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Does the early bird really get the worm? How chronotype relates to human intelligence

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ABSTRACT

Objectives: Chronotype impacts our state at a given time of day, however, chronotype is also heritable, trait-like, and varies systematically as a function of age and sex. However, only a handful of studies support a relationship between chronotype and trait-like cognitive abilities (*i.e.*, intelligence), and the evidence is sparse and inconsistent between studies. Typically, studies have: (1) focused on limited subjective measures of chronotype, (2) focused on young adults only, and (3) have not considered sex differences. Here, using a combination of cognitive aptitude and ability testing, subjective chronotype, and objective actigraphy, we aimed to explore the relationship between trait-like cognitive abilities and chronotype.
Design: Participants (N = 61; 44 females; age = 35.30 ± 18.04 years) completed the Horne-Ostberg Morningness-Eveningness Questionnaire (MEQ) to determine subjective chronotype and wore an activity monitor for 10 days to objectively assess bedtime, rise-time, total sleep time, inter-daily stability, intra-daily variability, and relative amplitude. Cognitive ability (*e.g.*, Verbal, Reasoning and Short-Term Memory) testing took place at the completion of the study.
Results: Higher MEQ scores (*i.e.,* more morning) were associated with higher inter-daily stability scores. Superior verbal abilities were associated with later bedtimes, younger age, but paradoxically, higher (*i.e.*, more morning) MEQ scores. Superior STM abilities were associated with younger age only. The relationships between chronotype and trait-like cognitive abilities were similar for both men and women and did not differ between younger and older adults.
Conclusions: The present study demonstrates that chronotype, measured by the MEQ, is highly related to inter-daily stability (*i.e.,* the strength of circadian synchronization). Furthermore, although evening types have superior verbal abilities overall, higher (*i.e.*, more morning) MEQ scores were related to superior verbal abilities after controlling for "evening type" behaviours.

1. Introduction

The behavioral and cognitive manifestation of underlying circadian rhythms (*e.g.,* hormone release and body temperature), reflecting individual differences in the preferred timing of sleep and activity (Horne & Ostberg, 1977; Roenneberg et al., 2007) constitutes an individual's chronotype; *i.e.*, whether one can be considered a "*Morning Lark*" or an "*Night Owl*". At the ends of the continuum of chronotypes are "extreme morning-types" (*i.e.,* individuals who prefer extremely early bedtimes and rise-times) to "extreme evening-types" (*i.e.,* individuals who prefer extremely late bedtimes and rise-times). Although recent work has aimed to develop a more nuanced categorization of chronotype (Putilov et al., 2019), people have traditionally been categorized as "*Morning Types*", "*Neither Types*", or "*Evening Types*", based on the results of self-report questionnaires such as the Horne-Östberg Morningness-Eveningness Questionnaire (MEQ; Horne & Ostberg, 1976). In addition to sleep timing differences, chronotype also reflects an individual's performance, physical and alertness peak times with Morning Types performing optimally in the morning hours and Evening Types performing optimally in the evening hours (Horne & Ostberg, 1977).

Although chronotype impacts our state at a given time of day, chronotype is also stable and trait-like. Chronotype is heritable (Barclay et al., 2010) and changes in a predictable manner as a fac-

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tor of age. Being a Morning Type is common among young children (Simpkin et al., 2014), whereas being an Evening Type is common among adolescents (Randler, 2011; Roenneberg et al., 2004; Tonetti et al., 2008) and a return to being a Morning Type is common among adults, with this association strengthening with increasing age (Andrade et al., 1992; Roenneberg et al., 2004). Sex differences have also been found to be associated across chronotypes, as Morning Type is generally more common among females and Evening Type is more common among males (Adan & Natale, 2002; Randler, 2011; Tonetti et al., 2008). As well, the functional consequences of chronotype have been investigated, and suggests an association with other stable, trait-like variables related to an individual's personality, such as extraversion (Díaz-Morales, 2007; Matthews, 1988), and subjective well-being or life quality (Biss & Hasher, 2012).

In addition, a handful of studies have suggested that chronotype is also related to trait-like cognitive aptitudes and abilities (*i.e.*, intelligence; Kanazawa & Perina, 2009; Killgore & Killgore, 2007; Preckel et al., 2011; Roberts & Kyllonen, 1999). Although some results vary, in general, most studies suggest that healthy, young adult Evening Types have higher intelligence scores than healthy, young adult Morning Types. More specifically, Evening Types were shown to have higher intelligence scores, related to measures of memory and processing speed (Gorgol et al., 2020; Roberts & Kyllonen, 1999; Ujma & Scherrer, 2021), and higher emotional intelligence (Stolarski & Jankowski, 2015) than Morning Types. Similarly, Kanazawa and colleagues (Kanazawa & Perina, 2009) found that Evening Types had higher childhood intelligence scores than Morning Types. Evening Type females have been shown to have higher Verbal intelligence quotient scores than Morning Type females, but this correlation was not significant for males (Killgore & Killgore, 2007). Evening Types have been shown to have higher Short Term Memory (**STM**) abilities than Morning Types, but not for Reasoning or Verbal abilities (Fang et al., 2017). However, a single study (Song & Stough, 2000) failed to identify any relationship between intellectual ability and chronotype.

