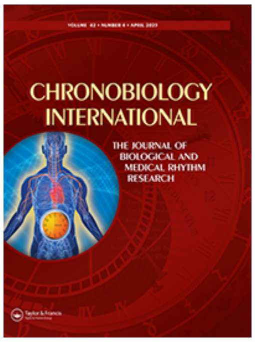

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REVIEW ARTICLE

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Chronotype and synchrony effects in human cognitive performance: A systematic review

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ABSTRACT

Chronotype is a proxy for various intra-individual rhythms (e.g. sleep-wake cycles) which fluctuate throughout the day. The extent to which chronotype modulates cognitive performance remains unclear. Here, we systematically reviewed studies to determine the influence of chronotype on its own, and/or in interaction with time of day (ToD; optimal/non-optimal), in cognitive function in healthy adults. Following PRISMA guidelines, data searches were conducted in PubMed and Web of Science databases (11 March 2024), yielding 65 studies (53 in adults aged 18–45 y; 11 comparing adults aged 18–32 and 50–95 y; one involving only morning type adults aged 60–76 y). Most of the reviewed studies (>80%) indicated no main effect of chronotype on cognitive function. There was evidence from 29 (45.31%) of 64 studies involving adults aged 18–45 y of a synchrony effect (i.e. superior performance at optimal ToD) in morning and/or evening types, mostly in attention, inhibition, and memory. In older adults, there was evidence of a synchrony effect from 10 (83.33%) of 12 studies, especially on tasks involving fluid abilities. Limited evidence suggested higher activation of inhibition-related brain regions at optimal ToD in both chronotypes, and synchrony effects being impacted by certain exogenous factors known to affect arousal and performance (e.g. task complexity, lighting conditions). Our findings highlight the need to carefully consider age along with endogenous and exogenous sources of intra-individual variations in arousal while determining synchrony effect in cognitive functions. Not acknowledging these synchrony effects may also result in exaggerated cognitive deficits especially in the elderly.

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Chronotype; morningness-eveningness; cognition; time of day; synchrony; circadian rhythms; ageing

Introduction

In humans, circadian rhythms oscillate with periodicity in length, causing considerable intra-individual variations (Czeisler and Gooley 2007) in various neurophysiological domains (Xu et al. 2021). These intra-individual variations are commonly referred to as "*chronotype*" (Adan et al. 2012; Chauhan et al. 2023) and include an individual's natural predisposition to feel sleepy or alert at particular times of the day or night. There is growing interest in how chronotype impacts human cognitive function but, despite a broadening corpus of literature, there is no consensus on the nature of this relationship. There are reports of morning types performing better academically (Cohen-Zion and Shiloh 2018) and having better fine motor skills and short-term memory relative to evening types (Atkinson and Speirs 1998; Drust et al. 2005; Facer-Childs et al. 2018), but there are also reports of no association between chronotype and cognitive function (Adan 1991; Cox et al. 2019), or of better performance in evening types compared to morning types (Preckel et al. 2011).

Over the years, it has been assumed that *"early to bed and early to rise, makes a man healthy, wealthy, and wise"* (Franklin 1855) but without clear empirical support for this assumption (Gale and Martyn 1998). On the contrary, a substantial body of evidence pointing towards optimal cognitive performance when tested in synchrony with an individual's biological rhythm (Barner et al. 2019; May and Hasher 1998; Taillard et al. 2021; Wyatt et al. 1999). This concept is known as the *"synchrony effect"* (May and Hasher 1998). Some studies report synchrony effects in attention (Martínez-Pérez et al. 2020), vigilance (Mongrain et al. 2008), inhibition (Lara et al. 2014; May and Hasher 1998), and memory (Schmidt et al. 2015) but its impact may not be the same across different cognitive tasks and domains (Barner et al. 2019; Bennett et al. 2008; Fabbri

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et al. 2013Natale et al. 2003; Wieth and Zacks 2011), especially in tasks demanding well-practised responses (May et al. 2023). Furthermore, synchrony effect might be age-dependent and not similarly present in different age groups (Adan et al. 2012; Schmidt et al. 2007).

The aim of this review, therefore, is to systematically review, synthesise and critically appraise the existing evidence for chronotype and synchrony effects in performance of healthy adults across and within general and specific cognitive domains.

Methods

The protocol for this systematic review was registered with PROSPERO (CRD42024498808). The review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) structure and guidelines (Page et al. 2021).

Information Source and Research

A literature search in PubMed, and Web of Science databases was conducted on 11 March 2024 using the following search terms: (chronot* OR "diurnal preference" OR "circadian preference" OR "morning type" OR "evening type") AND (cognit* OR memory OR attent* OR "verbal recall" OR "problem solving" OR "executive func*" OR "verbal fluency"). Search results were restricted to English, with no specific time window for publication. Cited references in the selected studies were also examined to identify further eligible literature.

Eligibility Criteria

Searched studies were assessed against the following inclusion criteria and deemed eligible for inclusion if they:

- Included adult (≥18 y) participants with no history or current diagnosis of mental illness, neurological impairment, and major physical illnesses.
- Determined chronotype via a standardised self-report assessment, actigraphy, and/or physiological data.
- Included at least one measure (experimental or standardised assessment) of cognitive function/s (attention, executive functions, working memory, reasoning, problem solving, and/or verbal learning).
- Were peer-reviewed primary research articles.

Studies without full text and methodology, meta-analyses, dissertation/PhD theses, unpublished papers, preprints, books, scoping and systematic reviews, animal studies, genetic and metabolic studies, were excluded. Studies examining only ToD effect without consideration of chronotype were also excluded.

Study Selection

All studies meeting our eligibility criteria were exported to Zotero (2016). Titles and abstracts were screened for relevance by two independent reviewers (SC, UT). If the abstract did not contain sufficient information, the full text was retrieved before deciding regarding its eligibility. The two reviewers (SC, UT) independently read the study title, abstracts, and full texts (where needed) and assigned each study a score of 0 (not suitable), 1 (probably suitable), or 2 (suitable). Subsequently, all the full-text articles rated as suitable for inclusion (i.e. received a score of 2) by both researchers were reviewed by a third reviewer (MV). The selection ratings of the two reviewers (SC, UT) were compared, and the degree of agreement was assessed. Any discrepancies, as well as any studies with at least one score of 1, were discussed with a fourth reviewer (VK) to reach a consensus. The reasons for excluding studies at all stages were documented (Figure 1).

Data Collection, Items, and Statistical Analysis

For each of the selected studies, the following data were extracted independently by SC and MA: authors, study year, month and time of testing, sample characteristics (sample size, mean age, and sex and chronotype distribution), study population, methods for assessing chronotype, measures/tasks used to assess the cognitive functions, and key study outcomes (Tables 1 and 2). If any of these factors were not reported, we made no specific assumptions regarding whether or not they had been assessed in the study, and noted them as "not reported" in our dataset. Extracted data were compiled into a Microsoft Excel spreadsheet and analysed descriptively, with regards to the significance of the findings as reported by the study authors.

Quality Appraisal

The quality of selected studies was assessed (SC, MA) using the Joanna Briggs Institute Quality Appraisal Rating for cross-sectional studies (Zeng et al. 2015). All eight criteria were graded as "yes," "no," "unclear" or "not applicable." One point was given for scoring

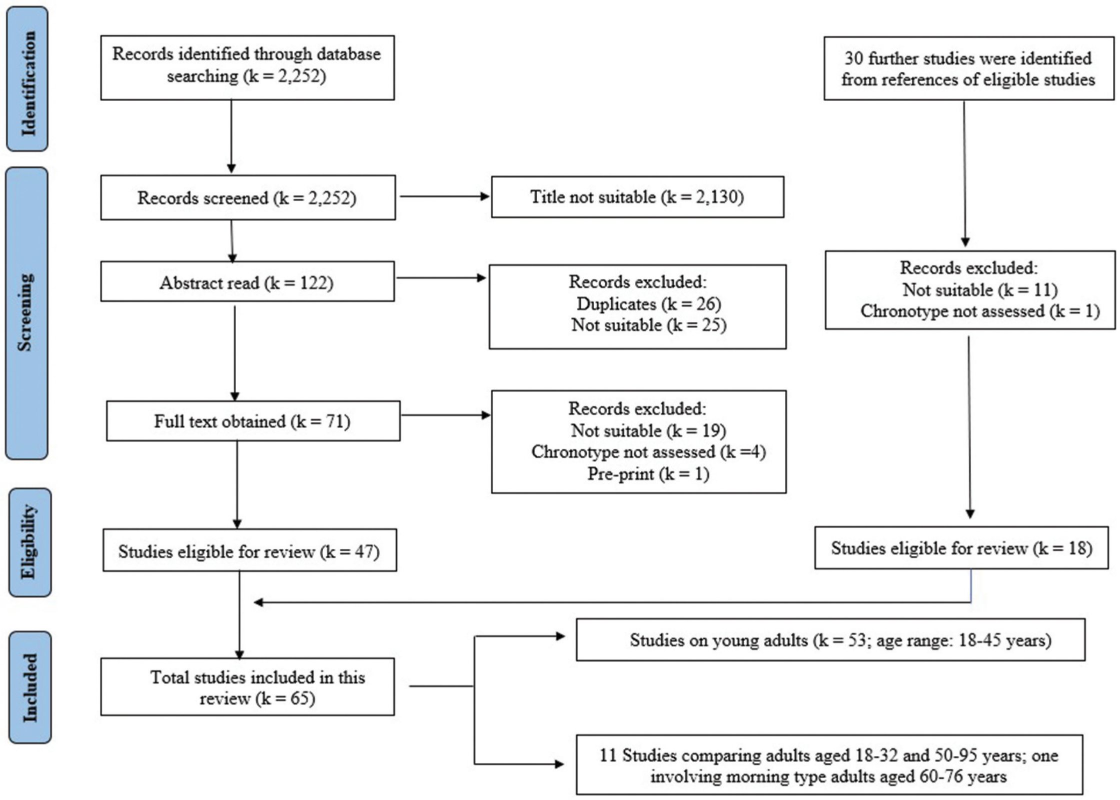

Figure 1. PRISMA flowchart.

"yes" on each criterion and then a total sum of all points was derived (Table 3).

Results

Overall, we analysed 65 studies conducted in 18 countries (Australia, Belgium, Brazil, Canada, China, Czech Republic, France, Germany, Hungary, Ireland, Israel, Italy, Netherlands, Poland, Spain, Switzerland, United Kingdom, and USA) examining one or more cognitive functions (Tables 1 and 2). There was considerable variability in the sample size, ranging between 15 and 1131. Most studies (57 of 65) employed a mixed factorial design with time of day (ToD) as a within-subject and chronotype as a between-subject factor and received acceptable quality ratings (Table 3). Of 65 in total, 53 studies investigated the effect of chronotype and/or ToD as well as their interaction in various cognitive functions in young adults (age range: 18–45; Table 1). The remaining 12 investigated the influence of age in the chronotype and/or synchrony effects in cognitive performance or simply investigated chronotype or synchrony effects in older adults (Table 2).

We grouped the findings of eligible studies, based on the cognitive parameters used and functions examined, as pertaining to intelligence, sensory processing, perception, attention, inhibition, working memory, decision-making, problem-solving, thinking, reasoning, verbal fluency, learning and memory (Table 4). We now report the findings for chronotype, also for time of day (ToD) and synchrony effect in young (k = 53) and older adults (k = 12), respectively.

Effects of Chronotype on Cognitive Performance in Young Adults

Five of the 53 studies (Ceglarek et al. 2021; Ge et al. 2020; Palmero et al. 2022; Petros et al. 1990; Schmidt et al. 2015) reported significant main effects of chronotype. Ge et al. (2020) reported better visuo-spatial working memory in morning types vs evening types. Petros et al. (1990) reported greater recall in evening types vs morning types in prose memory tasks. Some studies reported higher accuracy (Schmidt et al. 2015, N-Back; Ceglarek et al. 2021), although not consistently (see Palmero et al. 2022, Sustained Attention Response Task), and longer reaction time (RT; Palmero et al. 2022; Schmidt et al. 2015) in evening types than morning types.

In addition, four other studies (Evansová et al. 2022; Killgore and Killgore 2007; Nowack and Van Der Meer 2018; Palmero, Martínez-Pérez, et al. 2024) reported

Table 1. Summary of key data extracted from selected studies in young adults.

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes		Other Findings
						Main Effect of CT and ToD	Synchrony Effect	
Petros et al. (1990)	Season of testing not reported. Participants were tested in groups of 1–4 either at 9:00, 14:00, or 20:00 h	79 university students (all F; age range not reported; 40 MCs/39 ECs)	Morningness-Eveningness Questionnaire; Body Temperature	Eysenck Personality Questionnaire	Passage Difficulty Task	ECs recalled more idea units than MCs. A significant ToD effects was observed only for difficult passages.	A significant synchrony effect in both chronotypes with a linear increase in recall throughout the day for MCs and vice-versa for ECs.	
Anderson et al. (1991)	Season of testing not reported Participants were tested randomly either at 9:00, 14:00, or 20:00 h.	99 university students (all F; mean age not reported; 45MCs/54ECs)	Morningness-Eveningness Questionnaire; Body Temperature		Word-Pair Recognition	No significant CT effect. A significant ToD on speed of word encoding, lexical access, and semantic memory.	A significant synchrony effect in both chronotypes with a linear increase in semantic memory throughout the day for MCs and vice-versa for ECs.	
Song and Stough (2000)	Season of testing not reported. Participants were tested at 9:00 and 15:00 h.	70 university students (50 F, 20 M; mean age: 24.9 ± 8.3) Chronotype groups (N) not reported	Morningness-Eveningness Questionnaire Body Temperature MCs (9:00 h): 36.1 ± .9; (15:00 h): 36.2 ± .8 ECs (9:00 h): 35.9 ± .50; (15:00 h): 36.2 ± .5		Inspection Time; Digit Span; Picture Completion; Spatial subtest of MAB; Picture Arrangement; Object Assembly	No significant CT effect. No significant ToD effect.	A synchrony effect was observed with MCs performing better in the morning only on spatial subtest of MAB and vice-versa for ECs.	
Natale et al. (2003)	Season of testing not reported Participants were familiarised with the tasks a week before testing and were tested repeatedly over a period of 15 hours at 8:00 h, 11:00 h, 14:00 h, 17:00 h, 20:00 h, and 23:00 h.	48 university students (24F/ 24 M; mean age: 25.04 ± 2.92; 12MCs/ 24ICs/12ECs)	Morningness-Eveningness Questionnaire; Body Temperature	Global Vigour Scale; Wechsler Adult Intelligence Scale	Two-Letter Search; Syllogistic Reasoning; Overlapping; Crypto-Arithmetic	No significant CT effect. No significant ToD effect.	A significant synchrony effect was observed on Two-Letter Task with MCs and ECs performing faster at their optimal ToD. A synchrony effect was found with highest speed of execution at optimal ToD for MCs and ECs on Syllogistic Reasoning, Overlapping and Crypto-Arithmetic Tasks.	MCs reported higher subjective alertness at 8:00 h than 23:00 h, vice-versa for ECs.

