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Effects of school start time and its interaction with the solar clock on adolescents' chronotype and sleep: a Systematic Review and Meta-analysis

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Abstract

Adolescents' late chronotypes colliding with early school start times (SSTs) are proposed to be the cause of students' unhealthy sleep habits. Most studies comparing different SSTs associate later SSTs with longer sleep duration and lower social jetlag. However, the magnitude of the effect varies between studies and the effect of different SSTs on chronotype is not well established. Moreover, although human circadian rhythms are entrained by the sun, when studying the effect of different SSTs on adolescents' sleep habits usually only the social clock, and not the solar clock, is taken into consideration. This meta-analysis investigates whether later SSTs affect adolescents' sleep habits and chronotype and it assesses factors that can modulate this effect, including the relative importance of social and solar clocks. Here, through a database search we identify 35 studies comparing the effect of different SSTs on adolescents' sleep habits and/or chronotype. Random effect meta-analyses showed that later SSTs are associated with later sleep timings and longer sleep duration on weekdays, lower levels of social jetlag, and later chronotypes. Several meta-regressions reveal that not only the distance between compared SSTs but also the interplay between SSTs and the solar clock modulate the effect of different SSTs on sleep timings and duration on weekdays.

Keywords

School schedules, Adolescents, Sleep duration, Solar clock, Social clock, Chronotype, Social jetlag

Abbreviations

MSFsc	Midpoint of sleep on free days sleep corrected (chronotype index)
SDf	Sleep duration on free days
SDw	Sleep duration on weekdays
SJL	Social jetlag
SST	School Start Time
SSTearlier	The earliest of the two compared SSTs
$SSTearlier_{-sunrise}$	The distance between sunrise time and SSTearlier
$SSTLT_{earlier}$	SSTearlier according to local time
$SSTmc_{earlier}$	SSTearlier corrected by the distance between the meridian of the adopted time zone and local longitude
ΔSST	Distance between the two compared school start times (SSTlater-SSTearlier)

1. Introduction

Chronotype, defined as the expression of the internal clock under a specific environment, is modulated by several factors, including social cues and age. Even though adolescents present later chronotypes than children and adults [1], they still have to attend school early in the morning. Consistently, early school start times (SSTs) are proposed to be the main cause of adolescents' unhealthy sleep habits, such as short sleep duration on weekdays (SDw) and high levels of social jetlag (SJL) [2,3]. Several studies comparing different morning SSTs (longitudinally or cross-sectionally) have shown that later SSTs are associated with lower levels of SJL and longer SDw, mostly due to later wake-up times on weekdays [4–9]. Recently, the body of literature comparing school schedules starting at different moments of the day (e.g. morning and afternoon) has been rapidly growing [10–19]. These studies show similar results to those comparing only morning SSTs (i.e. later SSTs are associated with healthier sleep habits) but the magnitude of the effect tends to be higher.

A lower number of studies address the effect of different SSTs on chronotype and the results obtained are mixed, with some of them reporting no effect [6,20,21] and others reporting an association of later chronotypes with later SSTs [10,14,22]. However, the comparison between studies is extremely difficult because chronotype is evaluated using different instruments and proxies, for example: scores derived from standardized questionnaires, such as the Morningness-Eveningness Questionnaire [23]; or the midpoint of sleep on a free day (MSF), which is a proxy of chronotype that relies on sleep timing [24]. A particularly widely used and reliable proxy is the MSF corrected by sleep debt (MSFsc) [1], which can be derived from either questionnaire, sleep diaries or actigraphy records, because the information of sleep timings on week- and free days is enough to calculate it.

The effect of SST on sleep-related outcomes and chronotype could be modulated by different factors, e.g. the distance between the two compared SSTs (ΔSST) or the relation between the SST and the solar clock, as both physiological and behavioral human rhythms are mainly synchronized by sunlight [25,26]. Some previous studies in adolescents revealed a modulation of sleep habits and/or chronotype by latitude [27,28], by longitude within the same time zone [27], and also a bidirectional association between light exposure and sleep habits [29]. In fact, the debate over the relative importance of social and solar clocks in human chronobiology is still one of the hottest topics in the field [30,31]. Of course, the effect of social clocks might be direct or indirect, via light exposure (both natural and artificial) [26,32].

Despite all of this, most studies addressing the effect of SSTs on sleep-related outcomes and chronotype only take the social clock (i.e. SST evaluated as local time, SSTLT), and not the solar clock, into consideration. Different proxies of the relationship between both clocks can be proposed. First, it is possible to measure SST according to the solar time and not the local time, that is, correcting SST by the distance to the meridian of the adopted time zone (SSTmc) [33]. This proxy takes into consideration the effect of the time zone system, which generates a discrepancy between local time and solar time when the local longitude is not coincident with the meridian of the adopted time zone. Second, another possible proxy is the distance between sunrise and SST (SST-Sunrise) [33]. Unlike SSTmc, this proxy also considers the effect of latitude and seasonality, as sunrise time is affected by both factors. In addition, sunrise time could be important for modulating adolescents' wake-up time due to their temporal proximity.

Previous meta-analyses addressing the effect of different SST on adolescents' sleep found an association between later SSTs and longer sleep durations, but they did not study or did not find the association between later SST and chronotype [34,35]. Importantly, previous meta-analyses only included studies comparing morning SSTs and did not consider the importance of the solar clock.

In this systematic review and meta-analysis, we aim to address this gap in knowledge through two distinct approaches. Firstly, we will study the effect of later SSTs on adolescents' sleep and chronotype outcomes (i.e. SDw, sleep timings -Bedtime and Wake-up time- on weekdays, SJL and MSFsc) not only when comparing morning SST between them, but also with afternoon and evening school schedules. Secondly, we will evaluate whether the ΔSST and/or the social/solar clocks explain the effect size on chronotype and sleep outcomes when two morning SST are compared. We hypothesize that later SSTs are going to be associated with longer SDw, later MSFsc, lower levels of SJL and later bed- and wake-up times on weekdays. We also expect the effect size on these outcomes will be greater when the ΔSST is greater and when the earliest SST (i.e. SSTearlier), according to both social and solar clocks, is earlier. Finally, we hypothesize that the solar clock (i.e. SSTmc and, especially, SST-Sunrise) will better explain the effect of different school schedules than the social clock (i.e. SSTLT).

2. Methods

2.1 Protocol registration

The protocol was registered in the International Prospective Register of Systematic Reviews (PROSPERO) under the registration number CRD42022344582. This systematic review and meta-analysis were conducted following PRISMA guidelines [36].

2.2 Literature search

We conducted a systematic search in June 2022 in PubMed, Scopus and Web of Science. The search in Web of Science was limited to the period 2011–June 2022 due to the limited access to the resource. The search was updated in January 2023 using PubMed and Scopus databases. All searches were restricted to studies written in English.

The results of the first search were exported to Cadima (https://www.cadima.info/) to facilitate screening. Duplicates were removed and titles and abstracts of the remaining records were assessed by two independent coders (GRF and FL) against the eligibility criteria. In order to check whether inclusion criteria needed to be revised, agreement between coders was checked when 25% of the screening was completed. Such revision was not necessary (95% inter-coder agreement). Then, the totality of the full texts of retained studies were screened by GRF and 25% of them (randomly sampled) were screened in parallel by FL. Disagreements were solved through discussion (n=2) and, if consensus could not be reached, MJL was consulted for the final decision (n=1).

2.3 Selection criteria

We included original longitudinal or cross-sectional studies which: 1- compare the effect of attending 2 or more different School Start Times (SSTs) on adolescents' chronotype and sleep-related outcomes; 2- compare at least two well-defined SSTs (i.e. an earlier and a later school schedule), SST could not be entered as a continuous variable; 3- SST should be similar for every student in each group (e.g. if the groups compared were SSTs 'earlier than 08:30' and 'later than 08:30', the study was excluded); 4- SSTs should be stable along the week and should be the same for at least 1 month prior to data collection; 5- Classes should take place in the school (no virtual classes). Studies that took place during atypical situations due to COVID-19 pandemic were excluded.