Taken together, evidence to support a relationship between interindividual differences in trait-like cognitive aptitudes and abilities and chronotype is sparse and varied, most likely due to the great diversity of variables considered and the research methods used (Preckel et al., 2011). Until now, investigations of a link between cognitive abilities and chronotype have limited their focus to: **(1)** limited subjective measures of diurnal preferences, or chronotype alone, in the form of self-report questionnaires, **(2)** with correspondingly few studies also employing related objective measures such as actigraphy, **(3)** a small age range, usually 15-25 years even though correlations are stronger with increasing age, and, **(4)** have not used a sample of participants who have been rigorously screened using polysomnography. Rigorous screening for low-quality or disordered sleep is an important factor to consider as both sleep quantity and sleep quality have been shown to impact performance on tests of cognitive abilities (Nader & Smith, 2015; Smith et al., 2019), but also, are related to chronotype (Zisapel, 2001; Adan et al., 2012; Waterhouse et al., 2012; Smith et al., 2018; Regalia et al., 2021). Importantly, cognitive abilities are not unitary; human intellectual abilities have been shown to be composed of distinct domains including: Verbal, Reasoning and Short-term memory abilities that depend on distinct functional neuroanatomical substrates (Hampshire et al., 2012).

To our knowledge, no studies to date have specifically tested this relationship with the use of both subjective (*e.g.,* MEQ scores) and objective (*e.g.,* actigraphy data) means of data collection in the same set of subjects in a relatively large sample, comprised of a wide range of ages and in both males and females, employing cognitive assessments that take into account distinct domains of trait-like cognitive abilities and aptitudes. Here, using a combination of cognitive ability and aptitude testing, and both subjective and objective measures of chronotype, we aim to explore the relationship between trait-like cognitive abilities and chronotype within a large age range of adults who have been rigorously screened using polysomnography. We hypothesized that: **(1)** MEQ and actigraphy will be related, **(2)** greater STM and Verbal abilities will be associated with both subjective and objective measures indicative of eveningness, and that this relationship will: **(3)** differ between men and women, and **(4)** differ between younger and older adults.

2. Participants and methods

2.1. Participants

Sixty-one healthy adults (44 female [72%]; age = 35.30 ± 18.04 years; age range: 20-78 years) participated in this study. An a priori power analysis was preformed using G*Power3.1 (Faul et al., 2009) for linear multiple regression analyses using a two-tailed test, a small effect size ($f^2 = 0.15$), with nine predictors, and an alpha of 0.05. The results of the power analysis revealed that a sample of $N = 55$ was required to achieve 80% power. All participants were non-nighttime shift workers, medication free, had a medical history free from head injury, seizure or mental illness, a body mass index <30, and did not consume excessive caffeine, nicotine, or alcohol. Participants were required to refrain from recreational drug use (including but not limited to nicotine and alcohol) at least three days prior to, and throughout the duration of the study. During the study, participants consumed no more than a single caffeinated beverage per day upon awakening. To be included in the study, participants had to score ≤13 on the Beck Depression Inventory (Beck et al., 1974), ≤7 on the Beck Anxiety Inventory (Beck et al., 1988), and have no signs of sleep disorders indicated by the Sleep Disorders Questionnaire (Douglass et al., 1994). All participants underwent a single polysomnographic (PSG) recording that served to screen participants for sleep disorders. The screening recording included EEG recordings (via electrodes applied to their scalp and face, including EEG channels Fz, Cz, Pz and Oz), respiration (via thorax and abdomen belts), electrocardiographic activity (via electrodes placed below each clavicle), leg muscle activity (via electrodes placed on the outer, anterior tibialis muscle of each leg) and blood oxygen saturation (via a finger probe placed on the index finger of the right hand). Screening recordings were scored in accordance with clinical scoring guidelines established by the American Academy of Sleep Medicine (Iber et al., 2007). Participants were excluded from further participation in the study if the results of their screening night identified greater than 5 respiratory events per hour of sleep and/or greater than 10 periodic leg movements per hour of sleep.

2.2. Ethics statement

All participants were given a letter of information, provided informed written consent prior to participation, and were financially compensated for their participation. This research was approved by the Western University Health Science Research Ethics Board, the University of Ottawa Health Sciences Research Ethics Board and the Research Ethics Board of the University of Ottawa Institute of Mental Health Research at The Royal.