(*Continued*)

Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes: Main Effect of CT and ToD	Key Outcomes: Synchrony Effect	Other Findings
Hidalgo et al. (2004)	Data were collected between October-November (year not reported) Participants were tested at 7:30 h and 18:00 h.	47 adults (26F/ 21 M; age range: 20–35 y; 14MCs/ 16ICs/17ECs)	Morningness-Eveningness Questionnaire	Self-Report Questionnaire-20	Metamemory Questionnaire; Scale-Semantic Memory; Digit Span; Word List with Emotional Content Test; Word-pair Associated; Visual Memory Scale; Verbal Fluency Test	No significant CT effect. A significant ToD was found during second recall on *"word list with positive emotional content test"*, with all participants showing better performance in the evening.	A synchrony effect was found with both chronotypes showing better performance on metamemory test at their optimal ToD.	ICs showed better performance on Word List with Positive Content and Scale-Semantic Memory Tests in the evening.
Killgore and Killgore (2007)	Season and time of testing not reported.	54 young adults (25F/29 M; age range: 23.5 ± 4) Chronotype groups (N) not reported	Morningness-Eveningness Questionnaire		Wechsler Abbreviated Intelligence Scale	No relationship between MEQ scores and full-scale IQ and performance IQ. Although, MEQ was negatively correlated with verbal IQ. ToD effect not examined.	Not examined	Higher evening- ness was associated with higher verbal cognitive ability as measured only in females.
Barbosa and Albuquerque (2008)	Season of testing not reported 32 participants were tested between 7:30 and 9:30 h and 36 between 16:30 and 18:30 h. A week later 35 participants took part in long-term memory test in morning and 33 in the evening.	68 undergraduate students (40F/ 28 M; mean age: 21.0 ± 2.0; 23MCs/23 ICs/25 ECs)	Morningness-Eveningness Questionnaire MCs: 66 ± 6 ICs: 51 ± 4 ECs: 37 ± 4		Word-List Recognition Morning testing time: 4.25 ± .46 Evening testing time: 4.00±.48	No significant CT effect. No significant ToD effect.	No significant synchrony effect.	Training*ToD effect was found with better performance on long term explicit memory in the afternoon training group.
Bennett et al. (2008)	Season of testing not reported Participants were randomly tested either between 8:00 h-10:00 h or 15:00 h-17:00 h.	77 University students (54F/ 23 M; range: 18–29; 37MCs/40ECs)	Morningness-Eveningness Questionnaire MCs (8:00 h): 63.3 ± 3.1; (15:00 h): 63.7 ± 4 ECs (8:00 h): 34.3 ± 4.6; (15:00 h): 33.5 ± 6 Tympanic Temperature	Verbal Ability MCs (8:00 h):32.9 ± 9.8; (15:00 h): 32.6 ± 6.9 ECs (8:00 h):32.8 ± 7.4; (15:00 h): 36 ± 6.5	Continuous Performance Task; Controlled Oral Word Association Test; Digit Span Test; Wisconsin Card Sorting Task	No significant CT effect. A significant ToD only on Controlled Oral Word Association Test with more words being generated in the evening.	A significant synchrony effect was found only on Wisconsin Card Sorting Task with MCs performing better at their optimal ToD.	Overall, tympanic temperature was higher in MCs than ECs with even higher at 15:00 h.

(*Continued*)

Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes: Main Effect of CT and ToD	Key Outcomes: Synchrony Effect	Other Findings
Mongrain et al. (2008)	Season of testing not reported Participants were awakened 15 times per night and were tested every 4 h: 1.5, 5.5, 9.5 and 13.5 h after wake time, repeatedly over five days.	24 adults (12 F, 12 M; age range: 19–34 y; 12MCs/12ECs)	Morningness-Eveningness Questionnaire; Actigraphy; DLMO (using saliva samples); Body Temperature	Multiple Sleep Latency test; Visual Analogue Scale	Psychomotor Vigilance Task	No significant CT effect. No significant ToD effect.	A significant synchrony effect was observed with MCs having higher subjective alertness in the morning and vice-versa for ECs.	
Matchock and Toby Mordkoff (2009)	Season of testing not reported. Participants were tested at 8:00 h, 12 noon, 16:00 h, and 20:00 h.	80 university students (57F/23 M; mean age: 21.6 ±SD not reported; 36MCs/36ICs/ 44ECs)	Morningness-Eveningness Questionnaire		Attention Network Task; Thayer Activation-Deactivation Check List	No significant CT effect. A ToD effect was found only on conflict scores at 12:00 noon and 4:00 pm for MCs and ECs.	A found synchrony effect was found only on alerting scores, with MCs/ ICs being more alert in the morning and noon than ECs.	
Taillard et al. (2011)	Season of testing not reported. Participants were tested over 84-hour period with 48 hours observation in lab and 36 hours of wakeful period. On day 1 between 7:30–23:30 h and 00:30–6:30 h. On day 2 between 7:30–18:30 h.	18 adults (all males; mean age: 21.4 ± 1.9; 9MCs/9 ECs)	Morningness-Eveningness Questionnaire MCs:63 ± 3.6 ECs:32.6 ± 6.2 Basic Nordic Sleep Questionnaire; Melatonin; Body Temperature	Maintenance Wakefulness Test; Visual Analogue Scale	Reaction Time Task	No significant CT effect. ToD effect not examined.	Not examined	During 36 hours of wakefulness, ECs maintained optimal alertness. In MCs it significantly decreased after 17 hours of wakefulness due to increased sleep pressure.
Wieth and Zacks (2011)	Season of testing not reported. Participants were either tested between 8:30 and 9:30 h or 16:00 h and 17:30 h.	428 university students (sex not reported; mean age: 20.41 ± 1.91; 28 MCs/ 205 ICs/ 195ECs)	Morningness-Eveningness Questionnaire		Analytic Problems; Insight Problems	No significant CT effect. No significant ToD effect.	Participants had higher significant insight problem solving rate (but not for analytic problem) at the non-optimal than optimal ToD.	
Schmidt, Peigneux, Cajochen, et al. (2012)	Participants were tested over 2 nights, 1.5 h (morning session) and 10.5 h (evening session) after waking up	31 young adults (17F/14 M; age range: 22–32 y; 16MCs/15 ECs)	Morningness-Eveningness Questionnaire; Munich Chronotype Questionnaire; Actigraphy; Saliva	Epworth Sleepiness Scale MCs: 4.56 ± 1.8 ECs: 5.29 ± 3.12 Pittsburgh Sleep Quality Index MCs: 3.75 ± 1.0 ECs: 4.05 ± 1.03	Stroop Task	No CT effect for accuracy on Stroop task, but MCs were slower than ECs on RTs and overall Stroop task. No significant ToD effect.	No significant synchrony effect.	

(*Continued*)

Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes: Main Effect of CT and ToD	Key Outcomes: Synchrony Effect	Other Findings
Fabbri et al. (2013) (Experiment 1) (Experiment 2)	Season of testing not reported Participants were tested between 9:00 and 10:00 h, 13:00 and 14:00 h, and 17:00 and 18:00 h.	60 university students (39F/ 21 M; mean age not reported; 30MCs/30 ECs)	Morningness-Eveningness Questionnaire MCs:58.4 ± 4.35 ECs:35.95 ± 5.12 Reduced Morningness-Eveningness Questionnaire MCs:19.9 ± 1.37 ECs:8 ± 2.26		Semantic Classification Task	No significant CT effect. A significant ToD effect was found with lower percentage of retrieval efficiency in the evening than in afternoon and/or morning session.	No significant synchrony effect.	Both, MCs and ECs had higher percentage of retrieval efficiency for positive than negative words.
	Season of testing not reported Participants were tested between 9:00 and 10:00 h, 15:00 and 16:00 h, and 17:00 and 18:00 h.	60 university students (43F/ 17 M; Overall mean age not reported; 30MCs/30 ECs)	Morningness-Eveningness Questionnaire MCs:62.4 ± 2.37 ECs:37.5 ± 3.03 Reduced Morningness-Eveningness Questionnaire MCs:19.8 ± 1.47 ECs:8.55 ± 2.14		Number-Matching	No CT effect was found on RT and accuracy. But ECs showed a higher increase of sum interference effect than MCs. No significant ToD effect.	No significant synchrony effect.	
Baeck et al. (2014)	Season of testing not reported Participants were tested in two groups with group 1 (evening-morning-evening-morning) starting at 20:00, 21:00, or 22:00 h and group 2 (morning-evening-morning-evening) starting at 8:00, 9:00, or 10:00 h, followed by 3 sessions with 12 h interval.	32 university students (19F/ 13 M; mean age: 21.94 ± 1.24; 9MCs/ 13 ICs/10ECs)	Morningness-Eveningness Questionnaire	Raven Advanced Progressive Matrices	Visual Learning	No significant CT effect. No significant ToD effect.	No significant synchrony effect.	Independent of CT and ToD, perceptual learning improved as a result of sleeping in-between training sessions.
Correa et al. (2014)	Season of testing not reported Participants were tested on 2 consecutive days one at 8:00 and another at 20:00 h.	25 university students (all F; mean age: 21.09 ± 2.46; 13MCs/12ECs)	Reduced Morningness-Eveningness Questionnaire MCs:18.15 ± 1.34 ECs:9.17±.83 Body Temperature	Visual Analogue Scale; Monk's Activation Affect Scale	Psychomotor Vigilance Task; Stimulated Driving Task	No significant CT effect. No significant ToD effect.	No significant synchrony effect.	MCs reported higher levels of alertness at their optimal ToD.

(*Continued*)

Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes		Other Findings
						Main Effect of CT and ToD	Synchrony Effect	
Delpouve et al. (2014)	Season of testing not reported Participants were randomly tested at self-defined optimal (12.8 ± 2.9 h) and non-optimal time of day (15.7 ± 3.6 h)	36 university students (26F/10 M; mean age: 25.08 (SD not reported) Chronotype groups (N) not reported	Morningness-Eveningness Questionnaire Optimal group: 49.1 ± 6.1 Non-optimal group: 50.4 ± 6.3	Pittsburgh Sleep Quality Index Optimal group: 4.8 ± 1.4 Non-optimal group: 3.6 ± 1.5 St Marry Hospital Questionnaire Optimal group: 497.9 ± 97 Non-optimal group: 516.4 ± 50.6 Karolinska sleepiness scale Optimal group: 2.9 ± 1.1 Non-optimal group: 5.5 ± 1.3	Psychomotor Vigilance Task Optimal group: 315.6 ± 22.9 Non-optimal group: 349.6 ± 38.5 Artificial Grammar Learning; Digit Span	No significant CT effect. No significant ToD effect.	No significant synchrony effect.	Overall, non-optimal group reported poor sleep quality, higher subjective sleepiness, and longer RT during Psychomotor Vigilance Task than optimal group.
Lara et al. (2014)	Season of testing not reported Participants were tested at 8:00 h and 20:30 h, one week apart	27 university students (25F/ 2 M; age range: 18–27; 13MCs/ 14ECs)	Reduced Morningness-Eveningness Questionnaire MCs:17.85 ± 1.14 ECs:9.64±.84 Skin Temperature	Visual Analogue Scale; Barrett Impulsivity Scale-11 Attentional related Cognitive Error Scale: MCs: 29.18 ± 2.13 ECs: 34.14 ± 1.89	Psychomotor Vigilance Task; Sustained Attention Response Task	No significant CT effect. No significant ToD effect.	A significant synchrony effect with MCs and ECs performing better at their optimal ToD in no-go accuracy and precision strategy.	
Gobin et al. (2015)	Season of testing not reported Participants were randomly assigned to either morning session at 09:00 h or an evening session at 21:00 h.	154 undergraduate students (104F/ 50 M; mean age: 21.27 ± 4.03) Chronotype groups (N) not reported)	Morningness-Eveningness Questionnaire	Pittsburgh Sleep Quality Index; Centre for Epidemiologic Studies Depression Scale; State – Trait Anxiety Inventory; Profile of Mood States	Negative and Neutral Image Recognition Task; Sustained Attention Response Task; Continuous Performance Task	No significant CT effect. No significant ToD effect.	No significant synchrony effect.	ECs reported poor sleep quality, higher confusion, tension, mood disturbance, depressive symptoms and anxiety than MCs and ICs.

