

Impact case study (REF3)

Institution: University of Surrey		
Unit of Assessment: 10 Mathematical Sciences		
Title of case study: Influencing school start times, permanent daylight saving and shift workers: Mathematical models for sleep, light and the body clock		
Period when the underpinning research was undertaken: 2012 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Professor Anne Skeldon	Professor, Department of Mathematics	2000 – present
Professor Gerardina Derks	Professor and Head of Department of Mathematics	1995 – present
Period when the claimed impact occurred: 2014 – 2020		
Is this case study continued from a case study submitted in 2014? N		
1. Summary of the impact (indicative maximum 100 words)		
<p>Uniquely, our work has focused on the mathematical modelling of light, sleep, circadian rhythms and societal constraints to produce quantitative predictions of sleep timing across the human lifespan. Our resulting mathematical framework has: (i) informed policy on delaying school start times for adolescents in the USA and UK; (ii) influenced decisions on whether to move to permanent daylight saving time in the USA and Europe; (iii) resulted in changes to shift patterns for 2,600 engineers working for a major UK utility company; (iv) been used in educational tools aimed at the general public to explain the fundamental mechanisms underlying sleep and circadian rhythm and the role of light.</p>		
2. Underpinning research (indicative maximum 500 words)		
<p>In the natural world, the ~24-hour light-dark cycle is the primary regulator of our circadian rhythms. However, we have radically changed our exposure to the natural light-dark cycle by such means as using artificial lights after dusk and exposing ourselves to light from screens. This disruption of the natural light-dark cycle is known to result in reduced or mistimed sleep, with consequences to health, including an increased risk of diabetes, obesity, cardiovascular disease, and impaired vigilance and cognitive decline.</p> <p>The biological mechanisms underlying the health problems resulting from disruption to sleep are still poorly understood. Mathematical models are an important tool to further our understanding of these underlying phenomena and the regulation of the sleep-wake cycle.</p>		
Mathematical modelling and analysis		
<p>Work by Prof AC Skeldon, Prof G Derks (Mathematics, Surrey), and Prof D-J Dijk (Director, Surrey Sleep Research Centre) has critically demonstrated that the seminal two-process model that encoded the two principal biological mechanisms underlying sleep – homeostasis and circadian rhythmicity (Borbély, <i>Hum Neurobiol.</i> 1982;1:195-204; Daan, Beersma, Borbély <i>Am J Physiol Integr Comp Physiol.</i> 1984;246:R161-R183) and the well-known extended neuronal model (Phillips & Robinson, <i>J Biol Rhythms</i> 2007;22:167-79), can be explicitly related to each other and that the two-process model can be reduced to a one-dimensional map that may have discontinuities [R1]. Furthermore, the team have comprehensively analysed the bifurcations and</p>		

dynamics of such models [R2]. These analyses provide a critical bridge between sleep specialists and computational scientists, underpin our subsequent models and explain many published simulation results.

Working with Prof AJK Phillips (Harvard/Monash), the team developed a quantitative mathematical framework that incorporates the primary biological mechanisms, the primary external drivers (the light environment) and social constraints (e.g., getting up for work/school) and used this model to explain observed changes in sleep timing and duration across the lifespan [R3] and to systematically examine the role of the modern light environment [R4].

No other models currently exist that have as their focus the interaction of light and societal constraints on the timing of sleep and circadian rhythms.

Understanding the implication of social constraints on light consumption

The quantitative mathematical framework has relevance for understanding the effects of enforced social constraints, such as school start times, daylight saving, and shift-working on the sleep-wake cycle. This is of particular value because light exposure is a modifiable risk factor for ill-health.

1. Relevance to school start times: Sleep deprivation during the week and catching up at the weekend is particularly characteristic of adolescents and has led to calls in both the UK and USA for schools to start later. The team's work [R3, R4] highlights that unless we adequately manage our light environment, moving school start times will not reduce sleep deprivation. Instead, delaying school start times will result in a parallel delay to bedtimes and wake times, resulting in no/minimal reduction in sleep deprivation. Depending on the start time and individual characteristics, changing the light environment may be a more effective intervention.