2.4 Data extraction and treatment

Data extraction was performed independently by GRF (100%) and FL (25%). Sample characteristics (e.g. sample size and SSTs), time and geographic information of data collection and outcomes (sleep timings and sleep duration on week- and free days -SDw and SDf-, social jetlag -SJL- and MSFsc) were extracted.

We estimated sunrise time from the date and location of the data collection (we used the sunrise

time of the midpoint of the data collection period) and longitude (we used Google Maps to visually select a midpoint of the region). Using this information and the SST of the earlier group

(SSTearlier), we derived two proxies which represent the interplay between SSTearlier and the solar clock. First, we calculated school start time according to solar clock (SSTmcearlier) by correcting the SST expressed in local time (SSTLTearlier) by the

SSTmcearlier = SSTLTearlier - 4*DMATZ

distance (expressed in º) of the place of data collection to the center of the adopted time
Note that DMATZ is lower than zero when the place of data collection is west of the meridian of
zone (DMATZ) as:
the adopted time zone and, thus, SSTmcearlier < SSTLTearlier. Oppositely, DMATZ is greater than zero when the place of data collection is east of the meridian of the adopted time zone and, thus, SSTmcearlier > SSTLTearlier. SSTmcearlier is a local time [33].

Second, we calculated the temporal distance between the earliest SST and the sunrise time:

SSTearlier-Sunrise =SSTLTearlier - Sunrise time

Note that SSTearlier-Sunrise is a temporal distance, and consistently, the units of this variable are hours [33].

Additionally, if one of the sleep outcomes and/or chronotype was not reported, when possible, we estimated it using the means of other outcomes (e.g., mean sleep duration could be estimated from mean bedtime and wake-up times). In those cases, we used propagation of uncertainty equations to estimate the standard deviation of the calculated outcomes.

For some studies, we had access to unpublished information because of previous contact with the authors [20,37] or because they were studies of our group [10,14]. We also contacted authors of Wahlstrom et al., 2017 [38] to ask the exact values of data represented graphically but they could not provide us the required information.

2.5 Quality assessment

Quality assessment and risk of bias were performed using the checklist for assessing the quality of quantitative studies proposed by Kmet et al., 2004 [39]. Quality assessment results were not part of inclusion/exclusion criteria.

2.6 Data analysis

We conducted a random effect meta-analysis including three different subgroups for each outcome (i.e. sleep timing on weekdays -bedtime and wake-up time -, SDw, SDf, SJL and MSFsc). We use standardized mean difference (SMD, here Hedges' g) as measure of effect size. Hedges' g is a standardization of the subtraction between 'Outcome in SSTlater - Outcome in SSTearlier', where Outcome could be MSFsc, SJL, SDw, bedtime or wake-up on weekdays. As a reference, Hedges' g values of 0.2, 0.5 and 0.8 indicate small, medium and large effects, respectively.

Subgroups were defined depending on the timing distance between the two compared SSTs: 'Morning vs. Morning', 'Morning vs. Afternoon' and 'Morning vs. Evening'. Heterogeneity between studies was calculated using Q (the weighted sum of squared deviations of each study's effect estimate from the overall effect estimate) and I2 (interpreted as the percentage of the total variability in a group of effect sizes due to true heterogeneity) statistics [40]. Funnel plots and Egger's test were performed for each outcome and subgroup to address the possibility of publication bias,

To study the factors associated with the effect size of later SSTs, we ran four meta-regressions for each outcome, we compared them using the Akaike criterion and the most parsimonious model (i.e. lowest AIC) was selected for each outcome. All models (including the base model) include the magnitude of the difference between the two compared SSTs (ΔSST) as it probably is an important predictor of the effect of different SSTs on chronotype and sleep-related outcomes. The other three models included ΔSST and one of the three following predictors to study the relative importance of solar and social clocks SSTLTearlier, SSTmcearlier and SSTearlier-Sunrise.

Analysis was performed using the R system for statistical computing (v.4.0.2; R-Core-Team, 2020). For meta-analyses, the Meta package [41] was used, the Metafor package [42] for meta-regressions and the dmetar package [43] for Egger's tests and effect sizes calculation.

3. Results

3.1 Study selection

The database search resulted in 1581 publications, 948 remained after duplicates removal. The title and abstract of those studies were screened by two independent coders (GRF and FL), 80 studies were selected for full-text assessment (97% inter-rater agreement and κ = 0.81). GRF and FL read thoroughly the 100% and 25% of the 80 studies, respectively, and selected 35 of them to be included in this systematic-review (90% inter-rater agreement and κ = 0.79) and 30 of them were include in at least one part of the quantitative synthesis [4,5,7–22,37,44–54] (Fig. 1). The other 5 studies could not be included in the quantitative analysis because they only report means and/or variability graphically [6,38,55] or because they do not report means or any measure of variability [56,57].

3.2 Study characteristics and quality

Selected studies were extremely heterogeneous in several aspects, for example in their distribution across countries, the number of participants (Supp. Table 1) and the methods used to assess adolescents' sleep habits and chronotype (i.e. actigraphy, sleep diaries and different questionnaires). The effect of SST on adolescents' outcomes was cross-sectionally assessed in most studies (n=24) and the SST difference (ΔSST) between groups or between pre- and post-test range from 15 minutes to 11.5h. Interestingly, most studies reported sleep duration and sleep timing on week- and free days but not SJL and MSFsc (Supp. Table 1). Only two included studies addressed an advance of SST [21,47].

Most studies present a high quality according to our rating using the Checklist proposed by [39], even though blinding of subjects and investigators was not possible in any of them and, random allocation, only in a few [10,13,14,44] (Supp. Table 2). Importantly, considering the specific topic of the included studies, some relevant aspects of their quality were not evaluated in the mentioned checklist. For example, the duration of each point of data collection (i.e. the time lapse between the start and the end of each data collection period) is important as if it is too long it could affect the results (due to photoperiod changes) and it ranges from 1 day [14] to 6 months [20] in the included studies. Additionally, in some longitudinal studies pre- and post-SST-change data collection took place in different seasons or even different adopted time zones (i.e. ST or DST) [7,16,22,46–48].

3.3 Meta-analyses of sleep-related outcomes and chronotype

Here, we evaluated whether a later SST is associated with changes in adolescents' chronotype and sleep outcomes, when compared with an earlier SST. To assess the effect of SST, we defined three subgroups according to the timing difference between the two school schedules compared. The three subgroups were: 1- the two school schedules start in the morning ('Morning vs. Morning'); 2- One school schedule starts in the morning and the other in the afternoon ('Morning vs. Afternoon'); and 3- One school schedule starts in the morning and the other in the evening ('Morning vs. Evening'). Some papers included more than two SSTs and, consistently, we extracted more than one data point or comparison. For example, Goldin et al. 2020 [14] include two different age groups (younger and older adolescents) and their study presents three school timings. Then, we extracted four data points from this paper: two data points (one for each age group) are included in the 'Morning vs. Afternoon' subgroup and two are in the 'Morning vs. Evening' subgroup.

Figures 2 and 3 show the forest plots for each outcome: chronotype (MSFsc), social jetlag (SJL), Sleep duration on weekdays (SDw) and Bedtime and Wake-up time on weekdays), divided by subgroups. For each outcome, the effect size (SMD) on each subgroup might be significantly different from zero (or not) and/or significantly different from the other subgroups. Finally, the variability measurements (Q and I2) might be significant overall and/or on each subgroup, which suggest that some factors not included in the analysis might be explaining the differences on effect sizes among studies. A positive SMD means that the outcome is greater or later and a negative SMD indicates that the outcome is smaller or earlier in the later SST compared with the earlier SST. Accordingly, we expected positive SMD positive for MSFsc, SDw and sleep timings -both Bedtime and Wake-up time- and negative SMD for SJL.

3.3.1 Chronotype (MSFsc)

We observed an overall main effect of SST on chronotype (k = 32, SMD = 0.356, 95% Confidence Interval (CI) = 0.226–0.485; $p < 0.0001$), with a later SST associated with later chronotypes. Importantly, subgroups were significantly different ($p<0.0001$) showing a higher effect on chronotype when compared SSTs were more distant (Fig. 2). For example, ‘Morning vs. Afternoon’ subgroup showed a higher SMD than ‘Morning vs. Morning’ subgroup (k=12, SMD=0.527, 95%CI= 0.308 – 0.746; and k=16, SMD=0.152, 95%CI =0.110–0.194, respectively). Although, ‘Morning vs. Evening’ subgroup presents a higher SMD than the other two subgroups, ‘Morning vs. Evening’ SMD was not significantly different from zero (k=4, SMD=0.805, 95%CI= -0.062–1.673). Heterogeneity was significant overall and on each subgroup (Fig. 2a), suggesting that the effect of different SSTs on chronotype are modulated by other factors.