(*Continued*)

Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes: Main Effect of CT and ToD	Key Outcomes: Synchrony Effect	Other Findings
Reinke et al. (2015)	Data collected between April and May 2013. Participants were tested between 14:00 h and 16:00 h during day-shift and 4:00 h and 6:00 h at night shift.	96 Nurse (71F/ 25 M; F/M; overall mean age not reported; 61MCs/35 ECs)	Munich Chronotype Questionnaire	Samn Perelli 7 Level Fatigue scale; Karolinska sleepiness scale	Psychomotor Vigilance Task; Two-Digit Addition Test	No significant CT effect. A significant ToD was observed with participants having higher response times, increasing RTs, and lowered numbers of correct responses during night than day shift.	No significant synchrony effect.	No significant differences in sleep quality, sleepiness, and fatigue scores of MCs and ECs. MCs were reported to take naps prior to their shiftwork.
Schmidt et al. (2015)	Season of testing not reported Participants were tested 1.5 hours and 10.5 hour of wakefulness. Testing time for each session was adapted to participants' bedtime.	32 young adults (sex not reported; mean age: MCs: 4 ± 2.3, ECs: 24.8 ± 4.9; 16MCs/ 16ECs)	Morningness-Eveningness Questionnaire; Actigraphy	Pittsburgh Sleep Quality Index; Beck Anxiety Inventory; Beck Depression Scale; Epworth Sleepiness Scale; Visual Analogue Scale	N-back	A significant CT effect with ECs having higher accuracy but longer RTs than MCs. No significant ToD effect.	No overall synchrony effect was observed. But for 3-back condition ECs performed better than MCs in the evening.	fMRI results showed the modulation of cerebral activity by working memory load in the thalamus and in the middle frontal cortex.
Fimm et al. (2016)	Season of testing not reported. Participants were tested at 8:00, 11:00, 14:00, 17:00, and 20:00 h within 24 h interval.	15 university students (7F/8 M; age range: 20–39 y; 1MC/9 ICs/5 ECs)	Morningness-Eveningness Questionnaire – German Version; Body Temperature	Sleepiness Rating Scale; Alertness subtest of Test of Attentional Performance	Covert and Overt Orienting of Attention Task; Neglect Task	No significant CT effect. A significant ToD effect on all cognitive tasks (bar attentional asymmetry) especially at 8:00 h than later test sessions.	No significant synchrony effect.	No significant variation in negative or positive affect during the day.
Gijselaers et al. (2016)	Data were collected between September 2012-August 2013. Secondary data (time of testing not reported).	1131 university students (697F/ 434 M; mean age: 37.26 ± 10.65) Chronotype groups (N) not reported	Munich Chronotype Questionnaire	Pittsburgh Sleep Quality Index; Short Questionnaire to assess Health-Enhancing Physical Activity	Trial Making Task; N-Back Substitution Test	No significant CT effect. ToD effect not examined.	Not examined	Sedimentary behaviour significantly predicted processing speed.

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Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes: Main Effect of CT and ToD	Key Outcomes: Synchrony Effect	Other Findings
Maierova et al. (2016)	Season of testing not reported. Participants were tested for 3–6 days over 3 sessions (in dim light, bright light, and self-selected light) in Morning (average time: 7:16 ± 0:34 h) and evening (average time: 11:14 ± 1:01 h)	32 adults (18F/ 14 M; mean age: 22.7 ± 3.5;16MCs/ 16ECs)	Morningness-Eveningness Questionnaire MCs: 70.5 ± 3.1 ECs: 30.2 ± 5 Munich Chronotype Questionnaire MCs: 2.88 ± 0.81 ECs: 6.53 ± 0.82 Melatonin onset MCs: 19:33 ± 0:56 ECs: 23:26 ± 1:48	Pittsburgh Sleep Quality Index MCs: 2.94 ± 1.1 ECs: 3.50 ± 1.9 Epworth Sleepiness Scale MCs: 5.38 ± 2.9 ECs: 5.56 ± 2.1 Mental Effort Rating Scale	Auditory and Visual N-Back Task; Go-no-go Test; Psychomotor Vigilance Task;	Significant differences were observed in all cognitive tasks due to lighting conditions with little dependency upon chronotype. ToD effect not examined.	Not examined	Overall, ECs were significantly sleepier than MCs. Both groups were more alert in bright light condition than in dim light, with ECs showed higher alertness in self-selected light than dim light condition.
Rothen and Meier (2016)	Season of testing not reported. 31 MCs were tested at 6:00 h and 30 at 10:00 h, 49 ECs at 17:00 h and 50 at 21:00 h.	160 university students (93F/ 67 M; mean age: 22.52 ± 2.30; 61MCs/ 99ECs)	Morningness-Eveningness Questionnaire – German Version		184 Standardised Line Drawing (Snodgrass and Vanderwart (1980)	No significant CT effect. No significant ToD effect.	A significant synchrony effect on priming in both groups with better performance at the non-optimal than optimal ToD.	
Barclay and Myachykov (2017)	Season of testing not reported Participants were tested over a period of 18 hours. Starting at 7:45 h and were required to be awake until the next session at 2:00 h.	26 young healthy adults (12F/14 M; mean age: 25.58 ± 4.26) Chronotype groups (N) not reported	Morningness-Eveningness Questionnaire	Epworth Sleepiness Scale; Pittsburgh Sleep Quality Index	Attention Network Test	No significant CT effect. A significant main effect of ToD, with longer RTs at 2:00 h than 8:00 h. But not on error rates and attentional network scores.	No significant synchrony effect.	
Correa et al. (2017)	Season of testing not reported. Participants were tested within 24-h, at 9:00 h and 17:00 h.	64 university students (32F/ 32 M; mean age: 21.6 ± 2.3; 32 MCs/32 ECs)	Reduced Morningness-Eveningness Questionnaire; Body Temperature	Global Vigour-Affect Scale	Ultimatum game; Continuous Performance Test	No significant effects of CT on decision making patterns. Although, MCs were slower than ECs while responding to high-uncertainty offers in decision making game. No significant ToD effect.	No significant synchrony effect.	

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Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes		Other Findings
						Main Effect of CT and ToD	Synchrony Effect	
Fabbri et al. (2017)	Season of testing not reported. Participants were paired (81 pairs) and were assigned to one of three testing times: 9:00–10:00 h, 13:00–14:00 h or 17:00–18:00 h, with 27 pairs per session.	162 university students (81F/ 81 M; mean age: 23.84 ± 3.59; 30MCs/89 ICs/43Cs)	Reduced Morningness-Eveningness Questionnaire		Navon Task	No significant CT effect. A significant ToD effect with faster global and local foci of attention in the evening than morning or afternoon session. Faster RTs for global focus in the early afternoon and vice-versa for local focus.	A significant synchrony effect on joint Navon task with increased performance at optimal ToD for both MCs and ECs.	
Ritchie et al. (2017)	Season of testing not reported Participants were tested after 8 h of sleeping at 1, 10, 20, 30, 40, 60 mins with EEG verified awakening.	18 healthy adults (5F/13 M; mean age: 22.1 ± 3.7; 7MCs/7 ECs)	Munich Chronotype Questionnaire MCs: 4.2 ± .1 ECs: 5.8 ± 0.2 Melatonin onset (using saliva) MCs: 21.2 ± 0.2 ECs: 23.2 ± .2		Spatial Configuration Visual Search Task	Duration of Sleep inertia for cognitive throughput and RTs was significantly longer in ECs than MCs. ToD effect not examined.	Not examined	
Simor and Polner (2017)	Season of testing not reported. 40 participants (21 ECs, 19 MCs) were tested during their off-peak times and 32 (15 ECs, 17 MCs) at their peak times between 8:00 h and 18:15 h.	72 university students (27 M/45F; mean range:18–30; 36MCs/36ECs)	Morningness Eveningness Scale – Hungarian version	Athens Insomnia Scale MCs: 5.47 ± 3.71 ECs: 5.80 ± 3.63	Compound Remote Associate Problems Tasks; Just suppose subtest of the Torrance Tests of Creative Thinking	No significant CT effect. No significant ToD effect.	Reversed synchrony was only found in convergent task scores in ECs.	Insomniac symptoms predicted lower scores in the convergent thinking task.
Facer-Childs et al. (2018)	Season of testing not reported. Participants were tested at 14:00, 20:00 and 8:00 h.	56 healthy participants (23/33F; mean age: 21.8 ± 3.8; 25ECs/31 ECs)	Munich Chronotype Questionnaire	Karolinska Sleepiness Scale Dim light melatonin onset MCs: 20:27 ± 00:16 ECs: 23:55 ± 00:26 Cortisol peak time MCs: 7:04 ± 00:16 ECs: 11:13 ± 00:23	Psychomotor vigilance task; Memory and Attention Test	No significant CT effect. No significant ToD effect.	A significant synchrony effect on PVT performance only in ECs. Also, on executive function task in MCs.	

(*Continued*)

Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes		Other Findings
						Main Effect of CT and ToD	Synchrony Effect	
Lewandowska et al. (2018)	Season of testing not reported. MCs were tested at 8:00 and 17:00 h and ECs at 9:00 and 18:00 h.	52 young adults (38F/14 M; mean age: 23.96 ± 3.14; 18MCs/34ECs)	Morningness Eveningness Scale	Epworth Sleepiness Scale; Sleep Quality Index	Semantic Memory Task; Phonological Task; Global Processing Task; Local Processing Task	No significant CT effect. A significant ToD effect on response bias for semantic, phonological, global, and local processing tasks in evening than morning session.	No significant synchrony effect.	
Rodríguez-Morilla et al. (2018)	Study conducted between 4 April and 21 June 2016 Participants were tested at 8:00 h in blue-enriched white light and dim light and before and after driving task.	17 university students (11F/ 6 M; mean age: 20.25 ± 1.48; 17ECs)	Reduced Morningness-Eveningness Questionnaire; Wrist Temperature	Mood State Scale; Karolinska Sleepiness Scale	Psychomotor Vigilance Task; Simulated Driving Task	No significant CT effect. ToD effect not examined.	Not examined	Faster RTs in Psychomotor Vigilance Task and driving task were attenuated under blue-enriched white light than dim light.
Song et al. (2018)	Season of testing not reported. Participants were tested between 8:00 and 12:00 h (morning session) and 19:00 and 23:00 h (evening session). The sessions were counterbalanced.	32 young adults (15F/17 M; mean age: 21.7 ± 2.1; 16MCs/16ECs)	Morningness-Eveningness Questionnaire:		Stop Signal Paradigm	No significant CT effect. A significant ToD on accuracy i.e. higher accuracy in evening than in the morning. No effect of ToD on RTs.	No significant synchrony effect.	MCs had higher brain activity than ECs in right lateral IFG, MTG, and left-lateral MCC with the BOLD responses in MFG and MCC, thalamus decreased in the evening in the MCs, while the BOLD responses remained stable in ECs.
Nowack and Van Der Meer (2018)	Season of testing not reported. 50% of both MCs and ECs were testing between 8:00 and 11:00 am and 50% between 2:00 and 4:00 pm.	36 university students (24F/ 12 M; mean age: 26.4 ± 6.4; 18MCs/18ECs)	Munich Chronotype Questionnaire MCs: 4:10 ± 00:55 h ECs: 5:30 ± 00:59 h Morningness-Eveningness Questionnaire		Semantic Analogy Task; Raven Advanced Progressive Matrices; Mehrfachwahl Wortschatz test	A significant CT effect was observed only on analogical reasoning task, with MCs showing faster processing speed and lower error rates than ECs. A significant ToD effect was observed RTs but not on error rates on analogy conditions.	MCs significantly solved the analogy detection task at their non-optimal ToD than ECs.	

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Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes: Main Effect of CT and ToD	Key Outcomes: Synchrony Effect	Other Findings
Zion and Shochat (2018)	Data were collected between August 2011 and April 2014. Participants were tested twice per night at 3:00 h and 7:00 h.	109 nurses (all F; mean age: 39.29 ± 9.06; 73.5% participants were MCs)	Munich Chronotype Questionnaire	Pittsburgh Sleep Quality Index; Karolinska Sleepiness Scale	Digit Symbol Substitution Test; Letter Cancellation Task	No significant CT effect. Overall, performance on both tasks improved at 7:00 h, in younger nurses.	No significant synchrony effect.	
Barner et al. (2019)	Season of testing not reported. Participants were either tested between 8:30 h and11:00 h or between 19:00 h and 21:30 h.	39 young healthy adults (28F/11 M; overall mean age not reported; 20MCs/19ECs)	Morningness-Eveningness Questionnaire MCs tested in morning: 59.83 ± 1.99 MCs tested in evening: 58.75 ± 1.44 ECs tested in morning: 45.20 ± 1.94 ECs tested in evening: 45.83 ± 3.11 Munich Chronotype Questionnaire MCs tested in morning: 3.82 ± .19 MCs tested in evening: 3.92 ± .13 ECs tested in morning: 5.44 ± .18 ECs tested in evening: 5.36 ± .24	Pittsburgh Sleep Quality Index; Stanford Sleepiness Scale;	Syllable Detection Test (RT) Morning group:1042.5 ± 54.94 ms Evening group: 971.74 ± 60.91 ms Dresden Breakfast Task (task completion) Morning group: 70.83 ± 3.17% Evening group: 971.74 ± 60.91 ms Red Pencil Task; Colour Task (mean ± SD not reported)	No significant CT effect. A significant ToD effect was observed with better performance in the evening than in the morning on both cognitive tasks.	No significant synchrony effect.	
Facer-Childs et al. (2019)	Season of testing not reported. Participants were tested over 20 h at 14:00 h, 20:00 h, and 8:00 h.	38 healthy adults (24F/14 M; mean age: 22.7 ± 4.2; 16MCs/ 22ECs)	Munich Chronotype Questionnaire MCs: 2:24 ± 00:10 ECs: 6:52 ± 00:17 Melatonin onset in h) MCs: 20:27 ± 00:16 ECs: 23:55 ± 00:26 Cortisol peak time (in h) MCs: 7:04 ± 00:16 ECs: 11:13 ± 00:23	Karolinska Sleepiness Scale	Psychomotor Vigilance Task; Stroop Task	ECs performed significantly worse than MCs on Psychomotor Vigilance Task. No significant ToD effect.	A significant synchrony effect was observed only for Psychomotor Vigilance Task with both ECs and MCs showing better performance at their optimal ToD.	ECs reported higher sleepiness in morning than afternoon and evening and vice-versa for MCs.
Song et al. (2019)	Season of testing not reported. Participants were tested twice, at 8:00 h, a week apart (with a sleep deprivation session: 22:00–8:00 h).	45 university students (sex not reported; age range: 18-30 y; 24MCs/ 21ECs)	Morningness-Eveningness Questionnaire	Pittsburgh Sleep Quality Index; Epworth Sleepiness Scale; Positive and Negative Affect Schedule; NEO Five-Factor Inventory; Barrett Impulsiveness Scale; Dysexecutive Questionnaire	Psychomotor Vigilance Task; Go/ no-go task	A significant CT effect with ECs having lower stop rate than MCs. A marginally significant ToD effect on PVT with ECs performing worse at 2:00, 3:00, and 6:00 h following sleep deprivation.	No significant synchrony effect.	Sleep deprivation led to decreased response inhibition-related activation of the right lateral inferior frontal gyrus in MCs and vice-versa in ECs.