2.3. Cognitive ability testing

Cognitive abilities, including reasoning, problem solving, planning, attention and memory, were assessed using the Cambridge Brain Sciences (CBS) Trials (Hampshire et al., 2012). The CBS Trials platform is a web-based cognitive test battery consisting of 12 subtests adapted from the cognitive literature: deductive reasoning (Cattell R B, 1949), spatial rotation (Silverman et al., 2000), feature match (Treisman & Gelade, 1980), spatial planning (Shallice, 1982), interlocking polygons (Folstein et al., 1975), verbal reasoning (Baddeley, 1968), color-word remapping (Stroop, 1935), digit span (Wechsler, 1981), visuospatial working memory (Inoue & Matsuzawa, 2007), spatial span (Corsi, 1973), paired associates (Gould et al., 2006), and self-ordered

Table 1
Descriptive statistics of the three CBS subscales (Reasoning, Verbal and Short-Term Memory (STM)).

Cognitive Measure	Minimum	Maximum	Mean ± *SD*
Reasoning	45.78	127.83	96.40 ± *14.08*
Verbal	51.38	148.71	101.17 ± *17.96*
STM	77.26	159.22	107.03 ± *13.23*

search (Collins et al., 1998). The CBS Trials have a number of advantages over other tests of cognition, including ease of administration and the fact that the neural correlates of each subtest have been investigated using functional neuroimaging (Hampshire et al., 2012). Based on scores from 44,600 participants three factors were determined that reflect performance across the battery, which have been described as "reasoning ability" (analogous to Fluid Intelligence), "verbal ability" (analogous to Crystallized Intelligence) and "STM" (Hampshire et al., 2012). On the basis of previous literature (Fang et al., 2017; Hampshire et al., 2012) Reasoning, Verbal and STM sub-scores were calculated from the raw scores of each of the 12 subtests. To do this, the raw scores from each subtest were z score normalized using the mean and standard deviation of each subtest from a large (N=44,600) population (Hampshire et al., 2012) before being multiplied by the factor loadings from Hampshire et al. (Hampshire et al., 2012) to calculate factor scores for each participant. Lastly, the factor scores were transformed to a mean of 100 and a *SD* of 15 to be readily comparable to results from similar studies tapping into Reasoning, Verbal and STM abilities **(**Table 1**)**. The variables of interest from the CBS test battery include the factor scores for Reasoning, Verbal and STM abilities.

2.4. Chronotype

2.4.1. Subjective measure

The Horne-Ostberg Morningness-Eveningness Questionnaire (Horne & Ostberg, 1976) was administered to all participants to assess their chronotype (*e.g.,* Morning Types, Neither Types or Evening Types). The MEQ is a paper-and-pencil test consisting of 19 questions that address items such as subjective assessment of intellectual and physical peak times, sleep/wake habits, appetite, and alertness over the course of the day. Total scores for the MEQ range from 16 (*i.e.*, extreme Evening Type) to 86 (*i.e.*, extreme Morning Type). The variable of interest from the MEQ was the total score.

2.4.2. Objective measure

Participants were asked to wear either an Actiwatch (Philips-Respironics Inc., Andover, MA, U.S.A.) or a Motionlogger (Ambulatory Monitoring Inc. Ardsley, NY, U.S.A.) wrist actigraphy device (an accelerometer which measures sleep-wake-related limb movements) on their non-dominant wrist and to complete a log of their daily activities and sleep habits for a minimum of 10 consecutive days. The Actiware (Version 6.0.9) and Watchware (Version 1.99.17.4) software were used to score the activity data, sampled at an interval of 1 min. The beginning and end of each sleep period was visually confirmed and, if necessary, manually adjusted. The sleep parameters: average bedtime, rise-time, and total sleep time, were automatically generated by the scoring software. The average bedtime was calculated as the time of the beginning of the sleep period averaged across all recording days. The average rise-time was calculated as the time of the end of the sleep period averaged across all recording days. Finally, the average total sleep time was calculated as the time spent asleep between the beginning and the end of the sleep period averaged across all recording days. The circadian rhythm parameters inter-daily stability (IS), intra-daily variability (IV), the most active 10 hours (M10), the least active 5 hours (L5), and relative amplitude (RA), were calculated in MatLab R2019a (The MathWorks Inc., Natick, MA, United States) and are based on the analysis method developed by Van Someren et al. (Van Someren et al., 1999). IS is a measure of the day-to-day synchronization of an individual's circadian rhythm (Galasso et al, 2019), whereas IV is a measure of the consolidation or fragmentation of an individual's circadian rhythm within days. Lastly, the RA is a measure of the difference in activity level between the most active 10-hour period (M10) and the least active 5-hour period (L5) across the averaged 24-hour day. The variables of interest from the actigraphy data include the bedtime, rise-time, total sleep time, IS, IV, M10, L5, and RA.

2.5. Procedure

All participants were initially screened to verify that they met the inclusion criteria (see *Participant* section for details). Following this, each participant underwent a single PSG screening recording to confirm the absence of sleep disorders. Participants were then asked to complete the MEQ to determine their subjective chronotype and asked to wear an activity monitor on their non-dominant wrist for a minimum of 10 consecutive days to determine their objective chronotype and gather related objective measures about sleep, wake, and rhythmicity. Following completion of the activity monitoring, all participants completed the CBS Trials (see *Cognitive Ability Testing* section for details) online and in their own homes at their preferred/optimal time of day of their choosing between the hours of 9:00AM and 9:00PM.