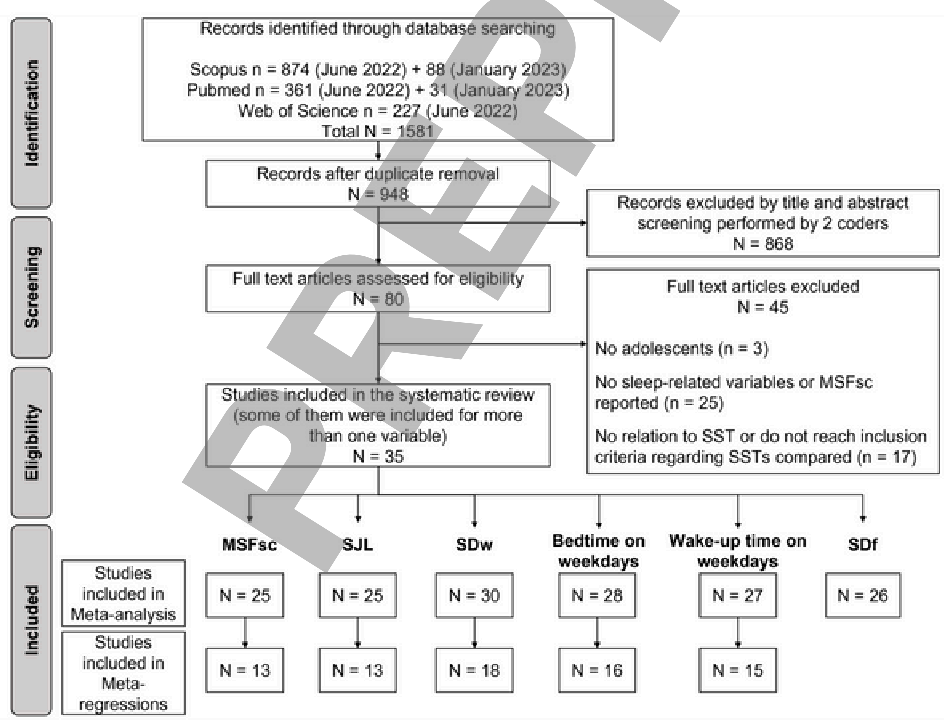

Figure 1. PRISMA flowchart. The PRISMA flow diagram detailing the process of studies selection and the number of studies included in each part of this work for each of the outcomes of interest (MSFsc, SJL, sleep duration and sleep timings). MSFsc = Midpoint of sleep on free days sleep corrected. SJL = Social jetlag. SDw = Sleep duration on weekdays. SDf = Sleep duration on free days.

3.3.2 Social jetlag

Overall, SJL is affected by SST (k = 32, SMD = -0.603, 95%CI = -0.782 to -0.431; p < 0.0001), with lower levels of SJL being associated with a later SST (i.e. a negative effect size). Importantly, subgroups were significantly different (p<0.0001) showing a greater effect on SJL when the compared SSTs are more distant (Fig. 3). For example, the SMD was more negative in the 'Morning vs. Afternoon' subgroup than in the 'Morning vs. Morning' subgroup (k=12, SMD= -0.877, 95%CI= -1.117 to -0.637; and k=16, SMD= -0.210, 95%CI = -0.305 to -0.115, respectively). Moreover, 'Morning vs. Evening' SMD was even more negative than the other two subgroups (k=4, SMD= -1.354, 95%CI= -1.712 to -0.996). Heterogeneity was significant overall and in 'Morning vs. Morning' and 'Morning vs. Afternoon' subgroups (Fig. 2b).

3.3.3 Sleep duration

Overall, SDw is affected by SST (k = 37, SMD = 0.963, 95%CI = 0.514 – 0.687; p < 0.0001), with longer sleep duration being associated with a later SST (i.e. a positive effect size). Importantly, subgroups were significantly different (p<0.001) showing a greater effect on SDw when the compared SSTs are more distant (Fig. 3a). For example, 'Morning vs. Afternoon' subgroup showed a higher SMD than 'Morning vs. Morning' subgroup (k=12, SMD= 1.129, 95%CI= 0.945–1.313; and k= 21, SMD= 0.368, 95%CI= 0.258–0.478, respectively). Interestingly, the mean effect size for 'Morning vs. Evening' subgroup does not differ from zero (k=4, SMD=1.009, 95%CI= -0.840 – 2.859), this seems to be due the opposite results obtained in Peixoto et al. [17] compared with Goldin et al. and Rodríguez Ferrante et al. [10,14]. Heterogeneity is significant overall and in all subgroups (Fig. 3a).

Studies that did not reach the criteria to be included in the meta-analysis also show an increase of SDw with a later SST [6,38,55–57]. The increase seems to depend on ΔSST [38] but also on age [55].

No overall effect of SST was found on SDf (k = 34, SMD = -0.039, 95%CI = -0.101–0.021; p= 0.193). In addition, subgroups do not differ between each other and SMD in each subgroup do not differ from zero (Supp. Fig. 1).