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Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes		Other Findings
						Main Effect of CT and ToD	Synchrony Effect	
Zion and Shochat (2019)	Data were collected between August 2011 and April 2014. Participants were tested on 2 nights (with and without naps) at 3:00 h and 07:00 h.	119 nurses (all females; mean age: 39.0 ± 9.1) Chronotype groups (N) not reported	Munich Chronotype Questionnaire MCs: 71 ECs: 22 (SD not reported)	Karolinska Sleepiness Scale; Pre-Sleep Arousal Scale-Somatic Subscale; Pre-Sleep Arousal Scale-Cognitive Subscale; Pittsburgh Sleep Quality Index	Digit Symbol Substitution Test; Letter Cancellation Task	No significant CT effect. Improved cognitive at 7:00 h as compared to 3:00 h in both nap and no-nap conditions.	No significant synchrony effect.	Cognitive performance improved following a nap.
Evansová et al. (2022)	Participants were tested on two consecutive days at 8:00 h and 20:00 h.	42 young adults (25 F/17 M; mean age: 28.12 ± 5.25; 14MCs/15ICs/ 13ECs)	Morningness-Eveningness Questionnaire; Actigraphy		Rey Auditory Verbal Learning Test; Trial Making Test; Digit Span; Letter-Number Sequencing; Stroop Test; Continuous Performance Test; Intelligence Quotient	MCs named more colours than ECs in naming subtest of Stroop task. A significant ToD effect on Rey Auditory Verbal Learning Test with better performance in evening than in the morning, independent of CT.	No significant synchrony effect.	
Ge et al. (2020)	Season of testing not reported. MCs were tested at 8:00 h and ECs at 16:00 h	42 young drivers (Sex not reported; mean age: 27.43 ± 3.46; 22MCs/20ECs)	Reduced Morningness-Eveningness Questionnaire		Visual-Spatial Working Memory Task; Syllable Detection Task	MCs had higher visual-spatial working memory than ECs. ToD not applicable.	Not examined	Age significantly predicted the accuracy of visual-spatial working memory.
Martínez-Pérez et al. (2020)	Season of testing not reported. Participants were tested at 8:00 h and at 20:30 h, one week apart.	34 university students (27F/ 7 M mean age: 21 ± 2.3; 16MCs/ 18ECs)	Reduced Morningness-Eveningness Questionnaire MCs: 19.4 ECs: 8.6 (SD not reported)		Optimal time Psychomotor Vigilance Task (RT): 300 ms Flanker Task:394 ms Non-optimal time Psychomotor Vigilance Task (RT): 319 ms Flanker Task:412 ms (SD not reported)	No significant CT effect. No significant ToD effect.	Shorter RTs were observed in Psychomotor in both chronotypes at their optimal ToD in Psychomotor Vigilance Task In the flanker task, only ECs showed a significant synchrony effect.	

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Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes		Other Findings
						Main Effect of CT and ToD	Synchrony Effect	
McGowan et al. (2020)	Data were collected between January-December (bar first weeks of December and January) (year not reported). Participants were tested between 12:00 h and 14:00 h.	188 university students (90F/ 98 M, mean age: 22.3 ± 3.6) Chronotype groups (N) not reported	Munich Chronotype Questionnaire	Pittsburgh Sleep Quality Index; Subjective Sleepiness Scale	Continuous Performance Test; Iowa Gambling Task	No significant CT effect. No significant ToD effect.	No significant synchrony effect.	Poor self-reported sleep quality was correlated with poor decision making on the Iowa Gambling Task.
Ceglarek et al. (2021)	Season of testing not reported. MCs were tested between 9:25 and 9:55 h (morning session) and between 18:30 and 19:02 h (evening session). ECs between 11:00 and 11:30 h (morning session) and 20:40–21:10 h (evening session).	65 young adults (40F/25 M; mean age: 24.29 ± 3.64; 33MCs/32ECs)	Chronotype Questionnaire	Epworth Sleepiness Scale	DRM paradigm (Atkins and Reuter-Lorenz 2011)	A significant CT effect on accuracy with higher accuracy in ECs than MCs, regardless of ToD. No CT effect on RTs. Slower RTs in the morning than evening session. No significant ToD effect for accuracy.	No significant synchrony effect.	
Kossowski et al. (2021)	Season of testing not reported. Participants were tested over 96 hours under 4 light conditions, with MCs tested either at 8:00 or 9:00 h and ECs either at 9:00 or 10:00 h	24 young adults (all M; mean age: 22.92 ± 1.38; 12MCs/12ECs)	Composite Scale of Morningness	Karolinska Sleepiness Scale	N-Back	No significant CT effect. No significant ToD effect.	No significant synchrony effect.	Significantly higher brain activity in frontal areas of the precentral gyrus, middle and superior frontal gyri and in the occipital gyrus in the morning for MCs but not for ECs.
Reiter et al. (2021)	Season of testing not reported. Participants were tested for 3 consecutive days between 8:00 h – 19:00 h.	72 young adults (36F/36 M; mean age: 23.1 ± 3.6; 23MCs/24ICs/ 23ECs)	Melatonin Onset (via saliva over 8 hours)	Karolinska Sleepiness Scale	Psychomotor Vigilance Task	No significant CT effect. No significant ToD effect.	No significant synchrony effect.	A significant effect of test session was found. Subjective alertness, Psychomotor Vigilance Task lapses, and RTs decreased between each consecutive test session.
Yaremenko et al. (2021)	Season of testing not reported 49 participants were tested between 7:40 and 9:00 h (optimal time) and 42 between 20:30 and 21:30 h (non-optimal time).	91 young adults (66F/25 M; mean age: 21.96 (SD not reported; 39MCs/52ECs)	Morningness-Eveningness Questionnaire MCs: 63.77 ± 4.46 ECs: 34.37 ± 5.05		Face Recognition Task; Source Monitoring Task	No significant CT effect. No significant ToD effect.	No significant synchrony effect.	

(*Continued*)

Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes		Other Findings
						Main Effect of CT and ToD	Synchrony Effect	
Palmero et al. (2022)	Season of testing not reported. All participants were tested 4 times during early and mid-follicular phase at 8:00 h and 20:30 h.	32 university students (all Females; age range: 19.75 ± 1.57; 16MCs/ 16ECs)	Reduced Morningness-Eveningness Questionnaire		Psychomotor Vigilance Task; Sustained Attention Response Task	MCs were slower but accurate than ECs on Sustained Attention Response Task. No significant ToD effect.	A significant synchrony effect on Psychomotor Vigilance Task, with faster RTs at optimal ToD in MCs during mid-luteal phase than follicular phase and vice-versa for ECs. In Sustained Attention Response Task, higher accuracy at optimal ToD in MCs during mid-luteal phase than follicular. No synchrony effects for ECs.	
Van Opstal et al. (2022)	Season of testing not reported Participants were tested twice, first at 8:00 h and then at 20:30 h.	130 university students (96F/ 33 M; mean age: 20.65 (SD not reported; 22MCs/56ICs/ 52ECs)	Morningness-Eveningness Questionnaire MCs: 64 ± 3.95 ICs: 64 ± 3.95 ECs: 35.6 ± 4.25	Sleep duration (single item) MCs: 7.59 ± 1.03 ICs: 7.3 ± 1.13 ECs: 6.68 ± 1.35	Sustained Attention Response Task	A significant CT effect with ECs having higher RTs and reduced accuracy on Sustained Attention Response Task than MCs and ICs. No significant ToD effect.	A significant synchrony effect with MCs and ECs performing better at their optimal ToD.	Disrupted and reduced sleep resulted in increased mind wandering in participants.
Carlson et al. (2023)	Season of testing not reported Participants completed an online battery twice: after 1 h of waking up and 30 mins before going to bed.	273 university students (216F/ 54 M; mean age: 24.3 ± 6.69) Chronotype groups (N) not reported	Morningness-Eveningness Questionnaire; Consensus Sleep Diary	Bedtime Procrastination Scale; Self-reported cognitive difficulties; Behavioural regulation difficulties; Emotion regulation difficulties	Stroop Task; Self-Reported Executive Functioning Difficulties	No significant CT effect. ToD effects not examined.	Not examined	ECs had higher bedtime procrastination, emotional, behavioural regulation difficulties, and poorer subjective executive functioning.

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Table 1. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex, age, chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Tasks/ Measures Used	Key Outcomes		Other Findings
						Main Effect of CT and ToD	Synchrony Effect	
(Palmero, Martínez-Pérez, et al. 2024) Experiment 1	Season of testing not reported. ICs were tested between 10:00 h and 16:00 h in one single session.	24 university students (Sex not reported; mean age not reported; 24ICs)	Reduced Morningness-Eveningness Questionnaire		Psychomotor Vigilance Task; Category Semantic Priming Task			A total of 64 participants with a mean age of 21.14 ± 5.45 Results on ICs served as a reference to assess the extreme MCs and ECs.
Experiment 2	MCs and ECs were tested in the morning at 8:00 h and 20:30 h twice, a week apart	40 university students (Sex not reported; mean age not reported; 20MCs/20ECs)				Significant controlled priming effects only in ECs. No significant ToD effect.	A significant synchrony effect on Psychomotor Vigilance Task, with shorter RTs in both chronotypes at their optimal ToD time. No synchrony effect of priming in MCs but it was present in ECs	
Palmero, Tortajada, et al. (2024)	Season of testing not reported. Participants were tested at 8:00 h and 20:30 h, one week apart.	40 university students (32 F/ 8 M; mean age: 21.14 ± 5.45; 20MCs/20ECs)	Reduced Morningness-Eveningness Questionnaire		Psychomotor Vigilance Task; Shape-Label Matching Task	No significant CT effect. No significant ToD effect.	A significant synchrony effect on Psychomotor Vigilance Task, with shorter RTs in both chronotypes at their optimal ToD time. A significant synchrony effect was found on automatic processing only in ECs.	

Abbreviations: CT, Chronotype; ECs, Evening Chronotypes; F, Females; fMRI, Functional Magnetic Resonance Imaging; H, Hour; ICs, Intermediate Chronotypes; IFG, Inferior Frontal Gyrus; IQ, Intelligence Quotient; M, Males; MCC, Middle Cingulate Cortex; MCs, Morning Chronotypes; MEQ, Morningness-Eveningness Questionnaire; MTG, Middle Temporal Gyrus; RTs, Reaction Time; ToD, Time of Day.

a main effect of chronotype on some but not all cognitive domains that were tested. Killgore and Killgore (2007), although not finding any chronotype effect on overall verbal IQ and performance, reported an association between a higher preference for eveningness (i.e. lower scores on the Morningness-Eveningness Questionnaire) and higher verbal cognitive ability in females (not in males). In other three studies, morning types were found to have faster processing speed and lower error rates (Nowack and Van Der Meer 2018), generate more colour names in the naming subtest of the Stroop task (Evansová et al. 2022), or easily shift from automatic to controlled processing-based responses, regardless of ToD during Category Semantic Priming Task (Palmero, Martínez-Pérez, et al. 2024).

As evident in Table 1, the remaining studies found no significant effect of chronotype on *intelligence* (Bennett et al. 2008; Evansová et al. 2022; Gijselaers et al. 2016; Hidalgo et al. 2004; Killgore and Killgore 2007; McGowan et al. 2020; Nowack and Van Der Meer 2018; Song and Stough 2000; Zion and Shochat 2018, 2019), *processing speed* (Evansová et al. 2022; Gijselaers et al. 2016; Reinke et al. 2015; Song and Stough 2000), *perceptual learning* (Baeck et al. 2014), *visual attention* (Matchock and Toby Mordkoff 2009), *visuo-spatial attention* (Fimm et al. 2016), *sustained attention* (Correa et al. 2014; Delpouve et al. 2014; Evansová et al. 2022; Facer-Childs et al. 2018; Gobin et al. 2015; Lara et al. 2014; Martínez-Pérez et al. 2020; Mongrain et al. 2008; Palmero, Martínez-Pérez, et al. 2024; Palmero, Tortajada, et al. 2024; Reinke et al. 2015; Reiter et al. 2021; Rodriguez-Morilla et al. 2018; Taillard et al. 2011; Zion and Shochat 2018, 2019), *joint attention* (Fabbri et al. 2017), *attentional control* (Natale et al. 2003), *inhibition* (Carlson et al. 2023; Facer-Childs et al. 2019; Martínez-Pérez et al. 2020; Schmidt, Peigneux, Cajochen, et al. 2012; Song et al. 2018), *executive functions* (Facer-Childs et al. 2018; Rodríguez-Morilla et al. 2018), *working memory* (Bennett et al. 2008; Evansová et al. 2022; Gijselaers et al. 2016; Kossowski et al. 2021; Lewandowska et al. 2018), *reasoning* (Natale et al. 2003), *verbal fluency* (Hidalgo et al. 2004), *problem-solving* (Natale et al. 2003, Wieth and Zacks 2011), *decision making* (Correa et al. 2014; McGowan et al. 2020), *convergent and divergent thinking* (Simor and Polner 2017), *implicit memory* (Fabbri et al. 2013; Rothen and Meier 2016), *explicit memory* (Barbosa and Albuquerque 2008; Yaremenko et al. 2021), *semantic memory* (Anderson et al. 1991; Fabbri et al. 2013), *prospective memory* (Barner et al. 2019), *visual memory* (Hidalgo et al. 2004), *verbal memory* (Hidalgo et al. 2004), *short-term memory* (Evansová et al. 2022), *source memory* (Yaremenko et al. 2021), and *emotional memory* (Gobin et al. 2015). Lastly, in two studies, regardless of chronotype, better cognitive performance was attributed to lower sleep inertia (Ritchie et al. 2017) or appropriate lighting during testing (Maierova et al. 2016) (see Figure 2).