2.6. Data analyses

To confirm that subjective and objective measures of chronotype were related to one another, Pearson r correlations were calculated between the participants' scores on the MEQ and the actigraphy variables of interest (*i.e.*, bedtime, rise-time, total sleep time, IS, IV, M10, L5, and RA). To investigate age as a potentially confounding variable in the relationship between MEQ score and actigraphy variables (Luik et al., 2013), partial correlations between MEQ and significant predictors were performed, controlling for participant age. False discovery rate correction (Benjamini & Hochberg, 1995) was applied to correct for multiple comparisons, and corrected significance values were reported.

Next, to investigate whether it's true that "the early bird gets the worm", and if so, which "worm" does it get, a series of linear regressions were conducted. In separate regression analyses, each cognitive variable (*i.e.*, Verbal, Reasoning, and STM) was entered as the criterion variable, with age, sex, MEQ score, and actigraphy variables (*i.e.*, bedtime, rise-time, wake time, total sleep time, IS, IV) as predictor variables. Actigraphy variables L5, M10, and RA were removed from subsequent regression analyses because those variables displayed high multicollinearity (VIF > 27.23). To investigate whether the time-of-day participants completed their cognitive testing was a confounding variable on test performance, bivariate correlations between testing time and cognitive ability (Verbal, Reasoning and STM) were computed. Significant relationships were further examined by calculating the partial correlations between cognitive ability and significant predictors, controlling for testing time-of-day.

Then, to investigate how age affects the relationships between cognitive variables and subjective chronotype, each cognitive variable (*i.e.*, Verbal, Reasoning, and STM) was entered into separate moderation analyses as the criterion variable, with MEQ score as the predictor, and age as the moderator variable. Lastly, the same analysis strategy used for age, was also used to investigate sex as a moderator.

All statistical tests were performed using SPSS (Version 27.0) for MacOS and all moderation analyses were conducted using the PROCESS v3.5 (Hayes, 2018) statistical package for SPSS.

Table 2
Pearson correlations between Morningness-Eveningness Questionnaire (MEQ) score and objective actigraphy variables.

Measure	M ± *SD*	Correlation with MEQ (*r*)	*p* value (corr)
MEQ	53.56 ± *8.39*		
Age (yrs)	35.30 ± *17.89*	*0.31*	**0.029*
Bedtime	11:46:19 PM ± *1:09:31*	*-0.54*	****< 0.001*
Rise time	7:54:13 AM ± *1:07:37*	*-0.61*	****< 0.001*
Sleep duration (mins)	429.16 ± *40.89*	*0.03*	*0.493*
Sleep Efficiency (%)	89.56 ± *5.00*	*-0.02*	*0.450*
Sleep Onset Latency (min)	11.17 ± *7.13*	*0.24*	**0.056*
Wake After Sleep Onset (min)	35.70 ± *17.84*	*-0.07*	*0.396*
Inter-daily Stability	0.63 ± *0.21*	*0.50*	****< 0.001*
Intra-daily Variability	0.37 ± *0.09*	*-0.02*	*0.467*
Least active 5 Hrs (active minutes)	12.68 ± *4.09*	*-0.28*	**0.032*
Most active 10 hrs (active minutes)	53.27 ± *7.11*	*0.41*	***0.002*
Relative Amplitude	0.62 ± *0.11*	*0.46*	****< 0.001*

Note: significant relationships indicated by: **p < 0.05,* ***p < 0.01,* ****p < 0.001*

3. Results

3.1. Relationship between subjective chronotype and actigraphy

As a preliminary step, prior to conducting multiple regression analyses, Pearson correlations between participants' scores on the MEQ and the actigraphy variables (summary in Table 2) revealed that, as expected, higher MEQ scores (greater morningness) were significantly related to earlier bedtimes ($r(57) = -0.535$, $p < 0.001$), and earlier rise-times ($r(57) = -0.610$, $p < 0.001$). Additionally, people with higher MEQ scores also showed greater IS ($r(57) = 0.498$, $p < 0.001$), indicating strong day-to-day synchronization of circadian indicators in Morning Types. Higher MEQ scores was also related to greater RA ($r(57) = 0.457$, $p < 0.001$), meaning that Morning Types tended to have larger differences between periods of activity and rest. Specifically, not only were Morning Types more active during M10 ($r(57) = 0.411$, $p = 0.002$), but Morning Types were also less active during L5 ($r(57) = -0.282$, $p = 0.032$).

