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BRIEF REPORT

Effects of Circadian Cortisol on the Development of a Health Habit

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Objective: Given the impact of individuals' habits on health, it is important to study how behaviors can become habitual. Cortisol has been well documented to have a role in habit formation. This study aimed to elucidate the influence of the circadian rhythm of cortisol on habit formation in a real-life setting. ***Method:*** Forty-eight students were followed for 90 days during which they attempted to adopt a health behavior (psoas iliac stretch). They were randomly assigned to perform the stretch either upon waking in the morning, when cortisol concentrations are high, or before evening bedtime, when cortisol levels approach the nadir. A smartphone application was used to assess the Self-Report Behavioural Automaticity Index every day and to provide reminders for salivary measurements every 30 days. The speed of the health habit formation process was calculated by modeling the learning curves. ***Results:*** Extrapolation of the curves indicated that the *morning* group achieved automaticity at an earlier time point (105.95 days) than did the *evening* group (154.01 days). In addition, the cortisol level during the performance of the health behavior was identified as a significant mediator of the time point when the health behavior became habitual. ***Conclusion:*** The present findings suggest that the time course of the development of healthy habits depends on the time of the day and that the effect is mediated through diurnal variation in cortisol levels. Future studies are now needed to determine to what extent cortisol rhythmicity can help individuals to adopt new health behaviors.

Keywords: health, habits, learning, stress, cortisol

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Attention should be paid to behavioral habits, given their important role in health (Wood & Neal, 2016). A behavioral habit is a process by which a stimulus automatically generates an impulse toward action, based on learned stimulus–response associations (Gardner, 2015). Recent studies have pointed to the critical role of stress and the stress hormones (mainly cortisol) in the development of habit behavior. For instance, it has been shown that stress induces a shift in the control of instrumental behavior from goal-directed toward habitual responding (e.g., Schwabe, Schächinger, de Kloet, & Oitzl, 2010). The endogenous level of cortisol varies according to a circadian rhythm. In humans, cortisol levels are low at midnight and increase overnight to a peak in the morning. Following this morning peak, cortisol levels slowly decline throughout the day (Weitzman et al., 1971). Although the impact of cortisol on habit behavior has been well established through stress manipulation or cortisol injection (e.g., Fournier, d'Arripe-Longueville, & Radel, 2017; Quirarte et al., 2009), the influence of cortisol's circadian rhythm on habit formation remains to be elucidated.

Many studies have demonstrated the predictive capacity of habits on health behavior (e.g., de Bruijn & Rhodes, 2011), but less is known about the process of habit formation in real-life settings. A previous study followed participants over 84 days while they adopted a new, daily health-promoting behavior such as eating fruit or exercising (Lally, van Jaarsveld, Potts, &

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Wardle, 2010). Although this protocol was innovative in tracking the formation of habits by collecting daily reports of experienced automaticity, the collected data proved challenging to model. In the present study, a similar protocol was used to investigate the influence of diurnal variations in cortisol concentrations on the dynamics of habit formation using a real-world application. To better fit the evolution of experienced automaticity in time, we used logistic curves (Murre, 2014). The level of circadian cortisol was manipulated by having two groups of participants perform a new health behavior at different times of the day. Given that cortisol levels are higher in the morning than in the evening, we hypothesized that the new behavior would become habitual more quickly if executed in the morning than in the evening. The cortisol level was expected to mediate this effect.

Method

Participants

On average, diurnal variations of cortisol can lead to a 20% difference in learning and memory (May, Hasher, & Stoltzfus, 1993; Petros, Beckwith, & Anderson, 1990; Wyatt, Ritz-De Cecco, Czeisler, & Dijk, 1999), which suggests that at least 46 participants were needed to observe such an effect with a power of .80. Forty-eight French students (28 male; age = 21.7 ± 1.78 years, range = 20–25) participated in exchange for course credit. Participation was limited to healthy nonsmokers with normal body mass index (22.4 ± 2.17 kg/m^2, range = 18.2–27.7 kg/m^2) not under contraceptive medication according to the recommendations for salivary cortisol measurements (Kirschbaum, Kudielka, Gaab, Schommer, & Hellhammer, 1999). The study was approved by the local ethics committee for the protection of individuals (Université de Nice Sophia-Antipolis) and conducted in accordance with the Declaration of Helsinki (1964) ethical guidelines.