In addition to chronotype, 45 of 53 studies in young adults (Table 1) also examined ToD effect. In 37 of these 45 studies (82.22%), there was no significant main effect of ToD on *intelligence* (Bennett et al. 2008; Evansová et al. 2022; Hidalgo et al. 2004; McGowan et al. 2020; Song and Stough 2000), *processing speed* (Evansová et al. 2022; Song and Stough 2000), *perceptual learning* (Baeck et al. 2014), *sustained attention* (Correa et al. 2014; Delpouve et al. 2014; Evansová et al. 2022; Facer-Childs et al. 2018, 2019; Gobin et al. 2015; Lara et al. 2014; Martínez-Pérez et al. 2020; Mongrain et al. 2008; Palmero et al. 2022; Palmero, Tortajada, et al. 2024; Reiter et al. 2021; Van Opstal et al. 2022), *attentional control* (Natale et al. 2003), *attentional asymmetry* (Fimm et al. 2016), *verbal fluency* (Hidalgo et al. 2004), *inhibition* (Facer-Childs et al. 2019; Martínez-Pérez et al. 2020; Schmidt, Peigneux, Cajochen, et al. 2012), *executive functions* (Facer-Childs et al. 2018), *working memory* (Evansová et al. 2022; Kossowski et al. 2021; Schmidt et al. 2015), *reasoning* (Natale et al. 2003, Nowack and Van Der Meer 2018), *thinking* (Simor and Polner 2017), *problem solving* (Natale et al. 2003, Wieth and Zacks 2011), *decision-making* (Correa et al. 2017; McGowan et al. 2020), *verbal fluency* (Iskandar et al. 2016), *implicit memory* (Fabbri et al. 2013; Rothen and Meier 2016), *explicit memory* (Barbosa and Albuquerque 2008; Yaremenko et al. 2021), *visual memory* (Hidalgo et al. 2004), *emotional memory* (Gobin et al. 2015), *short-term memory* (Evansová et al. 2022), *semantic memory and associated processing* (Palmero, Martínez-Pérez, et al. 2024) or *source memory* (Yaremenko et al. 2021). Five of these 37 studies, however, did find a ToD effect in some but not all cognitive measures that were tested (Bennett et al. 2008, Evansová et al. 2022; Fabbri et al. 2013; Fimm et al. 2016; Hidalgo et al. 2004). For instance, some studies reported greater word recall and generation, and better short-term memory in the evening (i.e. between 17:00–20:00 h) than morning session (Bennett et al. 2008, Evansova et al. 2022; Hidalgo et al. 2004). Two studies (Fabbri et al. 2013; Fimm et al. 2016) reported a poorer retrieval efficiency on semantic classification and higher visual-spatial attention in the evening session.

The remaining eight of 45 studies (Anderson et al. 1991; Barner et al. 2019; Ceglarek et al. 2021; Fabbri et al. 2017; Lewandowska et al. 2018; Matchock and Toby Mordkoff 2009; Song et al. 2018; Petros et al. 1990) reported a main effect of ToD. Five of these studies reported a ToD effect, regardless of chronotype, with majority suggesting better performance in late afternoon or evening in measures of prospective

Table 2. Summary of key data extracted from selected studies comparing young and old adults.

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex age, and chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Measures Used	Key Outcomes		Other Findings
						CT and ToD Effect	Synchrony Effect	
May et al. (1993)	Season of testing not reported. 50% of the participants in both groups were tested between 8:00 h and 9:00 h and remaining between 16:00 and 17:00 h.	20 young adults (Sex not reported; mean age: 18.8, all ECs) 22 old adults (Sex not reported; mean age: 70.5, all MCs) (SD not reported)	Morningness-Eveningness Questionnaire Old MCs: 70.2 ± 3.7 Young ECs: 29.3 ± 3.5	Vocabulary Test Old MCs: 39.7 Young ECs: 25.7 (SD not reported)	Verbatim Recognition of Sentences from a Series of Paragraphs.	Young ECs had higher recognition accuracy than the older MCs. No significant ToD effect was observed.	A significant synchrony effect was found on recognition accuracy with both groups performing better at their optimal ToD.	
May and Hasher (1998) Experiment 1	Season and time of testing not reported. 50% of the participants were tested at 8:00 h and remaining either at 16:00 or 17:00 h.	48 young adults (sex not reported; age range: 18–22 y; 5% MCs, 58% ICs, 37% ECs) 48 older adults (sex not reported; age range: 62–75 y; 73%MCs/ 25% ICs/2% ECs)	Morningness-Eveningness Questionnaire		Sentence Competition Task; Extended Range Vocabulary Test	No significant CT effect. No significant ToD effect.	A significant synchrony effect on priming of disconfirmed items with both younger ECs and older adults performing better at their optimal ToD.	No age-related differences in completion rates.
Experiment 2		36 young adults (sex not reported; age range: 18–21 y, all ECs) 36 older adults (sex not reported; age range: 62–76 y, all MCs)			Stop-Signal Task; Stroop Task; Trial Making Task	No significant CT effect. No significant ToD effect.	No synchrony effect on accuracy and RTs in go-trials. Younger adults were faster than older adults in Stop-Signal Task. Older adults performed better in the morning on Stroop Task and Trial Making Task. No difference in younger adults.	

(*Continued*)

Table 2. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex age, and chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Measures Used	Key Outcomes		
						CT and ToD Effect	Synchrony Effect	Other Findings
May (1999)	Season of testing not reported. 50% of the participants were tested at 8:00 h and remaining either at 17:00 h.	40 younger adults (sex not reported; age range: 18–25 y, all ECs) 48 older adults (sex not reported; age range: 60–75 y, all MCs).	Morningness-Eveningness Questionnaire		Word Problem; Extended Range Vocabulary Test	No significant CT effects. Cost and benefit scores were more reliable in the evening than morning session.	A significant synchrony effect in both younger and older adults with increased distraction when tested at their non-optimal ToD.	
Hasher et al. (2002)	Season of testing not reported. 50% of the participants were tested at 8:00 h and remaining either at 16:30 h.	48 younger adults (sex not reported; mean age: 20.29 ± 3.01, all ECs) 48 older adults (sex not reported; mean age: 67.96 ± 1.97, all MCs)	Morningness-Eveningness Questionnaire Young adults: 19.7 ± 6.84 Older adults: 67.3 ± 5.71		Memory Task; Mill Hill Vocabulary Scale; Extended Range Vocabulary Test	No significant CT effect. No significant ToD effect.	A significant synchrony effect on recall with both MC older adults and EC younger adults performing better at their optimal ToD.	older adults were more vulnerable to proactive interference than younger adults with heightened interference effects at non-optimal ToD.
West et al. (2002)	Season of testing not reported Participants were tested over 4-days with 50% tested at 9:00 h and 50% at 17:00 h. These were alternated between morning and evening sessions (i.e. morning-evening- morning-evening or evening-morning-evening-morning).	20 young adults (Sex and mean age not reported; 10MCs/10ECs) 20 old adults (Sex and mean age not reported; 10MCs/10ECs)	Morningness-Eveningness Questionnaire in morning Young adults: 46.8 ± 9.11 Old adults: 59.2 ± 7.44 Morningness-Eveningness Questionnaire in evening Young adults: 41.7 ± 11.72 Old adults: 58.5 ± 7.88	Alertness Rating Scale scores in morning Young adults: 62.94 ± 18.46 Old adults: 70.54 ± 11.69 Alertness Rating Scale scores in evening Young adults: 72.38 ± 16.74 Old adults: 67.73 ± 13.95 Wechsler Adult Intelligence Scale-Revised	Four-Box Task	No significant CT effect. No significant ToD effect.	A significant synchrony effect on error rate with both older MCs and younger ECs had significantly lower error rates at their optimal ToD.	Younger adults reported higher levels of alertness in the evening than morning and vice-versa for old adults. Due to practice effect, error rates increased from morning to evening on day 1 but not on day 3 for older MCs but not for younger ECs.

(*Continued*)

Table 2. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex age, and chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Measures Used	Key Outcomes: CT and ToD Effect	Key Outcomes: Synchrony Effect	Other Findings
Bonnefond et al. (2003)	Season of testing not reported. Participants were tested between 10:00 and 12:00 h, 18:00 h and 20:00 h, and 2:00 and 4:00 h, one week apart. Prior to the testing participants underwent 2 weeks of training.	12 young nurses (sex not reported; mean age: 27.5 ± 2.1; 1MC/10ICs/ 1EC) 12 old nurses (sex not reported; mean age: 52.1 ± 2.2; 2MCs/8ICs/ 1EC)	Morningness-Eveningness Questionnaire	Visual Analogue Scale (alertness, performance, and task duration rating)	Visual Discrimination Task; Descending Subtraction Test	No significant CT effect. A significant ToD effect was observed with both ECs and MCs having significantly longer RTs only in Visual Discrimination task at 2:00 h.	No significant synchrony effect.	No age effect was observed on RTs and error rates for the Visual Discrimination Task. Age effect was only present on tasks requiring higher cognitive load.
Yang et al. (2007) Experiment 1	Season of testing not reported. 27 participants were tested at 9:00 h and 26 at 16:00 h.	53 older adults (Sex not reported; mean age: 67.89 ± 4.19; all MCs)	Morningness-Eveningness Questionnaire	Short Blessed Test	Four List of Critical Words, One List of Fillers, and Eight Buffers by Wilson and Horton (2002)	CT effects not applicable. A significant ToD effect was found only on control retrieval with greater priming in the morning than afternoon session.	Participants using controlled retrieval strategy showed more priming at optimal than at non-optimal ToD.	
Experiment 2	22 participants were tested at 9:00 h and 24 at 16:00 h.	46 older adults (Sex not reported; mean age: 66.24 ± 4.51; all MCs)				CT effects not applicable. Greater priming was seen in the morning than afternoon.	A significant synchrony effect only on controlled retrieval.	
Hogan et al. (2009)	Season of testing not reported Participants were tested between 9:00 and 10:00 h and between 18:00 and 19:00 h.	48 young adults (37F/11 M; mean age: 20.17 ± 3.53; 48ECs) 48 old adults (28F/21 M; mean age: 69.70 ± 4.86; 48 MCs)	Morningness-Eveningness Questionnaire Old MCs: 63.6 ± 3.68 Young ECs: 35.55 ± 3.62	Hospital Depression Anxiety Scale Old MCs: 6 ± 3.3 Young ECs: 8.70 ± 3.98 National Adult Reading Test	Digit Symbol Paired Associate Learning Task; Wechsler Paired Associates Memory Test	A significant CT effect was found on Digit Symbol Paired Associate Learning Task with old MCs having poorer memory and slower RTs than young ECs. No significant ToD effect.	A significant synchrony effect was observed with older MCs having poorer memory at their non-optimal ToD.	

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Table 2. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex age, and chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Measures Used	Key Outcomes: CT and ToD Effect	Key Outcomes: Synchrony Effect	Other Findings
Schmidt, Peigneux, Leclercq, et al. (2012)	Season of testing not reported. Participants were tested consecutively for 2 days at 9:00 h and 18:00 h.	11 Young adults (6F/5 M; mean age: 25.6 ± 3.49) 14 Old adults (8F/6 M; mean age: 67.2 ± 3.98) Chronotype groups (N) not reported	Morningness-Eveningness Questionnaire Old adults: 72.43 ± 1.74 Young adults: 27.23 ± 1.63	Pittsburgh Sleep Quality Index Young adults: 25.6 ± 3.49 Old adults: 3.86 ± 1.96 Beck's Anxiety Inventory Young adults: 3.78 ± 1.56 Old adults: 5.07 ± 1.35 Beck's Depression Inventory Young adults: 4.12 ± 1.26 Old adults: 5.18 ± 1.58 Mattis Dementia Scale Old adults: 139.42 ± 3.76	Psychomotor Vigilance Task; Stroop Task	No significant CT effect. No significant ToD effect.	A significant synchrony effects was observed with young and older adults ECs having significantly improved RTs at their optimal time.	Young ECs woke up later and were significantly sleepy than older MCs. No age effect was found on Psychomotor Vigilance Task and Stroop task.
Anderson et al. (2014)	Season of testing not reported 16 young and older adults were tested between 13:00 and 17:00 h (average time: 14:42 h). Further 18 older adults tested between 8:30 and 10:30 h (average time: 8:47 h).	16 young adults (8 F/8 M; mean age: 23.94 ± 4.17) 16 old adults (10 F/4 M; mean age: 71.27 ± 7.68; 16 MCs) 18 old adults (12 F/6 M; mean age: 68.83 ± 7.2; 18 MCs)	Morningness-Eveningness Questionnaire Older adults tested in morning: 60.53 ± 8.17 Older adults tested in morning: 63.67 ± 10.81	Mini Mental State Exam	N-back; Flanker Task; Implicit Word-Fragment Completion Task	A significant CT effect was found on Flanker Task with smallest flanker effect in young adults, followed by older MCs tested in the morning and afternoon. Older adults tested in the morning ignore the unattended stimulus than older adults in the afternoon, and activate cognitive control regions (rostral prefrontal and superior parietal cortex) similar to young adults.	A significant synchrony effect on behavioural and fMRI tasks with older adults performing better at their optimal time.	

(*Continued*)

Table 2. (Continued).