2. Relevance to permanent daylight saving: There is international interest in abandoning the biannual clock change between standard time and daylight-saving time, with campaigners favouring a move to permanent daylight-saving time. Skeldon and Dijk [R5] demonstrated that under permanent daylight-saving, our endogenous biological clock, entrained by the light-dark cycle, would be out of sync with the numbers on the clock (i.e., noon would be solar noon +1 hour). This would exacerbate problems with waking in the morning in time for work/school, and instead, it is a move to permanent standard time that would reduce sleep-deprivation.

3. Relevance to shift work: Fatigue resulting from shift work is a health and safety concern for employers. Existing fatigue risk assessment tools are limited. Research conducted by Skeldon [R6] with Transport for London evaluated existing Fatigue Risk Tools, established their limitations and identified an urgent need for improved biomathematical models.

3. References to the research (indicative maximum of six references)

[R1] Skeldon, A.C., Dijk, D-J. & Derks, G. (2014) "Mathematical models for sleep-wake dynamics: comparison of the two-process model and a mutual inhibition neuronal model", *PLoS ONE*, **9**, e103877, DOI: [10.1371/journal.pone.0103877](https://doi.org/10.1371/journal.pone.0103877)

[R2] Bailey, M.P., Derks, G. & Skeldon, A.C. (2018) "Circle maps with Gaps: understanding the dynamics of the two-process model for sleep-wake regulation", *Eur. J. Appl Maths*, **29**, 845-868, DOI: [10.1017/S0956792518000190](https://doi.org/10.1017/S0956792518000190)

[R3] Skeldon, A.C., Derks, G. & Dijk, D-J. (2016) "Modelling changes in sleep timing and duration across the lifespan: Changes in circadian rhythmicity or sleep homeostasis?", *Sleep Med Rev*. **28**, 96-107, DOI: [10.1016/j.smrv.2015.05.011](https://doi.org/10.1016/j.smrv.2015.05.011)

[R4] Skeldon, A.C., Phillips, A.J.K & Dijk, D-J. (2017) "The effects of self-selected light-dark cycles and social constraints on human sleep and circadian timing: a modelling approach", *Sci. Rep.* **7**, 45158, DOI: [10.1038/srep45158](https://doi.org/10.1038/srep45158)

[R5] Skeldon, A.C. & Dijk, D-J. (2019) "School start times and daylight saving time confuse California lawmakers", *Curr. Biol.* **29**, R265-R279, DOI: [10.1016/j.cub.2019.03.014](https://doi.org/10.1016/j.cub.2019.03.014)

[R6] Cleator, S.F., Coutts, L.V., Philips, R., Turner, R., Dijk, D-J. and Skeldon, A. (2020). Fatigue, Alertness and Risk Prediction for Shift Workers. bioRxiv.
DOI: [10.1101/2021.01.13.426509](https://doi.org/10.1101/2021.01.13.426509) [Report initially prepared for Transport for London]

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4. Details of the impact (indicative maximum 750 words)

1. Informing national and international legislation on school start times

USA

School start times for middle- and high-school children can be as early as 7:00 am and have been linked to weaker academic performance, more car accidents, and increased absenteeism and exclusions. Our research [R4] informed the Californian State Bill (No. 328, Portantino) requiring California's middle and high schools to begin school no earlier than 8:30 am. The Bill's proposer, State Senator Anthony Portantino, told the New York Times that the Bill's benefits would include "better grades, reduced risk of depression and fewer vehicle accidents – that he said was borne out by research" [S1]. Supported by the American Academy of Pediatrics and the Centres for Disease Control, the State Bill was passed by Senate on August 31, 2018 and must be implemented in all California middle- and high-schools by July 1, 2021 [S2], directly impacting three-million school children. Our research also informed accompanying debates held in 2017 and was quoted in the Senate Bill Policy Committee's analysis conducted in 2019 for the amended Bill [S3].