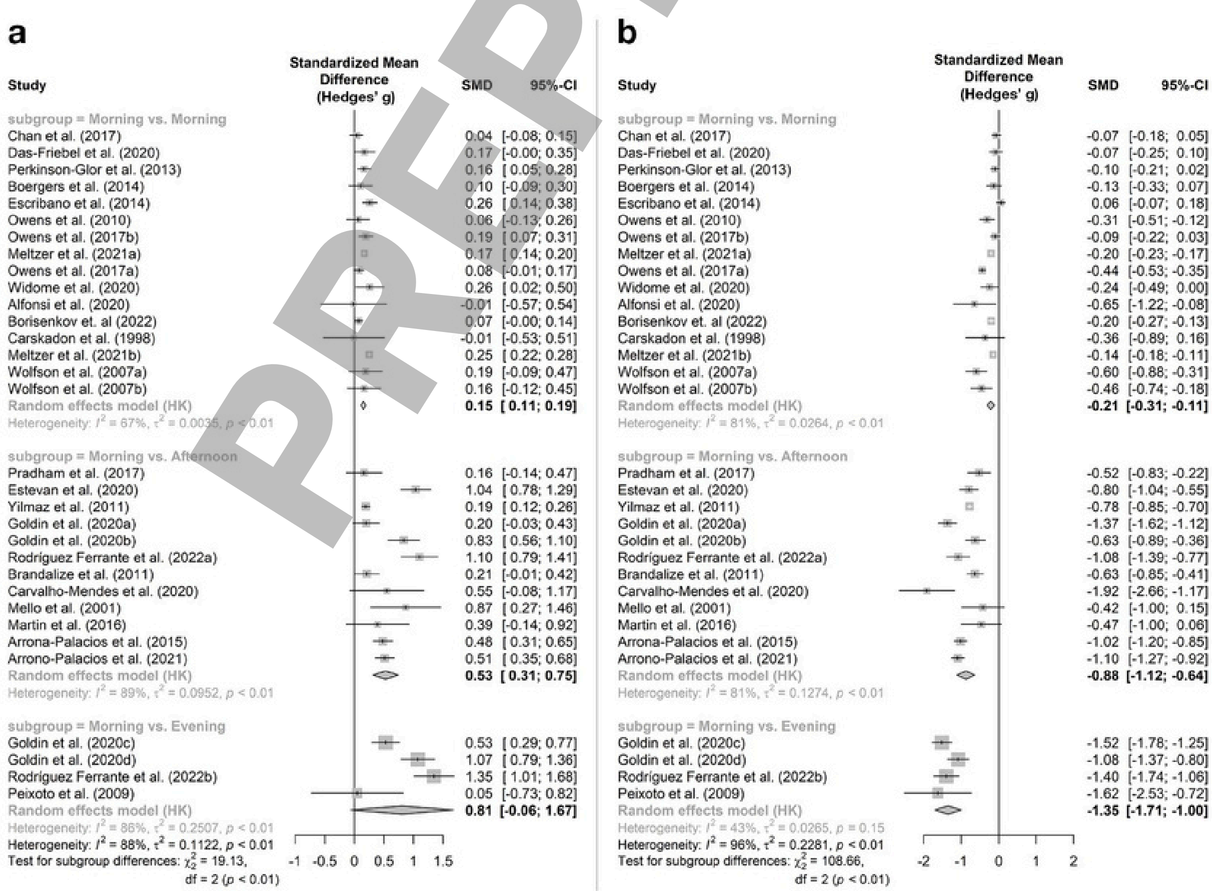

Figure 2. a- Forest plot for chronotype (measured as MSFsc -Midpoint of sleep on free days-). A positive SMD indicates that later SSTs are associated with later chronotypes. b- Forest plot for social jetlag. A negative SMD indicates that later SSTs are associated with lower levels of SJL. Subgroups were defined according to the moment of the day where the two compared school schedules start (e.g., if both school schedules start at morning, then the study is in 'Morning vs. Morning' subgroup). Studies are ordered in ascending order according to ΔSST and alphabetically when ΔSST is the same.

3.3.4 Sleep timing on weekdays

Overall, both bedtime and wake-up time are affected by SST (k= 35, SMD= 0.405, 95%CI = 0.253–0.558; p < 0.0001 and k = 34, SMD = 1.704, 95%CI = 1.372–2.035; p < 0.0001, respectively), with later bedtimes and wake-up times being associated with a later SST (i.e. a positive effect size). As expected, the effect is greater for wake-up times than for bedtimes, which is consistent with the fact that longer SDw is associated with later SSTs. While one study not included in the meta-analyses showed a delay in bedtime with a later SST [6], another study showed an advance of bedtime with a later school schedule [57]. However, the latter could be due to the fact that data was collected in 1999 and 2008 and, in this 9-year gap, a cultural change could occur.

The difference between subgroups was significant for both sleep timings (p<0.001) showing a higher effect when compared SSTs are more distant (Fig. 3b and 3c). While for Wake-up time, heterogeneity was significant overall and in all subgroups (Fig. 3c), for Bedtime the heterogeneity in the 'Morning vs. Evening' subgroup was not significant (Fig. 3b).

3.3.5 Assessment of publication bias

Funnel plots and Egger's test were conducted for dividing for subgroups each meta-analysis to assess risk of publication bias (Supp. Fig 2). Only the 'Morning vs. Afternoon' subgroup presents asymmetry in funnel plots for chronotype (p=0.038), SDw (p=0.010) and wake-up time (p=0.020) but not for SJL and bedtime. This result might imply a publication bias in this subgroup but this would be improbable as the large effect sizes of all studies indicate a real effect of afternoon SSTs on adolescents' sleep.