Procedure

Participants were invited to a first meeting with the experimenter. After providing written informed consent, they were randomly assigned to a *morning* or *evening* group according to a minimization algorithm, balancing for gender. Here, a chronotype questionnaire and a measure of intention to adopt the behavior was completed. The intervention commenced within a week of the first meeting. It consisted of performing a new behavior once daily for 90 days. The behavior was a stretching exercise that is highly recommended to maintain flexibility and prevent low back pain (i.e., psoas iliac stretch; see the online supplemental materials). Depending on group allocation, the stretch was completed in bed upon waking or before sleeping. Adherence and a visual analog scale version of the Self-Report Behavioural Automaticity Index (SRBAI; Gardner, Abraham, Lally, & de Bruijn, 2012) were recorded via a smartphone reminder application on a daily basis. A salivary sample was collected every 30 days. Details on the measures are provided in the online supplemental materials.

Data Analysis

To evaluate the evolution of automaticity, we fitted a four-parameter logistic function to participants' daily responses to the SRBAI (see the online supplemental materials). Although habit formation has previously been modeled using a power function (Lally et al., 2010), this method led to mixed results, providing a moderate fit ($R^2 > .70$) for only 48% of the participants. Because a logistic function can outperform a power function in modeling learning curves (Murre, 2014), this approach was adopted. We considered that, in line with Lally et al. (2010), automaticity was achieved at the time point at which 95% of the asymptote was reached ($x_{.95}$). This value served as the dependent variable.

To determine the group effect and the potential mediation effect of cortisol on $x_{.95}$, we employed a mediation model using the PROCESS toolbox (Hayes, 2012). Group (*morning* vs. *evening*) was applied as the independent variable, cortisol concentration as a mediator, and sex and intention as covariates for the prediction of the dependent variable. A bias-corrected bootstrapping method with 2,000 samples was used to evaluate the effects. The total effect of the independent variable and its indirect effect through the mediator are presented. To control for the chronotype, we used a moderation analysis to examine how the effect of group on $x_{.95}$ was influenced by the chronotype score. The mediation model was also used in a further configuration with the independent variable replaced by a Group × Chronotype interaction term. The interaction term adequately represented the hypothesis of a match between the moment of execution and the participants' chronotype score (Hasher, Goldstein, & May, 2005).

Results

Of the 48 recruited participants, 42 completed the experiment: 19 participants in the *morning* group and 23 in the *evening* group. The intention to adopt the behavior was high (4.74 ± 0.39), with no difference between groups ($p = .24$). The response rate to the daily questionnaire was high (89.2%), with no difference between groups ($p > .25$). Adherence was high (94.9%), with no difference between groups ($p > .25$). The curve-fitting process was highly successful. Fitting converged for each participant using the logistic function (by comparison, only 31 participants could be fitted using a power curve). A high adjustment quality index was obtained ($R^2 = .945 \pm .053$). Figure 1 presents the mean traces of the *morning* and *evening* groups obtained by averaging each of the four function parameters for each condition.