UK

An online petition titled 'School should start at 10 am as teenagers are too tired' was started in November 2018 and rapidly exceeded the threshold to trigger a Parliamentary debate (179,000 signatures). This debate, 'Secondary School Opening Hours', took place on 11 February 2019. Our research [R4] and accompanying Press Release titled 'Mathematicians predict delaying school start times won't help sleep deprived teenagers' were included in the Debate Pack [S4] provided to MPs. Our conclusion that "[our] model suggests that an alternative remedy to moving school start times in the UK is exposure to bright light during the day, turning the lights down in the evening and off at night" was explicitly highlighted for MPs [S4, pp.6]. During the debate [see transcript, S5], Martyn Day (MP Linlithgow and East Falkirk, SNP) cited our conclusion by way of opposition, adding our further conclusion that "... body clocks would drift even later in response to later start times, and, in a matter of weeks, [adolescents] would find it just as hard to get out of bed." Nick Gibb (The Minister for School Standards) also cited our research as he spoke in opposition to the proposed delay to school start times, stating, "The mathematical model showed that delaying school start times in the UK would not help reduce sleep deprivation" and "The mathematical model shows that the problem for adolescents is that their light consumption behaviour interferes with their natural interaction with the environmental clock – getting up late in the morning results in adolescents keeping the lights on until later at night." However, Mr Gibb did acknowledge that our results "lend some support to delaying school start in the US," where start times are earlier than the typical UK start time. The final response from the Government was that "The Department [for School Standards] has no plans to require secondary schools to start later." A decision that aligns with our research findings.

2. Informing public debate on permanent daylight-saving time

Our paper [R5] has been cited frequently in international debates on daylight-saving, News Media: 20 news stories, including Fox, CNN, and shared 129 times via Social Media: including 33 Facebook pages; 96 Twitter Tweets. It has also been used by the Save Standard Time Campaign in California to support their position [S6]. Skeldon was invited to co-author the Op-Ed article 'How New York should lock the clock: don't switch to daylight saving time, ditch it and stick with standard time' published in the New York Daily News (daily circulation ~200,000), which warned that the

proposed permanent change to daylight saving would have a negative effect on the health of 19.5 million New Yorkers [S7]. In a May 2019 CNN interview, Assemblyman Kansen Chu – who proposed the California permanent daylight saving bill (AB7) – was countered by the interviewer, who asked Chu to comment on the findings of Skeldon and Dijk's research [R5]. Later in September 2019, the San Francisco Chronicle reported that Chu “*is now considering a proposal for year-round standard time instead.*” [S8]

3. Impact on shift working patterns

On-call shifts are common in the utilities and transport industries. These shifts involve engineers working a standard (9am-5 pm) day, then subsequently working out-of-hours call-outs in response to urgent or unpredictable situations (i.e., gas leaks). An on-call worker may receive no call-outs or several, taking varying times to resolve. This unpredictability makes it challenging to model potential sleep deprivation and effectively manage employee working schedules, resulting in a health and safety risk. Existing Health and Safety Executive (HSE) Risk Tools are based on fixed shift working patterns.

Since 2019, Skeldon has worked with Scotia Gas Network (SGN) who provide gas to 5.9 million homes/businesses in the South of England and across Scotland. Skeldon used 3 years of timesheet data for their approximately 2,600 engineers to develop bespoke methods to analyse and model fatigue in call-out shift workers. SGN changed their shift patterns for engineers in November 2019 in response to her work and incorporated Skeldon's methods into their Business Intelligence tool allowing line managers and supervisors to more accurately monitor their staff working patterns and check safety-critical issues, such as back-to-back shift working. As a result of these changes, SGN saw a 74% reduction in people working over 16 hours. Initially, for engineers and maintenance operatives only, changes in working patterns were expanded to include support and management staff. Skeldon's work was crucial in SGN's negotiations with the HSE regulator, and ultimately their continued licencing (a further 5-year licence was awarded to SGN by the HSE on 6/12/2020) [S9].

Skeldon's collaboration with SGN has generated industry-wide interest. Consequently, an industry-wide working group including representatives of all UK gas networks and the HSE was established in 2019 to share data, knowledge and understanding across the sector, resulting in a sector-wide understanding of the extent of fatigue from on-call working as a health and safety issue [S9].