A multiple linear regression to determine which objective chronotype measures were most predictive of MEQ scores revealed that rise-time ($t(57) = -2.21$, $p = 0.031$, $\eta^2 = 0.09$) and IS ($t(57) = 3.13$, $p = 0.003$, $\eta^2 = 0.09$) both predicted a significant amount of unique variance in MEQ scores, ($F(6, 51) = 9.84$, $p < 0.001$, $r^2 = 0.537$). These results indicate that people with higher MEQ scores (greater morningness) are earlier to rise ($\rho_{xy.z} = -0.30$), which is to be predicted, but also that they have higher IS scores ($\rho_{xy.z} = 0.40$), which is a measure of circadian rhythm synchronization from day-to-day (Fig. 1).

Partial correlations, controlling for age, between MEQ score and significant actigraphy predictors (*i.e.,* rise-time and inter-daily stability) were calculated to rule out participant age as a potentially confounding variable in these relationships. The results of the partial correlations showed that, when participant age was controlled, MEQ score was still significantly correlated with both rise-time ($\rho_{xy.z} = -0.55$, $p < 0.001$) and IS ($\rho_{xy.z} = 0.46$, $p < 0.001$). These results suggest significant relationships of MEQ score with rise-time and IS (respectively) beyond that which is accounted for by participant age.

3.2. Relationship between chronotype and cognitive abilities

The multiple linear regression analysis revealed that bedtime ($t(55) = 3.19$, $p = 0.003$, $\eta^2 = 0.18$), MEQ scores ($t(55) = 2.71$, $p = 0.009$, $\eta^2 = 0.14$), and age ($t(55) = -2.35$, $p = 0.023$, $\eta^2 = 0.11$) contributed to the significant prediction of Verbal abilities ($F(10,45) = 4.52$, $p < 0.001$, $r^2 = 0.50$; Fig. 2). Specifically, the partial correlations between the significant predictors and verbal abilities indicated that higher Verbal abilities were associated with later bedtime ($\rho_{xy.z} = 0.43$), higher MEQ scores ($\rho_{xy.z} = 0.37$), and younger age ($\rho_{xy.z} = -0.33$). In contrast, only age ($t(55) = -2.76$, $p = 0.008$, $\eta^2 = 0.14$) predicted a significant proportion of STM variability ($F(10, 45) = 2.32$, $p = 0.027$, $r^2 = 0.34$; Fig. 3). Specifically, younger people showed higher STM ($\rho_{xy.z} = -0.38$). Lastly, as predicted, none of the chronotype or actigraphy variables were significantly related to Reasoning abilities.

To determine whether relationships existed between 'time-of-day' that testing was completed and performance on the cognitive tests, testing time was correlated with Verbal, Reasoning, and STM scores. The time of day that tests were completed was not related to either Verbal ($r(59) = .057$, $p = .670$), or Reasoning ($r(59) = -.185$, $p = .162$) abilities, but was related to STM ($r(59) = .333$, $p = .009$) ability. This suggests that those who completed testing later in the day showed greater STM abilities. A partial correlation, controlling for testing time, between STM and age was calculated to rule out testing time as a confounding variable. The results of the partial correlation showed that, when controlling for testing time, STM ability was still significantly correlated with age ($\rho_{xy.z} = -.410$, $p = .002$), suggesting a significant relationship between STM and age beyond that which is accounted for by test timing.

Despite the direct relationship between chronotype and STM or Reasoning abilities being non-significant, to be sure that age did not moderate the relationships between cognitive variables and subjective chronotype in a way that obscured an age-related effect, all cognitive variables were entered into separate moderation analyses. Although the previous analyses showed that both age and MEQ score were predictors of Verbal ability, age was not a significant moderator of the relationship between MEQ score and Verbal ability ($F(1, 53) = 1.08$, $p = 0.304$). Age also did not moderate the relationships between MEQ scores and Reasoning ability ($F(1, 53) = 0.18$, $p = 0.672$), or between MEQ score and STM ($F(1,53) = 2.37$, $p = 0.130$). Thus, although age does predict variability in verbal abilities, these results suggest that the relationship between chronotype and cognitive abilities is relatively consistent over the lifespan.

Lastly, sex did not moderate the relationships between MEQ score and Verbal ability ($F(1, 53) = 1.99$, $p = 0.165$), MEQ scores and Reasoning ability ($F(1, 53) = 0.02$, $p = 0.880$), or MEQ score and STM ($F(1, 53) = 0.01$, $p = 0.924$). These findings suggest that the relationship between chronotype and cognitive abilities is similar for both men and woman.