Automaticity ($x_{.95}$) was slightly positively skewed but did not significantly deviate from normality ($p = .10$). The results of the first mediation model populated with group as the independent variable are presented in Table 1. After controlling for covariates (sex and intention), we observed a significant total effect of time of day until habit development (effect = −26.74, SE = 10.25, 95% confidence interval [CI: −47.52, −5,96]), indicating that the behavior became habitual more quickly when it was performed in the morning (M = 105.95 ± 46.72 days) as opposed to the evening (M = 154.01 ± 71.05 days). Group (*morning* vs. *evening*) had a significant effect on the cortisol level, indicating that cortisol levels differed between groups (*morning:* 2.16 ± .87 ng/ml; *evening:* 1.10 ± .86 ng/ml). When included in the model predicting the time to form a habit ($x_{.95}$), cortisol was a significant predictor and the group effect was no longer significant, suggesting a me-

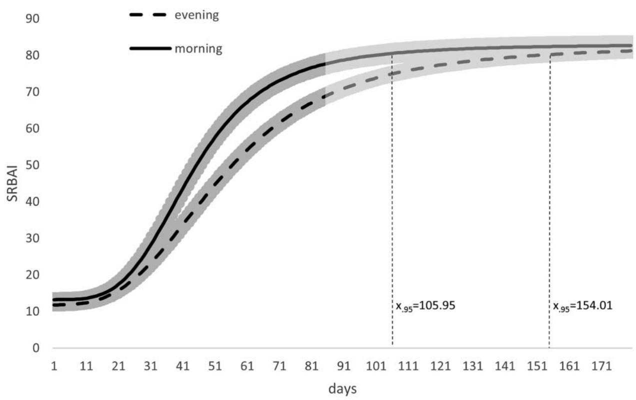

Figure 1. Fitted logistic function representating the evolution of behavioral automaticity (Self-Reported Behavioural Automaticity Index, SRBAI) in time in the morning and evening conditions. Shaded areas represent standard error of the mean. Data from after the measurement period (90 days) is extrapolated and indicated using light gray. The moment when participants reach 95% of the maximal asymptote (dotted line, $x_{.95}$) represents the time taken to form the habit. Traces are normalized for representation purposes.

diating role. Accordingly, the group effect had no significant direct effect (effect = −14.21, *SE* = 11.21, 95% CI [−36.93, 8.50]), but a significant indirect effect on the dependent variable through the effect of the cortisol (effect = −11.89, *SE* = 6.25, 95% CI [−30.39, −2.98]). Figure 2 illustrates the nature of the relation between cortisol levels and $x_{.95}$.

The second model, in which the independent variable group was replaced by the Group × Chronotype interaction, led to a similar pattern (see Table 2). The Group × Chronotype interaction had a significant total effect on $x_{.95}$ (effect = −.57, *SE* = .22, 95% CI [−1.02, −.12]). The total effect was decomposed into a nonsignificant direct effect (effect = −.29, *SE* = .25, 95% CI [−.79, 2.13]) and a significant indirect effect through cortisol (effect = −.27, *SE* = .15, 95% CI [−.65, −.04]).

Discussion

Because it has been shown that cortisol level has a strong connection to habit memory formation and that cortisol concentrations vary markedly over the day, this study aimed to test the influence of the circadian rhythm of cortisol on the development of a healthy habit. The presented findings indicate that the stretching behavior that participants intended to adopt became habitual more quickly when it was performed in the morning than in the evening. In addition, it seems that cortisol played a mediating role, because there was a significant indirect effect of the time of day on automatization speed through the level of cortisol displayed at the moment of behavior execution. Cortisol concentrations in the morning were higher than in the evening samples, and the cortisol level was negatively associated with the time taken to make the behavior habitual (see Figure 2). To our knowledge, this is the first time that habit formation has been studied through the prism of chronobiology. Our findings are consistent with those in other studies that have manipulated glucocorticoides GC levels with either pharmacological injection or stress induction, because they have all indicated that cortisol level has an impact on habit formation (e.g., Quirarte et al., 2009; Schwabe & Wolf, 2009).