4. Raising public awareness

Skeldon regularly engages and involves the public in her research by working with e.g., healthcare professionals and medics who treat sleep and circadian rhythm disorders, politicians and political advisors, and teachers and educators. She regularly presents her findings at major meetings e.g., World Sleep 2017 (~2,600 participants); Society for Research in Biological Rhythms Meeting 2018 (~800 participants); and the UK Clock Club 2017 (~100 participants). A Parliamentary Office of Science and Technology's briefing note (POSTnote) for MPs and advisors on Sleep and Health [S10] cited conclusions on school start times and adolescent sleep from [R4]. Skeldon proactively raises awareness of the impact of delayed school start times on adolescents and the move to daylight saving. For example, she has been interviewed for or had work featured in *The Times* (daily circulation ~368,929) and *The Daily Mail* (daily circulation ~1,169,241), the *TES* (aimed at teachers and educators), *Teen Ink* (a by Teens, for Teens blog with 460,000 registered users), and *Cosmopolitan* magazine [S10]. Furthermore, Skeldon and Dijk used their interactive sleep-wake model at the Natural History Museum's Universities' Week (2014), and at a Teachers and Advisers Conference (Surrey, 2014). The mathematical model that sits at the heart of the interactive model is an early version of a published one [R4]. It has been downloaded by 955 users (10/09/2020).

5. Sources to corroborate the impact (indicative maximum of 10 references)

[S1] McPhate, Mike (Aug. 2, 2017). California Today: Should the School Day Start Later? *The New York Times*. (pdf)

- [S2] Senate Bill – 328. Pupil attendance: school start time. SB 328 (Portantino). (pdf)
- [S3] Assembly Committee on Education (May 8, 2019). SB 328 (Portantino). Senate Bill Policy Committee Analysis. (pdf)
- [S4] Long, Robert., O'Donnell, Michael. & Bellis, Alexander (7 February 2019). *E-petition 229178 relating to secondary school opening hours* (Debate Pack – Number CDP-0023). House of Commons Library. (pdf)
- [S5] Transcript of Parliamentary debate on Secondary School Opening Hours (Monday 11 February 2019). Available from <https://hansard.parliament.uk/commons/2019-02-11/debates/E0FFB632-2FCA-4341-A9E1-CA6CFAE6BCEF/SecondarySchoolOpeningHours>
- [S6] Campaign website for Save Standard Time <https://savestandardtime.com/concerns/>
- [S7] Malone, Susan Kohl., Patterson, Freda. & Skeldon, Anne (March 04, 2020). How New York should lock the clock: Don't switch to daylight savings time, ditch it and stick with standard time. *New York Daily News* (pdf)
- [S8] Koseff, Alexi (September 10, 2019). Clock stops for bid to put California on year round daylight-saving time. *San Francisco Chronicle*. Available from <https://www.sfchronicle.com/politics/article/California-lawmaker-drops-bid-to-switch-to-14429003.php>
- [S9] Testimonial letter from Chris Trodds, Head of Health and Safety, Scotia Gas Network (pdf)
- [S10]
- a. The Parliamentary Office of Science and Technology (19 September 2018). Sleep and Health (Research Briefing) (pdf)
 - b. The Times (28 March 2017). 'Bright idea to get teenagers out of bed: turn down the lights at night'. The Times <https://www.thetimes.co.uk/article/bright-idea-to-get-teenagers-out-of-bed-turn-down-the-lights-at-night-395c9vhwm>
 - c. Victoria Allen (28 March 2017). 'Why teenagers have no excuse for staying in bed: Youngsters would wake more easily if they spent time outside and stopped using screens at night.' The Daily Mail <https://www.dailymail.co.uk/sciencetech/article-4355086/Why-teenagers-no-excuse-staying-bed.html?printingPage=true>
 - d. Catriona Harvey-Jenner (27 March 2019). 'Not to alarm anyone, but daylight saving time might be scrapped in two years.' *Cosmopolitan Magazine* <https://www.cosmopolitan.com/uk/reports/a26957777/daylight-saving-time-scrapped-eu-mps-vote/>
 - e. Rinsophi (September 29, 2018). 'Wake Up, Let's Go to School'. Teen Ink https://www.teenink.com/opinion/school_college/article/1008458/Wake-Up-Lets-Go-To-School
 - f. Tes Reporter (28 March 2017). 'Later school start time 'not the solution' for tired teens.' TES online <https://www.tes.com/news/later-school-start-time-not-solution-tired-teens>