4. Discussion

Here, we investigated the relationship between cognitive abilities and chronotype using a combination of cognitive aptitude and ability testing (*e.g.,* CBS Trials), and both subjective and objective measures of chronotype (*e.g.,* MEQ scores and actigraphy data, respectively) across a range of ages in both males and females. The current investigation revealed that: **(1)** as expected, individuals with higher MEQ scores (*i.e.*, greater morningness) are earlier to rise and have higher day-to-day circadian synchronization. As predicted, **(2a)** verbal abilities were associ-

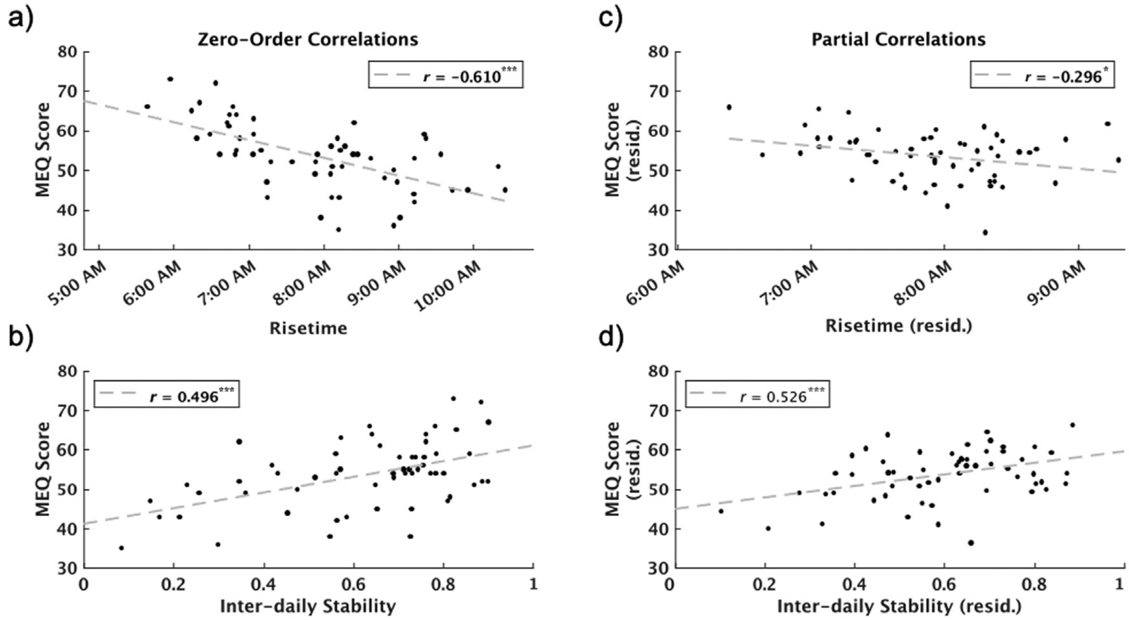

Fig. 1. Zero-order and partial correlations between Morningness-Eveningness Questionnaire (MEQ) and actigraphy variables. **Left panels:** Zero-order correlations between **a)** MEQ score and rise time and **b)** MEQ score and inter-daily stability (IS); **Right panels:** partial correlations between **c)** MEQ and rise time controlling for IS, and **d)** MEQ and IS controlling for rise time. **Note:** Significance of each relationship is shown by *, **, or *** indicating p < 0.05, 0.01 & 0.001, respectively.