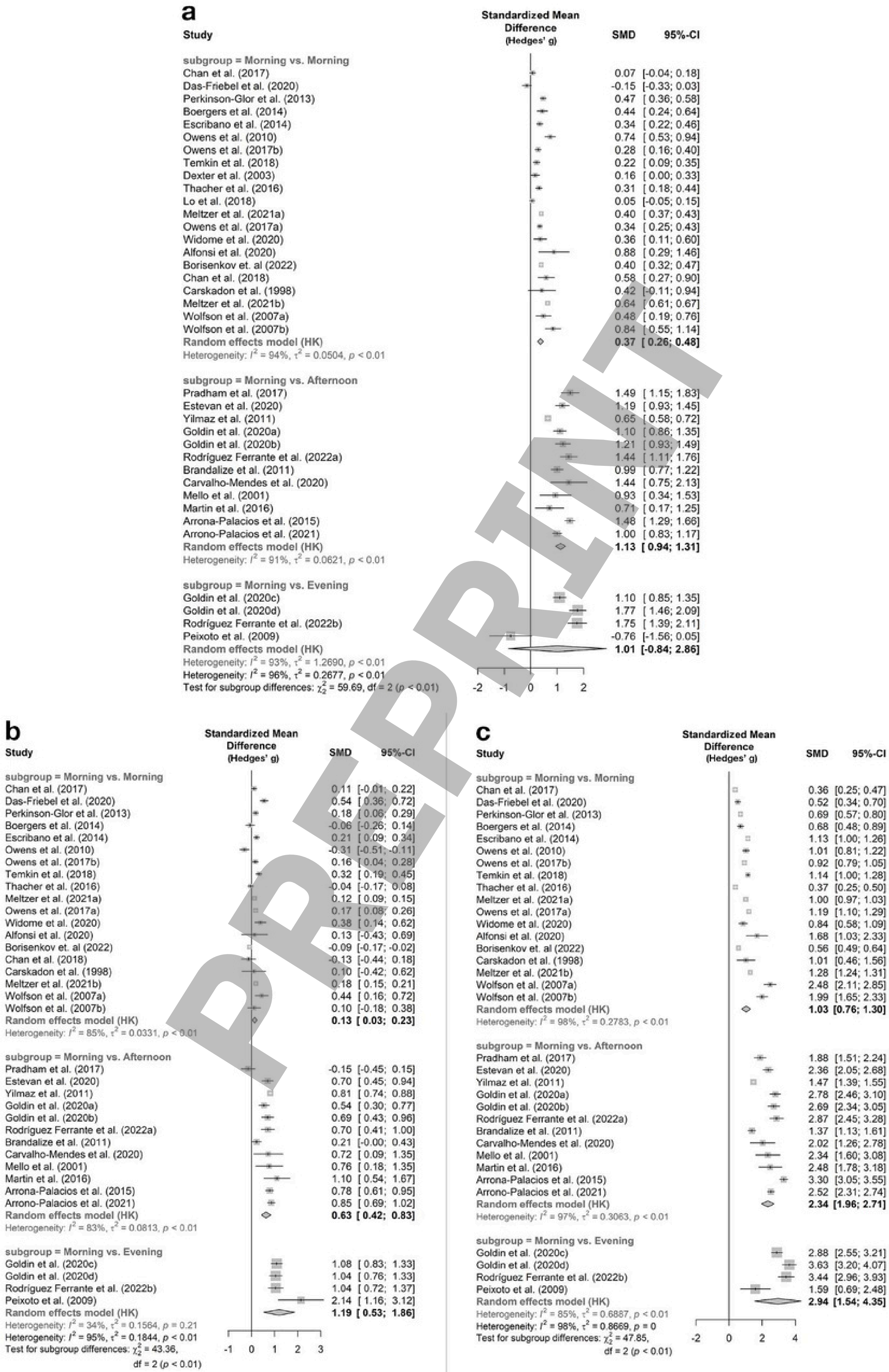
a
Study
Standardized Mean Difference (Hedges' g)
SMD
95%-CI
subgroup = Morning vs. Morning
Chan et al. (2017) 0.07 [-0.04; 0.18]
Das-Friebel et al. (2020) -0.15 [-0.33; 0.03]
Perkinson-Glor et al. (2013) 0.47 [0.36; 0.58]
Boergers et al. (2014) 0.44 [0.24; 0.64]
Escribano et al. (2014) 0.34 [0.22; 0.46]
Owens et al. (2010) 0.74 [0.53; 0.94]
Owens et al. (2017b) 0.28 [0.16; 0.40]
Temkin et al. (2018) 0.22 [0.09; 0.35]
Dexter et al. (2003) 0.16 [0.00; 0.33]
Thacher et al. (2016) 0.31 [0.18; 0.44]
Lo et al. (2018) 0.05 [-0.05; 0.15]
Meltzer et al. (2021a) 0.40 [0.37; 0.43]
Owens et al. (2017a) 0.34 [0.25; 0.43]
Widome et al. (2020) 0.36 [0.11; 0.60]
Alfonsi et al. (2020) 0.88 [0.29; 1.46]
Borisenkov et. al (2022) 0.40 [0.32; 0.47]
Chan et al. (2018) 0.58 [0.27; 0.90]
Carskadon et al. (1998) 0.42 [-0.11; 0.94]
Meltzer et al. (2021b) 0.64 [0.61; 0.67]
Wolfson et al. (2007a) 0.48 [0.19; 0.76]
Wolfson et al. (2007b) 0.84 [0.55; 1.14]
Random effects model (HK) 0.37 [0.26; 0.48]
Heterogeneity: I^2 = 94%, τ^2 = 0.0504, p < 0.01
subgroup = Morning vs. Afternoon
Pradham et al. (2017) 1.49 [1.15; 1.83]
Estevan et al. (2020) 1.19 [0.93; 1.45]
Yilmaz et al. (2011) 0.65 [0.58; 0.72]
Goldin et al. (2020a) 1.10 [0.86; 1.35]
Goldin et al. (2020b) 1.21 [0.93; 1.49]
Rodríguez Ferrante et al. (2022a) 1.44 [1.11; 1.76]
Brandalize et al. (2011) 0.99 [0.77; 1.22]
Carvalho-Mendes et al. (2020) 1.44 [0.75; 2.13]
Mello et al. (2001) 0.93 [0.34; 1.53]
Martin et al. (2016) 0.71 [0.17; 1.25]
Arrona-Palacios et al. (2015) 1.48 [1.29; 1.66]
Arrono-Palacios et al. (2021) 1.00 [0.83; 1.17]
Random effects model (HK) 1.13 [0.94; 1.31]
Heterogeneity: I^2 = 91%, τ^2 = 0.0621, p < 0.01
subgroup = Morning vs. Evening
Goldin et al. (2020c) 1.10 [0.85; 1.35]
Goldin et al. (2020d) 1.77 [1.46; 2.09]
Rodríguez Ferrante et al. (2022b) 1.75 [1.39; 2.11]
Peixoto et al. (2009) -0.76 [-1.56; 0.05]
Random effects model (HK) 1.01 [-0.84; 2.86]
Heterogeneity: I^2 = 93%, τ^2 = 1.2690, p < 0.01
Heterogeneity: I^2 = 96%, τ^2 = 0.2677, p < 0.01
Test for subgroup differences: χ^2_2 = 59.69, df = 2 (p < 0.01)
-2 -1 0 1 2
b
Study
Standardized Mean Difference (Hedges' g)
SMD
95%-CI
subgroup = Morning vs. Morning
Chan et al. (2017) 0.11 [-0.01; 0.22]
Das-Friebel et al. (2020) 0.54 [0.36; 0.72]
Perkinson-Glor et al. (2013) 0.18 [0.06; 0.29]
Boergers et al. (2014) -0.06 [-0.26; 0.14]
Escribano et al. (2014) 0.21 [0.09; 0.34]
Owens et al. (2010) -0.31 [-0.51; -0.11]
Owens et al. (2017b) 0.16 [0.04; 0.28]
Temkin et al. (2018) 0.32 [0.19; 0.45]
Thacher et al. (2016) -0.04 [-0.17; 0.08]
Meltzer et al. (2021a) 0.12 [0.09; 0.15]
Owens et al. (2017a) 0.17 [0.08; 0.26]
Widome et al. (2020) 0.38 [0.14; 0.62]
Alfonsi et al. (2020) 0.13 [-0.43; 0.69]
Borisenkov et. al (2022) -0.09 [-0.17; -0.02]
Chan et al. (2018) -0.13 [-0.44; 0.18]
Carskadon et al. (1998) 0.10 [-0.42; 0.62]
Meltzer et al. (2021b) 0.18 [0.15; 0.21]
Wolfson et al. (2007a) 0.44 [0.16; 0.72]
Wolfson et al. (2007b) 0.10 [-0.18; 0.38]
Random effects model (HK) 0.13 [0.03; 0.23]
Heterogeneity: I^2 = 85%, τ^2 = 0.0331, p < 0.01
subgroup = Morning vs. Afternoon
Pradham et al. (2017) -0.15 [-0.45; 0.15]
Estevan et al. (2020) 0.70 [0.45; 0.94]
Yilmaz et al. (2011) 0.81 [0.74; 0.88]
Goldin et al. (2020a) 0.54 [0.30; 0.77]
Goldin et al. (2020b) 0.69 [0.43; 0.96]
Rodríguez Ferrante et al. (2022a) 0.70 [0.41; 1.00]
Brandalize et al. (2011) 0.21 [-0.00; 0.43]
Carvalho-Mendes et al. (2020) 0.72 [0.09; 1.35]
Mello et al. (2001) 0.76 [0.18; 1.35]
Martin et al. (2016) 1.10 [0.54; 1.67]
Arrona-Palacios et al. (2015) 0.78 [0.61; 0.95]
Arrono-Palacios et al. (2021) 0.85 [0.69; 1.02]
Random effects model (HK) 0.63 [0.42; 0.83]
Heterogeneity: I^2 = 83%, τ^2 = 0.0813, p < 0.01
subgroup = Morning vs. Evening
Goldin et al. (2020c) 1.08 [0.83; 1.33]
Goldin et al. (2020d) 1.04 [0.76; 1.33]
Rodríguez Ferrante et al. (2022b) 1.04 [0.72; 1.37]
Peixoto et al. (2009) 2.14 [1.16; 3.12]
Random effects model (HK) 1.19 [0.53; 1.86]
Heterogeneity: I^2 = 34%, τ^2 = 0.1564, p = 0.21
Heterogeneity: I^2 = 95%, τ^2 = 0.1844, p < 0.01
Test for subgroup differences: χ^2_2 = 43.36, df = 2 (p < 0.01)
-1 0 1 2 3
c
Study
Standardized Mean Difference (Hedges' g)
SMD
95%-CI
subgroup = Morning vs. Morning
Chan et al. (2017) 0.36 [0.25; 0.47]
Das-Friebel et al. (2020) 0.52 [0.34; 0.70]
Perkinson-Glor et al. (2013) 0.69 [0.57; 0.80]
Boergers et al. (2014) 0.68 [0.48; 0.89]
Escribano et al. (2014) 1.13 [1.00; 1.26]
Owens et al. (2010) 1.01 [0.81; 1.22]
Owens et al. (2017b) 0.92 [0.79; 1.05]
Temkin et al. (2018) 1.14 [1.00; 1.28]
Thacher et al. (2016) 0.37 [0.25; 0.50]
Meltzer et al. (2021a) 1.00 [0.97; 1.03]
Owens et al. (2017a) 1.19 [1.10; 1.29]
Widome et al. (2020) 0.84 [0.58; 1.09]
Alfonsi et al. (2020) 1.68 [1.03; 2.33]
Borisenkov et. al (2022) 0.56 [0.49; 0.64]
Carskadon et al. (1998) 1.01 [0.46; 1.56]
Meltzer et al. (2021b) 1.28 [1.24; 1.31]
Wolfson et al. (2007a) 2.48 [2.11; 2.85]
Wolfson et al. (2007b) 1.99 [1.65; 2.33]
Random effects model (HK) 1.03 [0.76; 1.30]
Heterogeneity: I^2 = 98%, τ^2 = 0.2783, p < 0.01
subgroup = Morning vs. Afternoon
Pradham et al. (2017) 1.88 [1.51; 2.24]
Estevan et al. (2020) 2.36 [2.05; 2.68]
Yilmaz et al. (2011) 1.47 [1.39; 1.55]
Goldin et al. (2020a) 2.78 [2.46; 3.10]
Goldin et al. (2020b) 2.69 [2.34; 3.05]
Rodríguez Ferrante et al. (2022a) 2.87 [2.45; 3.28]
Brandalize et al. (2011) 1.37 [1.13; 1.61]
Carvalho-Mendes et al. (2020) 2.02 [1.26; 2.78]
Mello et al. (2001) 2.34 [1.60; 3.08]
Martin et al. (2016) 2.48 [1.78; 3.18]
Arrona-Palacios et al. (2015) 3.30 [3.05; 3.55]
Arrono-Palacios et al. (2021) 2.52 [2.31; 2.74]
Random effects model (HK) 2.34 [1.96; 2.71]
Heterogeneity: I^2 = 97%, τ^2 = 0.3063, p < 0.01
subgroup = Morning vs. Evening
Goldin et al. (2020c) 2.88 [2.55; 3.21]
Goldin et al. (2020d) 3.63 [3.20; 4.07]
Rodríguez Ferrante et al. (2022b) 3.44 [2.96; 3.93]
Peixoto et al. (2009) 1.59 [0.69; 2.48]
Random effects model (HK) 2.94 [1.54; 4.35]
Heterogeneity: I^2 = 85%, τ^2 = 0.6887, p < 0.01
Heterogeneity: I^2 = 98%, τ^2 = 0.8669, p = 0
Test for subgroup differences: χ^2_2 = 47.85, df = 2 (p < 0.01)
-2 0 2 4

Figure 3. a- Forest plot for sleep duration on weekdays (SDw). A positive SMD indicates that later SSTs are associated with longer SDws. b- Forest plot for bedtime. A positive SMD indicates that later SSTs are associated with later Bedtimes. c- Forest plot for wake-up time. A positive SMD indicates that later SSTs are associated with later Wake-up times. Subgroups were defined according to the moment of the day where the two compared school schedules start (e.g., if both school schedules start at morning, then the study is in the 'Morning vs. Morning' subgroup). Studies are ordered in ascending order according to ΔSST and alphabetically when ΔSST is the same.