Our results show that the indirect effect of time of day on habit formation through the circulating cortisol level persisted, and was even slightly stronger, when we took into account the match between chronotype and the time of behavior execution. This match effect contributes to the large body of literature on the effects of chronobiology on behavior (e.g., Hasher et al., 2005) showing that synchrony between individual preferences and the time of the day has an important effect on performance and particularly on tasks relying on attentional demands such as learning. It is thus not surprising that this individual trait further refines

Table 1
Regression Models Used to Determine the Mediating Role of Cortisol in the Effect of the Condition on the Time Taken to Form a Behavioral Habit

Model and variable	Coefficient	*SE*	*t*	*p*	95% CI LL	95% CI UL
Model predicting cortisol: R^2 = .28, F(1, 40) = 14.89, p = .0004						
Constant	1.627	.138	11.831	.000	1.349	1.905
Condition	.531	.138	3.859	.001	.252	.809
Model predicting $x_{.95}$ without inclusion of the mediator: R^2 = .20, F(3, 38) = 2.34, p = .09						
Constant	288.495	172.121	1.671	.102	−59.950	636.941
Condition	−26.601	10.169	−2.616	.013	−47.187	−6.015
Intention	−30.528	35.453	−.861	.395	−102.299	41.244
Sex	−25.043	20.269	−1.236	.224	−66.075	15.990
Model predicting $x_{.95}$ with inclusion of the mediator: R^2 = .29, F(4, 37) = 2.58, p = .053						
Constant	290.459	150.281	1.933	.061	−14.044	594.962
Cortisol	−22.413	10.779	−2.079	.045	−44.254	−.572
Condition	−14.218	11.213	−1.268	.213	−36.937	8.502
Intention	−23.578	31.366	−.752	.457	−87.133	39.976
Sex	−22.316	19.782	−1.128	.267	−62.398	17.767

Note. CI = confidence interval; LL = lower limit; ULCI = upper limit.

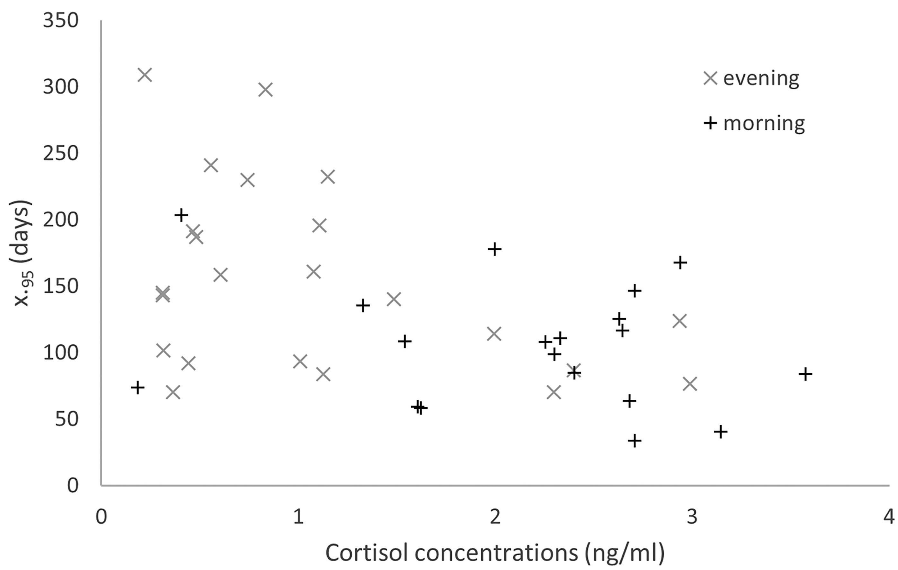

Figure 2. Relation between salivary cortisol values and the time necessary for behavior automatization ($x_{.95}$) for the morning and evening groups.

the effect of the moment of execution on the acquisition of behavioral habits.