Author & Year (In chronological order)	Month and Time of Testing	Sample Characteristics (n, sex age, and chronotype)	Chronotype Method (Questionnaire/ actigraphy, and/or physiological data)	Other Measures Used	Cognitive Measures Used	Key Outcomes		
						CT and ToD Effect	Synchrony Effect	Other Findings
Iskandar et al. (2016)	Season of testing not reported Participants were tested for 4 consecutive days with 2 morning sessions at 9:00 h and evening sessions at 17:00 h.	20 university students (10F/10 M; mean age: 24.20 ± 3.49, all ECs) 20 old adults (10F/10 M; mean age: 72.75 ± 4.63, all MCs)	Morningness-Eveningness Questionnaire Older adults: 58.85 ± 8.46 Younger adults: 45 ± 10.23	Younger adults Wechsler Adult Intelligence Scale-Revised: 13.6 ± 3.66 National Adult Reading Test Revised: 106.82 ± 9.05 Beck Depression Scale: 5.50 ± 4.8 Older adults Wechsler Adult Intelligence Scale-Revised:16 ± 3.43 National Adult Reading Test Revised: 115.44 ± 7.02 Beck Depression Scale: 4.58 ± 2.84	Category Fluency Test; Letter Fluency Test	No significant CT effect. No significant ToD effect.	A significant synchrony effect was found for word generation, switching more between subcategory exemplars during word generation with both groups performing better at their optimal ToD.	
Rothen and Meier (2017)	Season of testing not reported. Participants were randomly tested between 8:00 and 12:00 h and between 16:00 and 20:00 h.	115 young adults (66F/ 49 M; mean age: 23.05 ± 3.53) 113 old adults (68F/45 M; mean age: 67.58 ± 5.97) Chronotype groups (N) not reported	Morningness-Eveningness Questionnaire Old adults: 60.37 ± 8.95 Young adults: 49.51 ± 9.58		Prospective Memory Task	No significant CT effect. No significant ToD effect.	A significant synchrony effect was observed for younger adults (better performance on-peak than off-peak time), but not for older adults on prospective memory task.	Younger adults performed better than older adults in all conditions.

Abbreviations: CT, Chronotype; ECs, Evening Chronotypes; F, Females; ICs, Intermediate Chronotypes; M, Males; MCs, Morning Chronotypes; RT, Reaction Time; SD, Standard Deviation; ToD, Time of Day.

Table 3. The Joanna Briggs Institute (JBI) quality appraisal ratings of the selected studies.

Study Details		JBI Criteria								
Study	Study Design	Inclusion criteria clearly defined Were the criteria for inclusion in the sample clearly defined? Yes/No/Unclear/NA	Study subjects and setting described in detail Were the study subjects and the setting described in detail? Yes/No/Unclear/NA	Exposure measured in a valid and reliable way Was the exposure measured in a valid and reliable way? Yes/No/Unclear/NA	Objective, standard criteria used for measurement of condition Were objective, standard criteria used for measurement of the condition? Yes/No/Unclear/NA	Confounders identified Were confounding factors identified? Yes/No/Unclear/NA	Strategies to deal with confounders Were the criteria for inclusion in the sample clearly defined? Yes/No/Unclear/NA	Outcomes measured in a valid way Were the outcomes measured in a valid and reliable way? Yes/No/Unclear/NA	Appropriate statistical analysis Was appropriate statistical analysis used? Yes/No/Unclear/NA	Score
Petros et al. (1990)	Mixed: Between and within subject factors	0	1	1	1	1	0	1	1	**6**
Anderson et al. (1991)	Mixed: Between and within subject factors	1	1	1	1	1	0	1	1	**7**
May et al. (1993)	Mixed: Between and within subject factors	0	Unclear	1	1	1	Unclear	1	1	**5**
May and Hasher (1998)	Mixed: Between and within subject factors	0	1	1	1	0	0	1	1	**5**
May (1999)	Mixed: Between and within subject factors	0	1	1	1	0	0	1	1	**5**
Song and Stough (2000)	Mixed: Between and within subject factors	0	1	1	1	1	0	1	1	**6**
Hasher et al. (2002)	Mixed: Between and within subject factors	0	1	1	1	0	0	1	1	**5**
West et al. (2002)	Mixed: Between and within subject factors	Unclear	Unclear	1	1	0	0	1	1	**4**
Bonnefond et al. (2003)	Mixed: Between and within subject factors	1	Unclear	1	1	1	0	1	1	**6**
Natale et al. (2003)	Mixed: Between and within subject factors	1	1	1	1	0	0	1	1	**6**
Hidalgo et al. (2004)	Mixed: Between and within subject factors	1	1	1	1	0	0	1	1	**6**
Killgore and Killgore (2007)	Correlational	1	1	1	1	0	0	1	1	**6**
Yang et al. (2007)	Mixed: Between and within subject factors	0	1	1	1	1	1	1	1	**7**
Barbosa and Albuquerque (2008)	Mixed: Between and within subject factors	0	1	1	1	1	1	1	1	**7**
Bennett et al. (2008)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Mongrain et al. (2008)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Hogan et al. (2009)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Matchock and Toby Mordkoff (2009)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Taillard et al. (2011)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**

(*Continued*)

Table 3. (Continued).

Study Details		JBI Criteria								
Study	Study Design	Inclusion criteria clearly defined Were the criteria for inclusion in the sample clearly defined? Yes/No/Unclear/NA	Study subjects and setting described in detail Were the study subjects and the setting described in detail? Yes/No/Unclear/NA	Exposure measured in a valid and reliable way Was the exposure measured in a valid and reliable way? Yes/No/Unclear/NA	Objective, standard criteria used for measurement of condition Were objective, standard criteria used for measurement of the condition? Yes/No/Unclear/NA	Confounders identified Were confounding factors identified? Yes/No/Unclear/NA	Strategies to deal with confounders Were the criteria for inclusion in the sample clearly defined? Yes/No/Unclear/NA	Outcomes measured in a valid way Were the outcomes measured in a valid and reliable way? Yes/No/Unclear/NA	Appropriate statistical analysis Was appropriate statistical analysis used? Yes/No/Unclear/NA	Score
Wieth and Zacks (2011)	Mixed: Between and within subject factors	0	0	1	1	1	1	1	1	**6**
Schmidt, Peigneux, Cajochen, et al. (2012)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Schmidt, Peigneux, Leclercq, et al. (2012)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Fabbri et al. (2013)	Mixed: Between and within subject factors	1	1	1	1	0	0	1	1	**6**
Anderson et al. (2014)	Mixed: Between and within subject factors	1	1	1	1	0	0	1	1	**6**
Baeck et al. (2014)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Correa et al. (2014)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Delpouve et al. (2014)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Lara et al. (2014)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Gobin et al. (2015)	Mixed: Between and within subject factors	0	1	1	1	1	1	1	1	**7**
Reinke et al. (2015)	Prospective observational cohort design	Unclear	Unclear	1	1	1	1	1	1	**6**
Schmidt et al. (2015)	Mixed: Between and within subject factors	1	Unclear	1	1	1	Unclear	1	1	**6**
Fimm et al. (2016)	Mixed: Between and within subject factors	Unclear	1	1	1	1	1	1	1	**7**
Gijselaers et al. (2016)	Mixed: Between and within subject factors	Unclear	1	1	1	1	1	1	1	**7**
Iskandar et al. (2016)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Maierova et al. (2016)	Within-subjects and Cross-over	1	1	1	1	1	1	1	1	**8**
Rothen and Meier (2016)	Mixed: Between and within subject factors	1	1	1	1	0	0	1	1	**6**
Barclay and Myachykov (2017)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Correa et al. (2017)	Mixed: Between and within subject factors	0	1	1	1	0	0	1	1	**5**

(*Continued*)

Table 3. (Continued).

Study Details		JBI Criteria								
Study	Study Design	Inclusion criteria clearly defined Were the criteria for inclusion in the sample clearly defined? Yes/No/Unclear/NA	Study subjects and setting described in detail Were the study subjects and the setting described in detail? Yes/No/Unclear/NA	Exposure measured in a valid and reliable way Was the exposure measured in a valid and reliable way? Yes/No/Unclear/NA	Objective, standard criteria used for measurement of condition Were objective, standard criteria used for measurement of the condition? Yes/No/Unclear/NA	Confounders identified Were confounding factors identified? Yes/No/Unclear/NA	Strategies to deal with confounders Were the criteria for inclusion in the sample clearly defined? Yes/No/Unclear/NA	Outcomes measured in a valid way Were the outcomes measured in a valid and reliable way? Yes/No/Unclear/NA	Appropriate statistical analysis Was appropriate statistical analysis used? Yes/No/Unclear/NA	Score
Fabbri et al. (2017)	Mixed: Between and within subject factors	1	1	1	1	1	0	1	1	**7**
Ritchie et al. (2017)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Rothen and Meier (2017)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Simor and Polner (2017)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Facer-Childs et al. (2018)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Lewandowska et al. (2018)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Nowack and Van Der Meer (2018)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Rodríguez-Morilla et al. (2018)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Song et al. (2018)	Mixed: Between and within subject factors	1	1	1	1	1	0	1	1	**7**
Zion and Shochat (2018)	Mixed: Between and within subject factors	1	1	1	1	1	1	0	1	**7**
Barner et al. (2019)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Facer-Childs et al. (2019)	Mixed: Between and within subject factors	1	1	1	1	1	0	1	1	**7**
Song et al. (2019)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Zion and Shochat (2019)	Prospective within-subjects	1	1	1	1	1	1	1	1	**8**
Evansová et al. (2022)	Mixed: Between and within subject factors	1	1	1	1	1	Unclear	1	1	**7**
Ge et al. (2020)	Between-subjects	1	1	1	1	1	1	1	1	**8**
McGowan et al. (2020)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Martínez-Pérez et al. (2020)	Mixed: Between and within subject factors	1	1	1	1	0	0	1	1	**6**
Ceglarek et al. (2021)	Mixed: Between and within subject factors	1	1	1	1	1	0	1	1	**7**
Kossowski et al. (2021)	Mixed: Between and within subject factors	1	1	1	1	0	0	1	1	**6**

(*Continued*)

Table 3. (Continued).

Study Details		JBI Criteria								
Study	Study Design	Inclusion criteria clearly defined Were the criteria for inclusion in the sample clearly defined? Yes/No/Unclear/NA	Study subjects and setting described in detail Were the study subjects and the setting described in detail? Yes/No/Unclear/NA	Exposure measured in a valid and reliable way Was the exposure measured in a valid and reliable way? Yes/No/Unclear/NA	Objective, standard criteria used for measurement of condition Were objective, standard criteria used for measurement of the condition? Yes/No/Unclear/NA	Confounders identified Were confounding factors identified? Yes/No/Unclear/NA	Strategies to deal with confounders Were the criteria for inclusion in the sample clearly defined? Yes/No/Unclear/NA	Outcomes measured in a valid way Were the outcomes measured in a valid and reliable way? Yes/No/Unclear/NA	Appropriate statistical analysis Was appropriate statistical analysis used? Yes/No/Unclear/NA	Score
Reiter et al. (2021)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Yaremenko et al. (2021)	Mixed: Between and within subject factors	1	1	1	1	1	1	1	1	**8**
Palmero et al. (2022)	Mixed: Between and within subject factors	1	1	1	1	1	Unclear	1	1	**7**
Van Opstal et al. (2022)	Mixed: Between and within subject factors	0	1	1	1	1	Unclear	1	1	**7**
Carlson et al. (2023)	Correlational	1	1	1	1	1	1	1	1	**8**
Palmero, Martínez-Pérez, et al. (2024)	Mixed: Between and within subject factors	0	1	1	1	1	0	1	1	**6**
Palmero, Tortajada, et al. (2024)	Mixed: Between and within subject factors	1	1	1	1	1	0	1	1	**7**

One point was given for scoring "yes" on each of the criteria, and then all applicable points added to derive the total score for each study.

memory (Barner et al. 2019), response bias in working memory (Lewandowska et al. 2018), executive control (indicated via higher conflict scores; Matchock and Toby Mordkoff 2009), and faster global and local attentional foci (Fabbri et al. 2017). Song et al. (2018) reported higher accuracy (on go trials of Stop-Signal Task) but no effects on RT in the evening than in the morning. ToD was reported to influence comprehension and reading processing (Petros et al. 1990), and speed of access to long-term memory (Anderson et al. 1991), with better performance either in the morning or evening depending upon the type of person tested (i.e. the ToD effect attributable to chronotype characteristics of the sample). Ceglarek et al. (2021) reported faster RTs (but only in evening types and with greater efforts) on a test of short-term memory in the evening than morning session.

Synchrony Effect: Chronotype × ToD Interaction in Young Adults

In total, 45 of 53 studies examined the synchrony effect in cognitive function (Table 1). Twenty-two (48.88%) of these 45 studies reported a synchrony effect in morning and/or evening types. Of these 22 studies, nine (40.90%) reported better performance in both chronotypes or selectively in morning/evening types at their optimal ToD. Petros et al. (1990) reported a significant synchrony effect on probe memory with a linear decrease in performance across the day for morning types and vice-versa for evening types. Similar findings were reported by Anderson et al. (1991) on long-term memory access using word-pair recognition test. Synchrony effect in both chronotypes was also found in *sustained attention* (Mongrain et al. 2008; Van Opstal et al. 2022), *response inhibition* (Lara et al. 2014), *metamemory* (Hidalgo et al. 2004), *joint attention* (Fabbri et al. 2017), *attentional control*, *reasoning* and *problem-solving* (Natale et al. 2003). Lastly, Palmero et al. (2022) found a synchrony effect using sustained attention response task only in morning type females when they were tested during the luteal phase, relative to the follicular phase.

Nine (40.90%) of 22 studies found synchrony in some cognitive functions but not in others. For example, majority of the studies examining *sustained attention* especially using psychomotor vigilance task (PVT) reported a synchrony effect in both chronotypes (Facer-Childs et al. 2019; Lara et al. 2014; Martínez-Pérez et al. 2020; Palmero, Martínez-Pérez, et al. 2024; Palmero, Tortajada, et al. 2024). However, Facer-Childs et al. (2018) found this effect only in evening types. These studies (Facer-Childs et al. 2018, 2019; Martínez-Pérez et al. 2020; Palmero, Martínez-Pérez, et al. 2024; Palmero, Tortajada, et al. 2024) also reported selective or no synchrony in other cognitive functions. For instance, better *inhibition* (Martínez-Pérez et al. 2020), priming and automatic processing (Palmero, Martínez-Pérez, et al. 2024; Palmero, Tortajada, et al. 2024) was found only in evening types at their optimal ToD. Conversely, Facer-Childs et al. (2018) reported better executive functioning only in morning types at their optimal ToD. Lastly, Facer-Childs et al. (2019) reported no synchrony effect on inhibition using Stroop Task. Four further studies found expected synchrony in some tasks and no synchrony in other tasks. Song and Stough (2000) reported a synchrony effect only in morning types on the spatial subtest of multidimensional amplitude battery and showed no synchrony on inspection time, digit span, picture completion, picture arrangement, and object assembly tests. Similarly, Bennett et al. (2008) reported selective synchrony (in morning types) in executive functioning (Wisconsin Card Sort Task) but not in working memory, fluency or memory measures (digit span, controlled oral word association, and continuous performance test). Matchock and Toby Mordkoff (2009) reported increased alertness scores, but not on orienting and conflict scores, on the attentional network task in morning types. Schmidt et al. (2015) observed no synchrony effect in overall working memory (N-Back) performance but found the evening types to perform better during 3-Back condition at their optimal ToD.