3.4 Meta-regressions: the importance of social and solar clocks

Previous sections showed significant effects of later SSTs on sleep and chronotype, but most outcomes also present a significant heterogeneity (both overall and on each subgroup). Thus, there are probably some factors that are modulating the effect of SST on chronotype and sleep-related outcomes. The ΔSST is one of the main factors which might be involved in this modulation. Here we evaluated whether the effect size of the comparison of two SSTs on each outcome depends on ΔSST and/or on social or solar clocks. As we mentioned before, we expected a larger ΔSST to be associated with greater effect sizes. Importantly, we also predict that an earlier SSTearlier (i.e. the earlier of both SST compared) will be associated with greater effects, as an earlier SSTearlier would be more defiant for adolescents than a later SSTearlier and, consistently, greater changes in the outcomes will be obtained when an earlier SSTearlier is delayed. However, the earlier SST might be indexed only by its local time (i.e. SSTLTearlier) or its relation with the solar clock: a school starting at 07:30 might be very challenging when sunrise time is at 08:30 and less challenging if sunrise timing is at 06:30. Consistently, here we constructed two proxies of SST which consider the solar clock (SSTmcearlier and SSTearlier-Sunrise). These two predictors along with SSTLTearlier allowed us to test the relative relevance of solar or social clocks to predict the effect of different SSTs on chronotype and sleep-related outcomes.

Practically, we ran four meta-regressions for each outcome: the base model contains ΔSST, as the distance between the compared SSTs could explain the magnitude of the effect, and the other three models additionally contain either SSTLTearlier, SSTmcearlier or SSTearlier-Sunrise (Fig. 4). Finally, those four models were compared on each outcome and the more parsimonious model was selected using the Akaike criterion (i.e. the lower AIC value).

For these metaregression analyses we only included studies where two Morning SST were compared (i.e. 'Morning vs. Morning' subgroup) as we expect that the discrepancy between solar and social clocks would be less relevant on the SST effect when school starts in the afternoon or the evening. For these analyses, some studies were excluded because they did not inform SSTs [50] and/or they did not report when or where data was collected or the region and/or period of time are very extensive [4,20], which hinders the estimation of sunrise time and/or the estimation of the DMATZ.

3.4.1 Chronotype

The most parsimonious model was the base model (k=13; AIC=-15.921; weight =0.782). The association between ΔSST and the effect size of comparing two different SSTs on chronotype is positive and significant (coefficient = 0.163, p = 0.007), indicating that MSFsc delays more when ΔSST is greater (Fig. 4a). Residual heterogeneity was not significant (Qdf=11 = 11.130,

p=0.432, I2=28.42%), suggesting that the effect size differences between studies is explained by

ΔSST. Consistently, the time of the earlier school start, whether in relation to solar or social

clocks, is not a relevant predictor of the effect of SST on chronotype in the included sample of

studies. The forest plot of studies included in the MSFsc meta-regression is presented in Supp.

3.4.2 Social jetlag

The most parsimonious model was the base model (k=13; AIC=-4.235; weight =0.610). The association between ΔSST and the effect size of SST on SJL is negative and significant (coefficient = -0.290, p = 0.015), indicating that SJL decreases more when ΔSST is greater (Fig. 4b). However, in the SJL base model, residual heterogeneity was significant ($Q_{df=11} = 63.191$, $p<0.0001$, $I2=84.94\%$), indicating that there are still unknown factors explaining the difference of results between studies (e.g., meal time). The model with the lowest AIC did not include the timing of the earlier school start time (neither related with solar or social clocks) and, then, it suggests that this timing is not a relevant predictor of the effect of SST on SJL. A forest plot of studies included in the SJL meta-regression is presented in Supp. Fig. 4.

3.4.3 Sleep duration on weekdays

The most parsimonious model is the SSTmcearlier model (k=18; AIC=-0.817; weight =0.675). Both ΔSST (coefficient = 0.608, p < 0.0001) and SSTmcearlier (coefficient = 0.189, p = 0.003) exhibit positive and significant associations with the effect size of SST on SDw. As expected, a greater ΔSST is associated with a larger increase of SDw and an earlier SSTmcearlier. Neither SSTLTearlier nor SSTearlier-Sunrise were associated with the effect size of SST on SDw (Fig. 4c).

The residual heterogeneity of the SSTmcearlier model was significant ($Q_{df=16} = 79.724$, $p<0.0001$, $I2=84.34\%$), indicating that there are still unknown factors explaining the difference of results between studies. A forest plot of studies included in SDw the meta-regression is presented in Supp. Fig. 5.

3.4.4 Sleep timing (i.e. Bedtime and Wake-up time) on weekdays

The most parsimonious model explaining the effect size of SST on bedtime was the SSTmcearlier model (k=16; AIC=0.186; weight =0.772). SSTmcearlier, but not ΔSST, was significantly and negatively associated with the effect of SST on bedtime on weekdays (coefficient = -0.202, p = 0.0012 and coefficient = -0.051, p =0.695, respectively). As expected, an earlier SSTmcearlier is associated with a greater delay in Bedtime. The latter is particularly interesting considering that several papers have reported later bedtimes with later SSTs but, up to our knowledge, factors explaining the magnitude of this effect were not previously reported. Neither SSTLTearlier nor SSTearlier-Sunrise were significantly associated with the effect size of SST on bedtime (Fig. 4d). In SSTmcearlier model, residual heterogeneity was significant (Qdf=13 = 43.465, p<0.0001, I2=82.69%). A forest plot of studies included in Bedtime meta-regressions is presented in Supp. Fig. 6.

The most parsimonious model explaining the effect of SST on Wake-up time on weekdays is the SSTearlier-Sunrise model (k=15; AIC=13.903; weight =0.650). Both ΔSST (coefficient = 1.095, p < 0.0001) and SSTearlier-Sunrise (coefficient = -0.374, p = 0.0095) were significantly associated with the effect size of SST on Wake-up time on weekdays. The relation with ΔSST was positive and, with SSTearlier-Sunrise, negative: a greater ΔSST and a smaller SSTearlier-Sunrise are associated with greater delays on Wake-up Time. Please note that SSTearlier-Sunrise is close to or higher than 0 in all studies, which means that school started close to or after sunrise. Neither SSTLTearlier nor SSTmcearlier were associated with the effect size of SST on Wake-up time (Fig. 4e). In the SSTearlier-Sunrise model, residual heterogeneity was significant (Qdf=12 = 151.032, p<0.0001, I2=92.56%). A forest plot of studies included in Wake-up Time meta-regressions is presented in Supp. Fig. 7.

Summarizing, the effect sizes of SST on both Wake-up time and Bedtime are better explained by the solar clock than by the social clock. Interestingly, while SSTearlier-Sunrise is a better predictor of the effect on Wake-up time, SSTmcearlier is a better predictor of Bedtime. The higher impact of sunrise time on Wake-up time might be explained because Wake-up time is closer to sunrise than Bedtime.