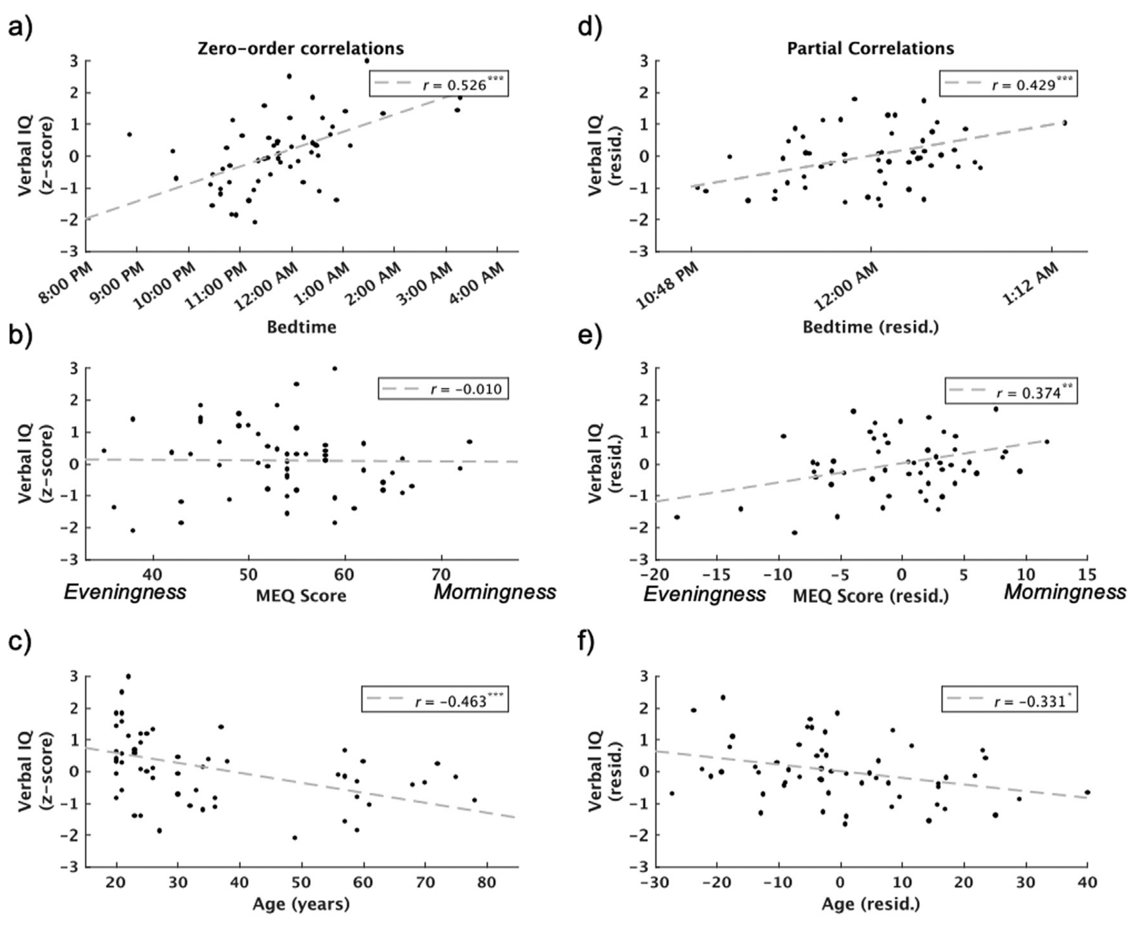

Fig. 2. Zero-order and partial correlations between verbal scores and chronotype measures. **Left panels (a, b, c)**: show zero-order correlation between verbal IQ and bedtime, MEQ score, and age (respectively). **Right panels (d, e, f)**: show the partial correlations of the same variables after controlling for the other predictors in the model. **Note:** Significance of each relationship is shown by *, **, or *** indicating p < .05, .01 & .001, respectively.

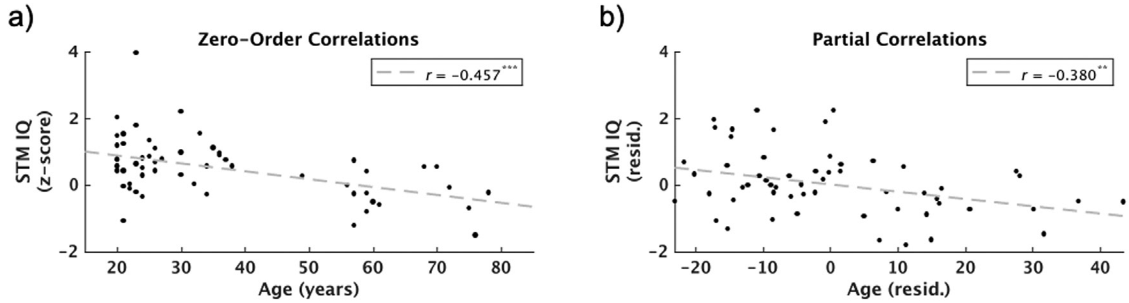

Fig. 3. Zero-order (**a**) and partial correlations (**b**) between short term memory (STM) scores and age. **Note:** Significance of each relationship is shown by **, or *** indicating p < .01 & .001, respectively.

ated with later bedtimes and younger age, but surprisingly, higher MEQ scores (*i.e.*, greater morningness). As expected, **(2b)** STM abilities were associated with younger age, but, contrary to our hypotheses and a previous study by our group (Fang et al., 2017), were not associated with chronotype. The current findings also suggest that contrary to our hypotheses and previous literature, the relationship between chronotype and cognitive abilities was **(3)** similar for both men and woman, and **(4)** relatively consistent over the lifespan.

MEQ scores were strongly related to actigraphy measures, as expected. Although it is not surprising that people's preferences and optimal performance times for early *vs*. late activity are reflected in the sleep-wake cycle, it is an important result as it supports the validity of previous work which used subjective measures of chronotype in their investigations. Especially interesting, however, is the current, novel finding that higher morningness scores on the MEQ are associated with higher inter-daily stability scores. Although previously hypothesized and associated with *preferred* timing of daily activities (Thun et al., 2012), the current study is the first to demonstrate this relationship using objective measures of behaviour after controlling for participant age. These findings suggest that those who are more phase advanced (*i.e.*, more morningness) have higher day-to-day stability of their daily sleep-wake cycle (Galasso et al., 2019) compared to those who are more phase delayed (*i.e.*, more eveningness). Previous work has found evidence that certain genetic variants are associated with chronotype (Roenneberg et al., 2007). Taken together, these findings add to previous evidence which suggests that chronotype itself results from a complex interplay between genetic predisposition of internal hormone cycles, influence of environmental factors, and many potential social zeitgebers (Lack et al., 2009). Moreover, it makes sense that genetic factors, which influence biological factors like perceptual sensitivity and hormone regulation/production, may also influence the strength of environmental influences and day-to-day circadian synchronization. However, more work is needed to build on the current knowledge of the genetic links between chronotype and a range of complex social and biological factors.