Our study was designed to test habit formation in real life and therefore makes an original contribution to the literature by having greater ecologic validity than do the laboratory tasks (i.e., instrumental tasks) that are generally used to study the habit formation process. The short SRBAI and smartphone reminder application made it possible for us to track the participants for 3 months. However, self-reported habit measures have been criticized (Hagger, Rebar, Mullan, Lipp, & Chatzisarantis, 2015) because people may have limited conscious knowledge of automatic behaviors. Nevertheless, some researchers have still contested the belief that people can provide valid information on their habits using such self-reports (Orbell & Verplanken, 2015). In addition, there are no current alternatives for measuring behavioral habits and automaticity, particularly for frequent repeated measurements. To successfully analyze the evolution of automaticity we used a new type of learning curve that seems to better represent the habit-formation process. Unlike power learning curves, which show a substantial gain at the beginning, the logistic function suggests that some

Table 2
Regression Models Used to Determine the Mediating Role of Cortisol on the Effect of the Product Representing the Condition × Chronotype Interaction on the Time Taken to Form a Behavioral Habit

Model and variable	Coefficient	*SE*	*t*	*p*	95% CI LL	95% CI UL
Model predicting Cortisol: R^2 = .33, F(1, 40) = 20.699, p = .0001						
Constant	1.634	.132	12.366	.000	1.367	1.901
Condition × MEQ	.012	.003	4.544	.000	.007	.018
Model predicting $x_{.95}$ without inclusion of the mediator: R^2 = .20, F(3, 38) = 2.18, p = .10						
Constant	281.140	171.910	1.635	.110	−66.879	629.159
Condition × MEQ	−.566	.219	−2.591	.013	−1.009	−.124
Intention	−28.987	35.409	−.819	.418	−100.671	42.696
Sex	−25.203	20.360	−1.238	.223	−66.419	16.014
Model predicting $x_{.95}$ with inclusion of the mediator: R^2 = .28, F(4, 37) = 2.51, p = .058						
Constant	284.753	148.792	1.914	.063	−16.733	586.239
Cortisol	−22.404	11.129	−2.013	.051	−44.955	.146
Condition × MEQ	−.283	.248	−1.141	.261	−.787	.220
Intention	−22.369	31.232	−.716	.478	−85.652	40.914
Sex	−22.369	19.934	−1.122	.269	−62.760	18.023

Note. CI = confidence interval; LL = lower limit; ULCI = upper limit; MEQ = Morningness-Eveningness Questionnaire.

participants may actually start more slowly (see Murre, 2014), which is often the case for complex learning such as the adoption of a new healthy behavior that requires plenty of conscious effort at the beginning to accommodate the behavior in the living context and evaluate its costs and benefits (Wood & Neal, 2016). Only when these obstacles have been overcome may the automatization process begin.

A limitation of our work concerns the relatively small sample size of this study due to a limited recruitment capacity and attrition throughout the duration of the intervention. Although the significant results indicate that sufficient evidence was obtained to reject the null hypothesis despite the limited power, this study should be replicated to ensure reproducibility. In future studies, other mediators should also be tracked. We could not demonstrate a full mediation effect, and it therefore seems likely that other factors may come into play. As Schwabe, Tegenthoff, Höffken, and Wolf (2012) indicated, cortisol alone does not affect habitual behavior, and concurrent glucocorticoid and noradrenergic activity may have a role since it is known that this concurrent activity is needed to shift learning from goal-directed to habitual control. Some psychological factors might also explain the effect. For example, it is possible that the behavior was perceived as less difficult, more satisfying, or more easily cued in the morning than in the evening. Moreover, people assigned to the *morning* group were given a prior cue (i.e., do the stretch after waking up), but those in the *evening* group were not (i.e., do the stretch before going to bed). Because cueing is a critical aspect of habit formation (Gardner, 2015), it could have led to reinforcement of automatization in the *morning* condition.

Conclusion

In this study, we demonstrated that a newly adopted stretching behavior became habitual more quickly when it was performed in the morning as opposed to the evening. This effect was mediated by cortisol levels—higher cortisol levels in the morning resulted in accelerated automatization. By matching the intervention time with individuals' chronobiology, faster automatization and therewith higher success rates are likely. The extent to which these results can be translated to applied settings and more complex behaviors should be further investigated.

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