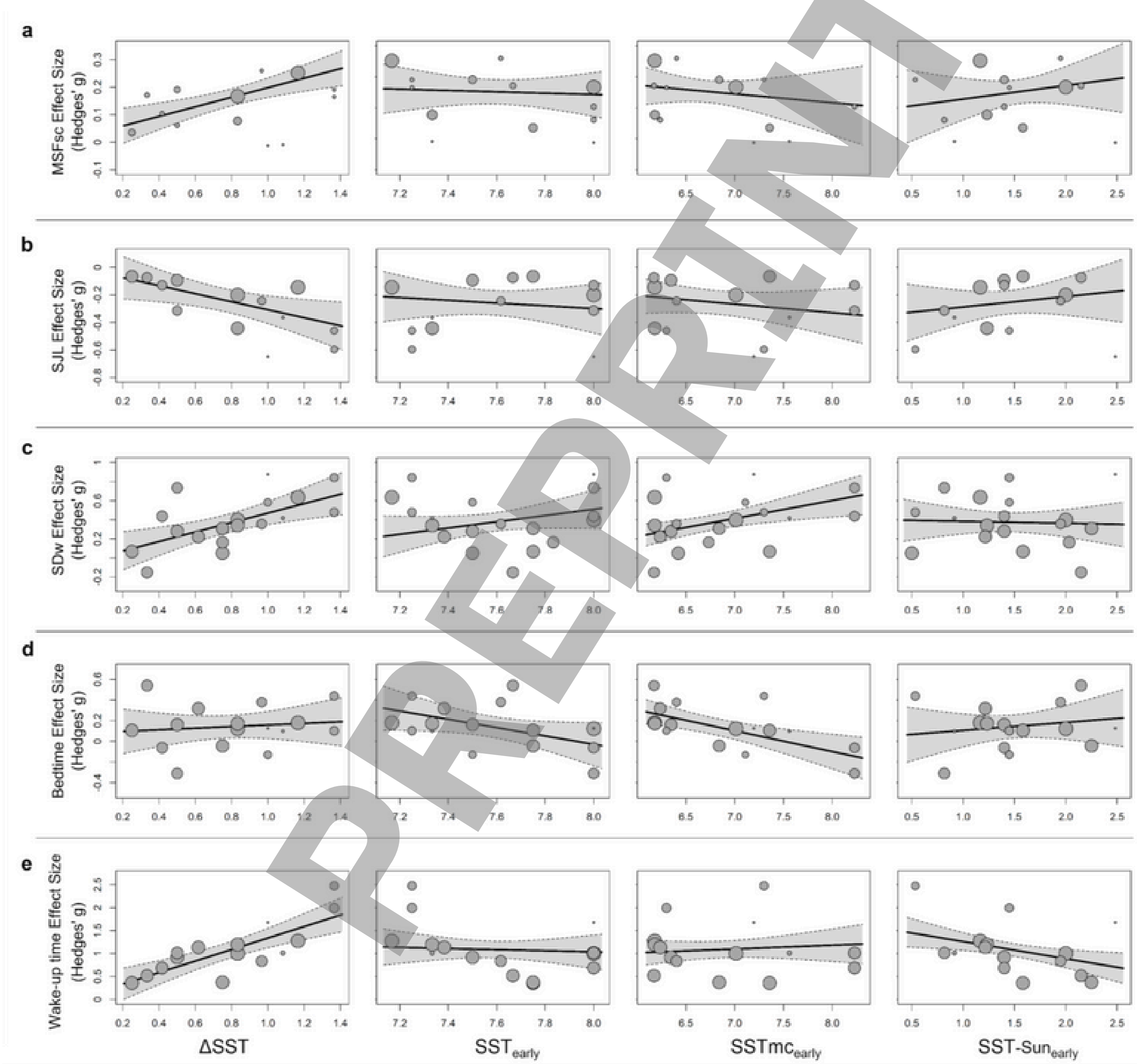

Figure 4. Meta-regression for chronotype and sleep-related outcomes. meta-regressions with (from left to right) ΔSST, $SST_{LT\ earlier}$, $SSTmc_{earlier}$ and $SST_{earlier}$-$_{Sunrise}$ as predictors of effect sizes of: a- Chronotype (MSFsc); b- Social

jetlag; c- Sleep duration on weekdays; d- Bedtime on weekdays; and e- Wake-up time on weekdays. Please note that the effect size range varies between outcomes, as reported in the previous section.

4. Discussion

Adolescents' late chronotypes colliding with early SSTs are considered to be the cause of unhealthy sleep habits such as chronic sleep deprivation and high levels of Social jetlag (SJL) [2,3]. Here we assessed the effect of SSTs on sleep and chronotype outcomes in two ways.

First, we evaluated whether a later SST is associated with the effect size on each outcome, comparing not only two morning SSTs but also Morning SSTs with Afternoon or Evening SSTs. The results showed that the effect sizes were significant on the three subgroups. Briefly, we found that later morning SSTs are associated with longer Sleep Duration on weekdays (SDw), lower levels of SJL, later Bedtimes and Wake-up times on weekdays, and later Chronotypes. Moreover, the effect size was greater for all outcomes when Morning SSTs are compared with later SSTs (afternoon or evening). Importantly, for most outcomes and subgroups, the heterogeneity of results was significant indicating that there could be unknown factors modulating the effect of different SSTs on sleep-related outcomes and chronotype.

Then, we zoom in and, using meta-regressions, we evaluate whether and how both the magnitude of the difference between the two compared morning SSTs and the social/solar clocks modulate the effect size of SST on each sleep and chronotype outcome. We proposed that the time of the earliest SST (SSTearlier) will be associated with the effect size of the SST on these outcomes, and that the solar clock (indexed by SSTmcearlier and SSTearlier-Sunrise) will be more relevant than the social one (SSTLTearlier). Our results showed that the effect sizes on MSFsc and SJL were significantly explained (either fully or partially) for the distance between compared SSTs (ΔSST) but not by SSTearlier. Importantly, SSTmcearlier partially explained the effect sizes on SDw and Bedtime, with earlier SSTmcearlier associated with larger effect sizes. Finally, a lower SSTearlier-Sunrise was associated with larger effect sizes on Wake-up time.

4.1 Effect of SST on sleep related outcomes and chronotype

The magnitude of the effect size of different SSTs on adolescents' sleep habits and chronotype varies according to the outcome under study and the difference between the two compared SSTs. When comparing two morning SSTs, the magnitude of the effect size was small for chronotype (i.e. MSFsc), SJL and Bedtimes; medium for SDw and large for Wake-up time. These differences in the magnitude of the effect were expected. First, bedtimes are not as directly affected by early social cues like SST, as wake-up time on weekdays, probably due to its temporal proximity but also because, due to their late chronotypes, adolescents' bedtimes might not change as much as their wake-up times [6,24]. Second, the effect of sleep duration is the result of both a small delay in bedtimes and a greater delay in wake-up times associated with later SSTs and, thus, the magnitude of the effect is lower than for wake-up time but greater than for bedtimes. Third, although SST acts as a social cue that modulates chronotype, the modulation is expected to be only partial (i.e. the early morning SSTs will not be fully aligned with the late chronotype of adolescents) and, the magnitude of the effect, smaller than weekdays outcomes because the effect is indirect for MSFsc. Finally, SJL depends on sleep timing on week- and free days and, even though sleep timings on weekdays are more affected, both of them are delayed with later SSTs and that is why it is reasonable to observe a small effect size for SJL. Interestingly, although not all studies comparing morning SSTs showed effect sizes significantly different from zero for these outcomes, for most of them the direction of the change is coincident with the direction of the observed overall effect.

Importantly, here we compared and found that the magnitude of the effect of a later SST is larger for all outcomes when comparing a morning and an afternoon SSTs than when comparing two morning SST, with medium effects for Chronotype and Bedtime on weekdays and large effects for SJL, SDw and Wake-up time on weekdays. In contrast to the results reported for morning-attending students, most previous studies showed that adolescents attending school in the afternoon [15,16,18,51] reach the recommended 8h of sleep per night [58] and their SJL levels are similar to those of the adult population or even nonexistent [1,12–14,44]. These results could indicate that afternoon school timings are better for adolescents than morning school timings which is particularly relevant because most countries do not have an afternoon school timing and when a delay of SSTs is proposed only morning SSTs are evaluated (and/or considered) [6,37,46,48].

