making scenarios.

2. Methods

2.1. Data acquisition

All games were downloaded from FICS (*Free Internet Chess Server*, http://www.freechess.org/), a free ICS-compatible server for

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