The finding that greater verbal abilities were associated with later bedtime and younger age is consistent with previous work which has shown a relationship between intelligence and chronotype (Arbabi et al., 2015; Gorgol et al., 2020; Kanazawa & Perina, 2009; Preckel et al., 2011; Roberts & Kyllonen, 1999; Ujma & Scherrer, 2021), and also that cognitive abilities peak in young adulthood, and decline as one ages. Surprisingly, when controlling for age and bedtime, the results of the current study show a seemingly paradoxical relationship between higher MEQ score (indicating morning chronotype) and verbal IQ scores. This is surprising not only because evidence from previous studies supports a relationship in which lower MEQ scores are associated with superior verbal abilities (Gorgol et al., 2020; Preckel et al., 2011; Roberts & Kyllonen, 1999), but also because when examining bivariate correlations, the findings of the current study show negative correlations between both bedtime and MEQ score, and between MEQ and verbal ability (see **Table 1**). This finding suggests that after controlling for the typical Evening Type tendencies (*i.e.*, later bedtimes) found in younger adults, those who are more "morning type" have paradoxically higher verbal abilities, suggesting that circadian-related aspects other than bedtime alone are associated with higher verbal abilities in younger individuals. When controlling for variance accounted for by bedtime, our results suggests that the relationship between chronotype and Verbal abilities might be more complex than previously reported and warrants further investigation.

As expected, STM abilities were associated with younger age, but, contrary to our hypotheses, and previous work (Fang et al., 2017), were not associated with chronotype. Recent work in this area suggests that the relationship between chronotype and IQ is largely mediated by work/testing times and is not present when comparisons corrected for chronotype are made (Ujma et al., 2020). That is, when the potential state-dependent mismatch between testing time and individual chronotype is accounted for, IQ and trait-like chronotype may not be as related as earlier work found. It is possible that, in the current study, allowing participants to complete the cognitive testing at a time of day that was ideal/preferable for them had a similar effect on the relationship between STM and chronotype, that controlling for chronotype had in previous studies. Also, several previous studies (*e.g.*, Roberts & Kyllonen, 1999, Kanazawa & Perina, 2009, Preckel et al., 2011, Killgore & Killgore, 2007, etc.) which found a relationship between chronotype and IQ used samples of young adults (usually ≤ 25 yrs old), whereas the current study participants (M_{age} = 35.3 ± 18.04 yrs) ranged from 20-78 years. As IQ is relatively stable throughout the lifetime (Barclay et al., 2010), but chronotype is not (Randler & Truc, 2014), the relationship between chronotype and intelligence may change throughout the lifespan, making a linear relationship difficult to detect across such a wide age range. Unfortunately, the ability of the current study to detect whether the relationship between chronotype and intelligence is moderated by age is limited by the small subsample of middle-aged adults in the study. However, this is an important question for future studies to explore with larger samples across a wide range of age groups.

Although testing at home was convenient for the participants and is advantageous to avoid inducing "test anxiety" in a more formal, laboratory setting, there are potential limitations. For example, in a home environment, it is difficult to control for distractions. Home testing environments also make it difficult for researchers to note whether participants employed any unusual strategies that may have either helped or hindered performance, or to ensure that participants correctly understood task instructions. Every effort was made to limit the impact of such limitations on the current study and participant data was inspected and compared to established population norms (Hampshire et al., 2012) to indicate serious testing issues. However, these limitations could have potentially introduced additional variability into the cognitive ability testing scores, so confirmation of these findings in a more tightly controlled, laboratory setting would be beneficial.

5. Conclusion

The results of the current study add to the current chronotype literature in two important ways: 1) these findings show that people with earlier, morningness chronotypes have higher inter-daily stability. That is, morning-types show stronger day-to-day synchronization of their sleep/wake cycle than evening-types, and 2) this study also demonstrates that the link between chronotype and cognitive abilities might be more nuanced than previously thought. For example, once differences in age and bedtime are controlled for, higher verbal ability is associated with morningness (rather than eveningness). Also, chronotype is unrelated to short-term memory performance when participants are tested at their individual optimal/preferred times – an important methodological consideration for future studies to account for. Thus, these results suggest a more complex relationship between chronotype, and cognitive abilities than previously thought. Taken together, the results of this study suggest that other circadian-related factors, beyond one's preference for early or late bed/rise times, may play a role in determining cognitive ability. Thus, although conventional wisdom tells us: "*The early bird gets the worm*", the findings of the current study suggest that night owls may have an advantage, and that the relationship between trait-like cognitive abilities and chronotype is more nuanced than previously thought.

Data and code availability statement

Reasonable requests to access the related data will be considered on a case-by-case basis and should be made to the corresponding author. Ethical approval for data sharing agreements is required to share data, in order to protect participant confidentiality.

Author contributions

Study design: SMF & LBR. Data collection: NvdB, BT, VS, & JV. Data processing and statistical analysis: AG, LBR, DS, & SMF. Manuscript creation: AG, LBR, SMF. Edits/revisions: AG, LBR, SMF.

Declaration of Competing Interest

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

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