Finally, there are just a few studies comparing morning and evening SSTs [10,14,17] and results are consistent for some outcomes but differ for others between studies. All previous studies reported later Bedtime and Wake-up times on weekdays, and lower levels of SJL on evening SSTs. However, while MSFsc delays and SDw increases in the studies that took place in Argentina [10,14], MSFsc does not change and SDw shortens in the study that took place in Brazil [17]. Argentinian adolescents present later chronotypes than adolescents from other countries and, in particular, in comparison with Brazilian youth [3], which could at least partially explain the difference in results. However, the causes of such a difference in chronotypes seems to be mostly cultural (e.g. late dinner times in Argentina) and reinforced by entertainment mechanisms: Brazilian adolescents wake-up earlier and, consistently, they expose themselves to sunlight earlier, which, in turn, advance their chronotype [3,29]. Taking into consideration the relevant role of culture in adolescents' sleep and that most studies assessing the effect of different SSTs took place in the US and in urban areas, it is important to increase the evidence in different countries and different environments (e.g. rural or low income populations).

4.2 Relative importance of social and solar clocks

Meta-regressions allow us to evaluate whether and how both ΔSST and the solar/social clocks are related with the effect size of SST on each outcome.

For both MSFsc and SJL, ΔSST significantly predicted the magnitude of the effect (i.e. SMD or Hedges' g) of a later SST but the time of earliest school start (SSTearlier) did not, neither when measured according to the social clock (SSTLTearlier) nor according to the solar clock (SSTmcearlier and SSTearlier-Sunrise). As meta-regressions weigh each study according to their variance [59], the lack of relevance of SSTearlier could be partially influenced by the fact that standard deviations of MSFsc and SJL were mostly estimated from other outcome's standard deviations and, therefore, they are probably overestimated due to the error propagation method [60]. However, it is also possible that the range of SSTearlier, measured according to social or solar clock, of the published studies is not wide enough to impact MSFsc and/or SJL because SSTearlier only indirectly affects the free days schedule. Importantly, the effect sizes of different SSTs on weekday sleep timings were modulated by SSTearlier measured according to the solar clock. On the one hand, a smaller SSTearlier-Sunrise was associated with larger delays on Wake-up times associated with a later SST: the impact of delaying SST is higher the closer the SST is to sunrise time. The latter is expected considering that sunlight is the main entrainment factor of human circadian rhythms (including the sleep-wake cycle) [25,26]. When school starts several hours after sunrise, it should be less difficult for adolescents to wake up on time to attend school and, consistently, a delay of SST may not have an important impact. However, if school starts before or close to sunrise time, and considering that adolescents present late chronotypes, it should be extremely defiant for them to wake up that early to attend school. In that case, a later SST would imply an opportunity to wake up later and extend sleep for most adolescents.

Other important results reported here are those related with the impact of ΔSST on sleep and chronotype outcomes. ΔSST was a significant predictor of Wake-up time: SSTs are very early for late chronotypes and, consistently, ΔSST represents the window opportunity to extend sleep, the wider the window the greater the effect. On the other hand, our results showed that the effect size on Bedtime on weekdays associated with a later SST is larger the earlier SSTmcearlier is. Considering that sunlight entrains human circadian rhythms [25,26], an early SSTmcearlier would probably imply that students have to wake-up earlier than what their own physiology indicates. Moreover, if SSTmcearlier is early, adolescents would be extremely sleep deprived and, thus, they would need to go to bed earlier than they prefer due to sleep pressure to reach the minimum amount of sleep hours they require. The results obtained here are consistent with this: if students were advancing their bedtime because of an early SSTmcearlier, a delay of SST would allow them to wake-up later, increasing the sleep window opportunity and allowing them to go to bed later without shortening their sleep duration. Interestingly, literature studying the effect of SSTs on bedtime have reported mixed results, some previous works reported delays in bedtimes, others reported no changes and some studies even reported advances in the bedtime associated with a later SST [6,7,9,37,48,49]. Up to our knowledge, this is the first report of a factor that predicts the effect of a later SST on adolescents' bedtime, that is, the discrepancy between solar and social clocks is relevant to explain the effect of different SSTs on weekdays bedtime. Finally, and as expected, considering that the change in SDw is a result of the change in sleep timings, the effect of SSTs on SDw is also modulated by both ΔSST and the solar clock (SSTmcearlier).

4.3 Strength and limitations

This systematic review and meta-analysis has several limitations. First, only a few studies present a random assignment of participants to different groups and all of them compare a morning SST with a later SSTs (morning, afternoon or evening). Second, most studies were carried out in the US which present different patterns of sleep than other regions [3,61] and, thus, the results are not necessarily generalizable to other countries. Third, some of the studied outcomes and their standard deviations were estimated from other outcomes, which could imply an overestimation of the variance. However, those estimations allowed us to include outcomes that would not be possible in other cases and, in any case, the magnitude of the reported effect size would be underestimated and not overestimated because of the estimations. Finally, in our analysis we do not differentiate between longitudinal (i.e. within subjects) and cross-sectional (i.e. between subjects) studies. Nevertheless, as within subject comparisons tend to throw bigger effect sizes [59], the real effect size will not be overestimated by including cross-sectional studies. Importantly, a previous meta-analysis found similar results for longitudinal and cross-sectional studies [34].

This work addresses a literature gap and it has several strengths. Up to our knowledge, this is the first meta-analysis including studies not only comparing two morning SSTs but also comparing a morning SST with an afternoon or evening SST, and including some sleep and chronotype outcomes which were not previously evaluated. Additionally, here we evaluated the impact of the magnitude of the difference between the compared SSTs and, importantly, we discussed the relative importance of social and solar clocks on the effect of a later SST on adolescents' sleep habits and chronotype, which is not usually taken into consideration.

4.4 Conclusions

This meta-analysis shows that later SSTs are associated with healthier sleep habits (i.e. longer SDw and lower SJL levels), later sleep timings on weekdays and later chronotypes. The magnitude of the effect depends on how different the SSTs compared are. In particular, effect sizes are higher when comparing a morning SST with an afternoon or evening SST than when comparing two morning SSTs, with afternoon attending students showing low levels of SJL and close to or higher than 8h sleep duration [10–12,18,19,51]. Thus, policy makers should consider not only later morning SST but also afternoon SST to improve adolescents' sleep health and well-being. The two proposed proxies of SST considering the solar time (SSTmcearlier and SSTearlier-Sunrise) are useful to explain the variability on some outcomes associated with later SSTs. Of course, future works will be responsible for judging them. Our results are promising: the solar clock appears to be an important predictor of the effect of a later SST on sleep timings and duration on weekdays, highlighting the importance of considering not only local time but also the solar time when reporting and assessing changes or comparisons between SSTs.

4.5 Practice points

1. Later SSTs are associated with later chronotypes, which reinforce that SST acts as a social cue that can modulate chronotype. However, the chronotype modulation is only partial [10,14]: later SSTs are also associated with lower SJL levels and longer sleep duration, which add evidence to the causal role of early SSTs on adolescents' unhealthy sleep habits.
2. It is important to report not only sleep duration and timings, but also chronotype and SJL. Most previous studies focused on sleep duration and sleep timings and only a few of them reported SJL and chronotype. When reporting chronotype, studies used different proxies hiding the comparison between studies.

3. Studies addressing the effect of different SST on adolescents' sleep habits should take into account not only the social clock (i.e. local time, SSTLT) but also the solar clock.
4. The magnitude of the effect of different SST on sleep-related outcomes and chronotype depends on the distance between the compared SST but, for sleep timing and duration on weekdays, it depends on the timing of the earlier SST measured according to the solar clock (SSTmcearlier or SSTearlier-Sunrise).
5. Each data collection point should be done in a short period of time to avoid the effect of photoperiod changes, which might affect the results. Dates and place of the different data collection points should be always reported.

4.6 Research agenda

1. Address the effect of season, geographic position, culture, socioeconomic status and level of urbanization on the effect of different SSTs. An interesting approach for that would be multi-site studies with more than one data collection point along the year. Studies on non- WEIRD populations could also be extremely enriching.
2. Future studies should consider the relevance of the solar clock when studying the effect of delaying SSTs.

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