Four (of 22; 18.88%) studies found reversed synchrony with better performance at non-optimal ToD. Rothen and Meier (2016) reported increased effect on priming at non-optimal ToD in both chronotypes. Similarly, Wieth and Zacks (2011) also reported reversed synchrony in both chronotypes on an insight problem task but showed no effect analytical problems. Nowack and Van Der Meer (2018) found morning types to be better at analogical reasoning and to show fewer difficulties than evening types in reverse analogy conditions at their non-optimal ToD. Conversely, Simor and Polner (2017) observed better convergent thinking (but not divergent thinking) performance in evening types than morning types when tested at their non-optimal ToD.

The remaining 23 (of 45; 51.11%) studies found no synchrony effect in *Intelligence* (Delpouve et al. 2014; McGowan et al. 2020; Zion and Shochat 2018, 2019), *processing speed* (Evansova et al. 2022; Reinke et al. 2015), *perceptual learning* (Baeck et al. 2014), *implicit learning* (Delpouve et al. 2014), *visual attention* (Barclay and Myachykov 2017), *visuo-spatial attention* (Fimm et al. 2016), *sustained attention* (Correa et al. 2014; Gobin et al. 2015; Reinke et al. 2015; Reiter et al. 2021;

Table 4. List of cognitive functions examined, and neuropsychological tests/subtests used.

Cognitive function assessed		Cognitive test/subtest	Studies
Intelligence	Arithmetic, comprehension, information, spatial, vocabulary	Multidimensional Aptitude Battery (Digit Symbol, Picture Completion, Spatial, Picture Arrangement, and Object Assembly Task.	Song and Stough (2000)
	Mathematical	Digit Span Task	Delpouve et al. (2014); Evansová et al. (2022)
	Fluid and verbal	Raven Advanced Progressive Matrices	Nowack and Van Der Meer (2018)
	Mathematical	Wechsler Adult Intelligence Scale (Digit Symbol Substitution Task)	Gijselaers et al. (2016); Zion and Shochat (2018), Zion and Shochat (2019)
	Verbal and performance	Wechsler Adult Intelligence Scale (Semantic Memory, Digit Span, Word-Pair Associates, and Verbal Fluency Test)	Hidalgo et al. (2004)
		Wechsler Adult Intelligence Scale-III (Digit Span Subtest, Controlled Oral Word Association Test)	Bennett et al. (2008)
		Wechsler Abbreviated Scale of Intelligence	Killgore and Killgore (2007)
	Speed	Inspection Time	Song and Stough (2000)
Sensory Processing		Trial Making Task	Evansová et al. 2022; Gijselaers et al. (2016); May and Hasher (1998)
		Two Digit Adding Test	Reinke et al. (2015)
Perception		Visual Discrimination Task	Bonnefond et al. (2003)
		Shape-Label Matching Task	Palmero, Tortajada, et al. (2024)
Attention	Control	Two Letter Search Task	Natale et al. (2003)
	Joint	Navon Task	Fabbri et al. (2017)
	Sustained	Letter Cancellation Task	Zion and Shochat (2018), Zion and Shochat (2019)
		Continuous Performance Task	Bennett et al. (2008); Correa et al. (2017); Evansová et al. 2022; McGowan et al. (2020)
		Psychomotor Vigilance Task	Correa et al. (2014); Delpouve et al. (2014); Facer-Childs et al. (2018), (2019); Lara et al. (2014); Martínez-Pérez et al. (2020); Mongrain et al. (2008); Palmero et al. (2022); Palmero, Martínez-Pérez, et al. (2024); Palmero, Tortajada, et al. (2024); Reinke et al. (2015); Reiter et al. (2021); Rodríguez-Morilla et al. (2018); Schmidt, Peigneux, Cajochen, et al. (2012); Song et al. (2019)
		Reaction Time Task	Taillard et al. (2011)
		Sustained Attention Response Task	Correa et al. (2014); Gobin et al. (2015); Lara et al. (2014); Palmero et al. (2022); Van Opstal et al. (2022)
	Visual selective	Spatial Configuration Visual Search Task	Ritchie et al. (2017)
	Visual (altering orienting, conflict)	Attentional Network Test	Barclay and Myachykov (2017); Matchock and Toby Mordkoff (2009)
	Visuo-spatial	Covert Orientation Task of attention	Fimm et al. (2016)
		Overt Orienting Task of attention	
		Neglect Task	
Inhibition		Flanker Task	Anderson et al. (2014); Martínez-Pérez et al. (2020)
		Go-No-Go Task	Maierova et al. (2016); Song et al. (2019)
		Memory Task	Hasher et al. (2002)
		Sentence Competition Task	May et al. (1993)
		Stop-Signal Task	May and Hasher (1998); Song et al. (2018)
		Stroop Task	Carlson et al. (2023); Evansová et al. 2022; Facer-Childs et al. (2019); May and Hasher (1998); Schmidt, Peigneux, Cajochen, et al. (2012); Schmidt, Peigneux, Leclercq, et al. (2012)
		Word Problem Task	May (1999)
Working memory		Descending subtraction test	Bonnefond et al. (2003)
		Global Processing Task	Lewandowska et al. (2018)
		Local Processing Task	Lewandowska et al. (2018)
		Phonological Task	Lewandowska et al. (2018)
		Four box tasks	West et al. (2002)
		N-back	Anderson et al. (2014); Gijselaers et al. (2016); Kossowski et al. (2021); Maierova et al. (2016); Schmidt et al. (2015)
		Number-Letter Sequencing Task	Evansová et al. (2022)
		Semantic Processing Task	Lewandowska et al. (2018)
		Visual-Spatial Working Memory Task	Ge et al. (2020)
		Wisconsin Card Sorting Test	Bennett et al. (2008)
Multi-tasking		Stimulated Driving Task	Ge et al. (2020); Rodríguez-Morilla et al. (2018)
Decision making		Iowa Gambling Task	McGowan et al. (2020)
		Ultimatum Game	Correa et al. (2017)
Problem solving		Analytic and Insight problems	Wieth and Zacks (2011)
		Crypto-arithmetic tasks	Natale et al. (2003)
Thinking	Convergent-Divergent	Compound Remote Associate Problems Tasks	Simor and Polner (2017)
Reasoning	Analogical	Semantic Analogy Task	Nowack and Van Der Meer (2018)
	Syllogistic	Syllogistic Reasoning Task	Natale et al. (2003)
Verbal fluency		Language Dependent Task	Iskandar et al. (2016)
		Letter Fluency Task	Iskandar et al. (2016)
		Verbal fluency task	Hidalgo et al. (2004)

(*Continued*)

Table 4. (Continued).

Cognitive function assessed		Cognitive test/subtest	Studies
Learning	Associate	Digit Symbol Paired Associate Learning Task	Hogan et al. (2009)
	Implicit	Artificial Grammar Learning Task	Delpouve et al. (2014)
	Perceptual	Visual Learning Task	Baeck et al. (2014)
Memory	Emotional	Negative and Neutral Image Recognition Task	Gobin et al. (2015)
	Implicit	Number-Matching Task	Fabbri et al. (2013)
		184 standardised line drawing (Snodgrass and Vanderwart 1980)	Rothen and Meier (2016)
		Four list of critical words, one list of fillers, and eight buffers by Wilson and Horton (2002)	Yang et al. (2007)
	Explicit	Word-List Recognition Test	Barbosa and Albuquerque (2008)
		Facial Recognition Task	Yaremenko et al. (2021)
	Prospective	Colour Task	Barner et al. (2019)
		Dresden Breakfast Task	
		Prospective Memory Task	Rothen and Meier (2017)
		Red Pencil Task	Barner et al. (2019)
		Syllable Detection Task	
	Prose	Passage Difficulty Task	Petros et al. (1990)
	Semantic	Category Semantic Priming Task	Palmero, Martínez-Pérez, et al. (2024)
		Word-pair Recognition Test	Anderson et al. (1991)
		Semantic Classification Task	Fabbri et al. (2013)
	Short-Term	DRM Paradigm (Atkins and Reuter-Lorenz 2011)	Ceglarek et al. (2021)
		Rey Auditory Verbal Learning Test	Evansová et al. (2022)
	Source	Source Monitoring Task	Yaremenko et al. (2021)
	Verbal	Verbatim Recognition of Sentences from a Series of Paragraphs.	May et al. (1993)
		Wechsler Paired Associates Memory Test	Hogan et al. (2009)
		Word List with Emotional Content test	Hidalgo et al. (2004)
	Visual	Visual memory scale	Hidalgo et al. (2004)

Song et al. 2019; Zion and Shochat 2018, 2019), *inhibition* (Evansova et al. 2022; Kossowski et al. 2021, Schmidt, Peigneux, Cajochen, et al. 2012; Song et al. 2018, 2019), *working memory* (Evansova et al. 2022; Lewandowska et al. 2018), *decision making* (Correa et al. 2017; McGowan et al. 2020), *short-term memory* (Ceglarek et al. 2021; Evansova et al. 2022), *explicit memory* (Barbosa and Albuquerque 2008; Yaremenko et al. 2021), *prospective memory* (Barner et al. 2019), *source memory* (Yaremenko et al. 2021), and *emotional memory* (Gobin et al. 2015).

Notably, four of 23 studies that we described earlier as showing no significant synchrony effect in cognitive data also obtained neuroimaging data, and their findings

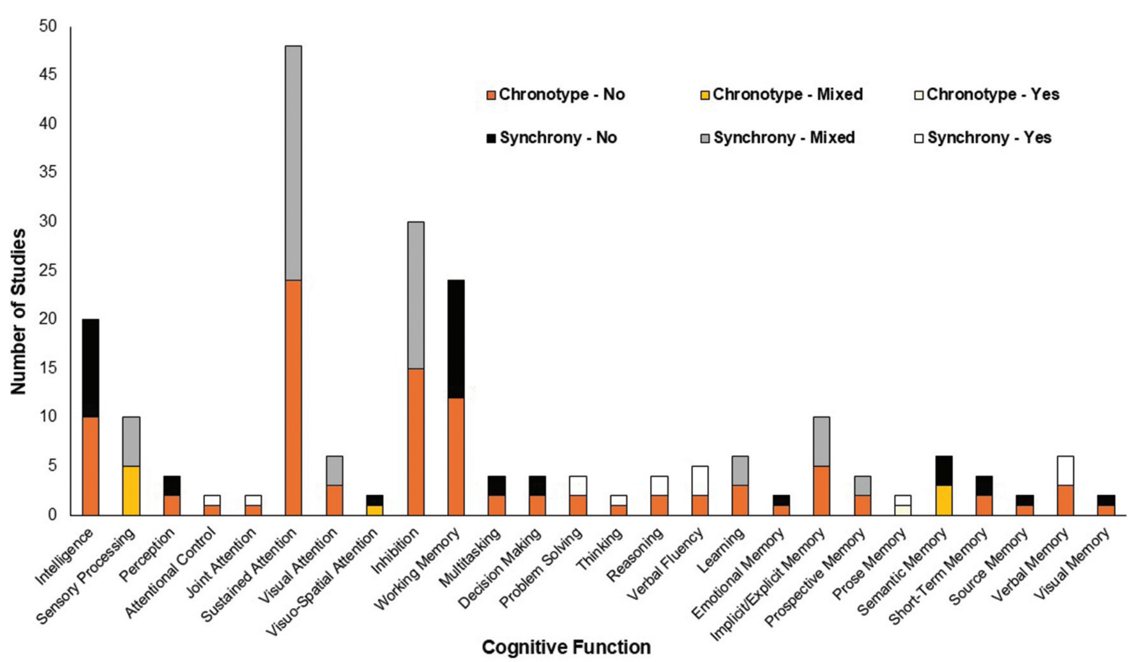

Figure 2. Graphical summary of the findings in relation to observed chronotype and synchrony effects in cognitive function.

hinted towards a synchrony effect in brain activity. Specifically, while Schmidt et al. (2012) reported no synchrony effect on the overall Stroop task, they did find a stable or increased interference-related hemodynamic responses from morning to evening in the evening types, while it decreased in the morning types under similar conditions. Schmidt et al. (2015) did not find a synchrony effect in the overall N-Back task performance but observed better performance and increased thalamic activity during the 3-Back condition in evening types, and higher middle frontal gyrus activation in morning types, at their optimal times. Similarly, Kossowski et al. (2021) did not find a synchrony effect in the overall N-Back task but reported higher brain activity in frontal areas of the precentral gyrus, middle and superior frontal gyri and in the occipital gyrus in the morning types at their optimal ToD. Song et al. (2018) also did not find an overall synchrony effect in the Stroop task but did report a significant decrease in the medial frontal gyrus, middle cingulate cortex, and thalamus in the morning types at their non-optimal time, while the activity in right inferior frontal gyrus, medial frontal gyrus, and middle cingulate cortex remained stable in evening types.

Modulation of Chronotype, Time of Day, and Synchrony Effects by Age

Of 12 (of 65) studies that examined age-related influences, 11 studies examined synchrony effect comparing young and older adults (Anderson et al. 2014; Bonnefond et al. 2003; Hasher et al. 2002; Hogan et al. 2009; Iskandar et al. 2016; May 1999; May et al. 1993; May and Hasher 1998; Rothen and Meier 2017; Schmidt, Peigneux, Leclercq, et al. 2012; West et al. 2002), and one study used a within-subject design assessing older morning (but not evening) types in the morning and late afternoon (Yang et al. 2007).

Of 11 studies comparing younger (18–32 y) and older adults (50–95 y), seven studies reported a significant synchrony effect with both younger evening types and older morning types performing better at their optimal ToD on *verbal fluency* (Iskandar et al. 2016), *recognition* (May et al. 1993), *memory* (Hasher et al. 2002; May 1999; May and Hasher 1998), had lower error rates (West et al. 2002) and faster RTs (Schmidt, Peigneux, Leclercq, et al. 2012). However, Hogan et al. (2009) reported a synchrony effect on *associate learning* only in older morning type adults.

Anderson et al. (2014) reported a synchrony effect in priming only in old adults. They also conducted fMRI analysis in the same sample and reported that older adults tested in the morning were able to ignore more unattended stimuli than older adults tested in the afternoon and also showed higher activation in the rostral prefrontal and superior parietal cortex (similar to young adults). Rothen and Meier (2017) reported a significant synchrony effect in prospective memory in younger evening-type adults but not in older morning-type adults. Bonnefond et al. (2003) did not report any synchrony effect on visual discrimination and descending subtraction tasks. Lastly, Yang et al. (2007) reported that older morning types using a controlled retrieval strategy showed higher priming at optimal ToD; however, this relationship was not found for automatic retrieval.

Discussion

In this systematic review, we evaluated existing evidence to identify possible chronotype, ToD and synchrony effects in cognitive function in healthy adults. Our findings are discussed below.

Chronotype, ToD and Synchrony Effects

Our review showed no main effect of chronotype in the majority of reviewed studies (>80%; Section: *Effects of Chronotype on Cognitive Performance in Young Adults*). The findings concerning the main effect of ToD also indicated no significant ToD effect in more than 2/3 of the studies (>70%; Section: *Effects of Chronotype on Cognitive Performance in Young Adults*).

Our review concerning the synchrony effect revealed a mixed picture with about 45.31% of the examined studies in young adults (k = 64, including 11 studies that examined both young and older age groups) reporting synchrony in both chronotypes or selectively in morning or evening types. Synchrony effects were majorly but not entirely seen in three interrelated cognitive functions of *memory* (Anderson et al. 1991; Bennett et al. 2008; Hasher et al. 2002; Hidalgo et al. 2004; Iskandar et al. 2016; May 1999; May et al. 1993; Petros et al. 1990), *attention* (Facer-Childs et al. 2018, 2019; Fabbri et al. 2017; Lara et al. 2014; Martínez-Pérez et al. 2020; Matchock and Toby Mordkoff 2009; Mongrain et al. 2008; Natale et al. 2003; Palmero et al. 2022; Palmero, Martínez-Pérez, et al. 2024; Palmero, Tortajada, et al. 2024; Van Opstal et al. 2022), and *inhibition* (Lara et al. 2014; Martínez-Pérez et al. 2020) using different neuropsychological tests (e.g. PVT, spatial subtest of multidimensional aptitude battery, Wisconsin card sorting test, attentional network task, analogy detection task). It can be argued that cognitive parameters used in these studies required participants to suppress irrelevant thoughts, demanded higher attention, and critical information processing, suggesting cognitive operations involving executive control are more sensitive to synchrony effect. Furthermore, fMRI results also hinted towards an increased activation of inhibition-related brain regions [prefrontal cortex areas including percental, occipital gyrus and middle and superior frontal gyri (Kossowski et al. 2021), lateral inferior frontal gyrus (Song et al. 2018), and thalamus (Schmidt et al. 2012, 2015)], in both chronotypes during the inhibition tasks.

Interestingly, an asynchrony effect or better performance at a non-optimal time on insight problems, implicit memory task, convergent task, and semantic analogy task can also be observed (Nowack and Van Der Meer 2018; Rothen and Meier 2016; Simor and Polner 2017; Wieth and Zacks 2011) especially when attentional and inhibitory controls are weakened, which allows infiltration of stimuli less relevant to working memory, leading to novel, divergent, and creative ideas (Radel et al. 2015).

Chronotype, ToD, and Synchrony Effect Modulation by Age

About 63.63% (7 of 11) of the studies reported a significant synchrony effect with both young evening and old morning types performing better at their optimal ToD on tasks involving memory and recognition (Hasher et al. 2002; Iskandar et al. 2016; May 1999; May and Hasher 1998; May et al. 1993), higher accuracy (West et al. 2002) and RTs (Schmidt, Peigneux, Leclercq, et al. 2012). Furthermore, there was evidence of a synchrony effect in older adults from the three of 12 studies that involved individuals aged 50–95 y on priming (Anderson et al. 2014; Yang et al. 2007) and associate learning (Hogan et al. 2009). The diurnal preference shifts from eveningness to morningness in adults aged over 55 (Adan et al. 2012; Chauhan et al. 2023), and this may make older adults more vulnerable towards cognitive deficits when tested in the evening. Therefore, the time when testing occurs is crucial in determining age-related differences in cognitive performance both in healthy and clinical samples, of note, neurocognitive disorders (e.g. dementia). These findings are clinically relevant, especially when conducting assessments for diagnosis of potential dementia or other cognitive disorders in older adults and determining treatments based on the assessment outcomes. Therefore, not acknowledging these synchrony related influences may result in exaggerated deficits and biased test outcomes in cognitive performance.

Limitation of the Reviewed Studies

In this section, we discuss some of the key methodological issues that are likely to have impacted the findings of the reviewed studies.

Inconsistency in Testing Time and Sub-Optimal Study Designs

There's no consensus in chronobiology literature regarding time of testing to best capture chronotype and/or synchrony effects. The examined studies employed a range of methods to investigate chronotype and/or ToD effects, as well as their interactions at various time points ranging from a 24-h (Natale et al. 2003) to an extended period of two to five days (e.g. Baeck et al. 2014; Barclay and Myachykov 2017; Correa et al. 2014; Facer-Childs et al. 2019; Iskandar et al. 2016; Mongrain et al. 2008; Reiter et al. 2021; Schmidt, Peigneux, Leclercq, et al. 2012; Schmidt, Peigneux, Cajochen, et al. 2012; Song et al. 2019; West et al. 2002), under different conditions including 36-h wakefulness (Taillard et al. 2011), nap vs no nap (Zion and Shochat 2019), and using bright vs dim light (Kossowski et al. 2021; Maierova et al. 2016; Rodríguez-Morilla et al. 2018). The testing period shows significant variability with morning sessions starting at 7:30 and/or 8:00 am in some studies (e.g. Barbosa and Albuquerque 2008; Hidalgo et al. 2004; Lara et al. 2014; Rothen and Meier 2016; Song and Stough 2000), afternoon sessions at 12 noon, 2:00, 3:00, 4:00 pm and/or 6:00 pm (Anderson et al. 2014; Barbosa and Albuquerque 2008; Hidalgo et al. 2004), and night session at 8:00 pm, 10:00 pm, midnight, and/or 2 am (e.g. Gobin et al. 2015; Lara et al. 2014; Martínez-Pérez et al. 2020; Reinke et al. 2015; Rothen and Meier 2016; Van Opstal et al. 2022; Yaremenko et al. 2021). Furthermore, some studies did not report the exact time of testing (Carlson et al. 2023; Gijselaers et al. 2016; Killgore and Killgore 2007; Ritchie et al. 2017; Schmidt, Peigneux, Leclercq, et al. 2012; Schmidt, Peigneux, Cajochen, et al. 2012). The reviewed studies varied considerably in procedures and cognitive parameters, and some studies had very limited range of chronotype scores which may have led to attenuated synchrony effects.

Not Accounting for Individual Differences

Chronotype is a heavily studied construct, from Asia to Europe and the Americas to Oceania, with consistent findings reporting that chronotype may be sex- and age-dependent (Adan et al. 2012). The findings of this review, as discussed earlier, suggest a more consistent synchrony effect in older adults. Of the 65 studies we reviewed, 12 studies considered a potential influence of sex. Of these 12 studies, seven controlled for sex (Gijselaers et al. 2016; Kossowski et al. 2021; McGowan et al. 2020; Song et al. 2018, 2019; Zion and Shochat 2018, 2019), two reported not finding any sex-related differences in decision-making (Correa et al. 2017) and memory (Fabbri et al. 2013), and the remaining three reported sex-related differences in cognitive performance (Ceglarek et al. 2021; Killgore and Killgore

2007; Palmero et al. 2022). Ceglarek et al. (2021) found males exert more effort on short-term memory in the evening while females remain unaffected. Killgore and Killgore (2007) found a positive association between higher eveningness and higher verbal cognitive ability in females. Recently, Palmero et al. (2022) reported an increased performance in the morning-type females and a decreased performance in the evening-type females, especially in the mid-luteal phase, compared to the follicular phase in sustained attention assessed using SART and PVT. Chronotype has also been linked to certain personality traits (Adan et al. 2012; Chauhan, Pandey, Vakani et al. 2024; Chauhan, Faßbender, Pandey et al. 2024; Randler et al. 2017; Tsaousis 2010), for example, extraversion and neuroticism (Chauhan et al. 2023). Most of the literature examining chronotype effects on cognitive functions, however, does not take into account or control for sex differences and/or personality traits.

Overlooking Seasonal Variations

Only six of the examined studies provided information on the season/s of testing (Gijselaers et al. 2016; Hidalgo et al. 2004; McGowan et al. 2020; Reinke et al. 2015; Zion and Shochat 2019), with the majority (k = 59) not reporting variations in day length over the year, especially in countries which use daytime saving methods (e.g. UK, USA, Germany, Poland). Seasonal changes and daylight saving time temporarily disrupt the human circadian system, further influencing sleep-wake patterns and chronotypes (Adan et al. 2012; Chauhan et al. 2023).

Neglecting Reporting of Physiological Markers of Chronotype

Melatonin and cortisol secretion, as well as body temperature, are considered the gold-standard physiological biomarkers of chronotype, with studies reporting that peak secretion level and offset occur 3 h earlier in morning types than evening types, at least in healthy samples (Adan et al. 2012; Chauhan et al. 2023). Forty-eight of the 65 examined studies did not examine any physiological data. Only 17 used a physiological marker (melatonin and/or body temperature), alongside a subjective measure of chronotype (Bennett et al. 2008; Bonnefond et al. 2003; Correa et al. 2014, 2017; Facer-Childs et al. 2019; Fimm et al. 2016; Lara et al. 2014; Maierova et al. 2016; Mongrain et al. 2008; Natale et al. 2003; Petros et al. 1990; Reiter et al. 2021; Ritchie et al. 2017; Rodríguez-Morilla et al. 2018; Schmidt et al. 2012; Song and Stough 2000; Taillard et al. 2011), which provides more comprehensiveness and robustness to the reported chronotype and/or ToD findings.

Environmental and Other Potential Confounding Factors

As expected, all examined studies were based on the chronotype approach, with some also measuring sleep quality, latency, inertia, alertness/arousal levels, daytime sleepiness, light conditions, napping, and wakefulness, task familiarisation in either laboratory settings or online. However, most of the reviewed studies did not report controlling for confounding variables. Not surprisingly, some studies reported that independent of chronotype, improved sleep quality was linked to better memory, sustained attention (Gobin et al. 2015), and decision-making (McGowan et al. 2020). Other studies reported the role of sedimentary behaviour in predicting processing speed (Gijselaers et al. 2016), poor cognitive performance attributed to sleep inertia (Ritchie et al. 2017), severe social jetlag (McGowan et al. 2020), dim light condition (Maierova et al. 2016; 1000 l×), and sleep deprivation (Song et al. 2019), and good performance after napping (Zion and Shochat 2019). It is worth mentioning the role of environmental temperature (e.g. testing laboratory) in influencing an individual's arousal level and cognitive performance (Zhang et al. 2019).

Conclusion and Future Directions

Based on the findings of this review, we conclude that chronotype (on its own) does not strongly or consistently impact cognitive function in healthy adults. We highlight the importance of synchrony (chronotype x ToD) effects in inter-individual differences in cognitive performance, especially in older adults. These effects have far-reaching implications ranging from education, well-being to clinical diagnosis and treatment. To capture them more fully and accurately, we make a number of recommendations for future research.

First, we suggest that future studies should aim to employ a consistent testing time within a study and transparency in reporting the season of testing to allow robust replication studies and reduce between-study variations. This is particularly relevant given that post-COVID-19 work lifestyle and work-schedule are largely influenced by individuals' abilities and preferences for setting their schedules, making it harder to replicate any previously reported chronotype and synchrony related effects.

Second, we recommend future studies to control for season of testing, seasonal daytime changes, light conditions in the laboratory, room temperature, and other relevant exogenous factors that might influence chronotype and certain cognitive indices (e.g. alertness and vigilance) in all age groups.

Third, we recommend future studies to use comprehensive cognitive batteries to delineate chronotype, ToD and synchrony effects. Cognitive domains are not unitary in nature and involve a cohesive set of functions which could be measured via various parameters, both simple and complex, requiring crystallised and fluid sources of information, respectively (e.g. Hopkins Verbal Learning vs N-Back). With respect to task sensitivity, they may not behave similarly to circadian fluctuations and produce non-existent, attenuated or strong synchrony effects.

Fourth, we recommend future studies to also control for sleep-wake patterns, sleep disruption and quality, personality and to have large enough samples to accurately detect the relationship. We further call for transparency in reporting chronotype classification (e.g. the exact criteria for defining morning, evening, and intermediate types rather than groups based on arbitrary median splits). Studies should also aim to have a sufficient number of males and females to allow meaningful investigation of sex differences and control for or report hormonal variations and contraception use, given their influence on cognitive performance (Munro et al. 2012; Palmero et al. 2022).

Lastly, we encourage future studies to examine physiological data (e.g. body temperature, melatonin and cortisol levels, heart rate, actigraphy, and skin conductance) while studying chronotype and ToD effects on cognition, considering that chronotype has a specific physiological manifestation which fluctuates throughout the day and is linked to arousal and alertness levels.

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