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RESEARCH ARTICLE

# Pilot feasibility testing of biomathematical model recommendations for personalising sleep timing in shift workers

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## Summary

Sleep disturbances and circadian disruption play a central role in adverse health, safety, and performance outcomes in shift workers. While biomathematical models of sleep and alertness can be used to personalise interventions for shift workers, their practical implementation is undertested. This study tested the feasibility of implementing two biomathematical models—the Phillips–Robinson Model and the Model for Arousal Dynamics—in 28 shift-working nurses, 14 in each group. The study examined the overlap and adherence between model recommendations and sleep behaviours, and changes in sleep following the implementation of recommendations. For both groups combined, the mean (SD) percentage overlap between when a model recommended an individual to sleep and when sleep was obtained was 73.62% (10.24%). Adherence between model recommendations and sleep onset and offset times was significantly higher with the Model of Arousal Dynamics compared to the Phillips–Robinson Model. For the Phillips–Robinson model, 27% of sleep onset and 35% of sleep offset times were within ± 30 min of model recommendations. For the Model of Arousal Dynamics, 49% of sleep onset, and 35% of sleep offset times were within ± 30 min of model recommendations. Compared to pre-study, significant improvements were observed post-study for sleep disturbance (Phillips–Robinson Model), and insomnia severity and sleep-related impairments (Model of Arousal Dynamics). Participants reported that using a digital, automated format for the delivery of sleep recommendations would enable greater uptake. These findings provide a positive proof-of-concept for using biomathematical models to recommend sleep in operational contexts.

KEYWORDS
alertness, circadian rhythms, healthcare, shift-work disorder, sleep disorder

## 1 | INTRODUCTION

Approximately 15%–20% of the global workforce is engaged in shift work, which results in sleep loss and circadian disruption, with adverse effects on physical and mental health, safety, and performance (Ganesan et al., 2019; Rajaratnam et al., 2013; Sletten et al., 2020; Tucker et al., 2021). Up to two-thirds of shift workers experience insomnia (Brito et al., 2021), a rate that is more than double the estimates for the general population. Compared to day workers, shift workers have an increased risk of fatigue, sleepiness-related motor vehicle crashes, and workplace errors (Brito et al., 2021; Shen et al., 2006). Existing approaches for managing shift work are largely aimed at making behavioural changes, such as improving sleep hygiene, reducing insomnia, creating an environment conducive to good quality sleep, and using caffeine or light exposure as sleepiness countermeasures, with the latter also used to promote circadian adaptation (Crowther et al., 2021; Shriane et al., 2020; Sletten et al., 2021; Vetter et al., 2015). While helpful, these interventions typically use a 'one-size fits all' approach, which may not address the considerable variability in shift schedules and inter-individual variability found in physiological response to shift work (Booker et al., 2018; Saksvik et al., 2011; Stone et al., 2019). Further research is necessary to examine the feasibility of implementing tailored sleep interventions for shift work.

Biomathematical models have been developed to account for sleep and circadian rhythm regulation across multiple physiological levels (Abel et al., 2020; Van Dongen, 2004). These models incorporate dynamic homeostatic and physiological processes that predict alertness based on physiology and sleep–wake constraints. A variety of these models have been designed to predict sleep based on work–rest schedules of shift workers (Ingre et al., 2014; McCauley et al., 2009; Riedy, Fekedulegn, et al., 2020; Riedy, Roach, & Dawson, 2020). Biomathematical models are used as an adjunct in safety management across industries, providing a global risk assessment for when an average employee will be most sleepy or to predict performance (Dawson et al., 2017; Ramakrishnan et al., 2015). Biomathematical models have been tested for the accuracy of their predictions of sleep and alertness in shift work, as well as prediction of circadian phase (Åkerstedt et al., 2007; Dawson et al., 2017; Flynn-Evans et al., 2020; Ingre et al., 2014; Knock et al., 2021; Riedy, Fekedulegn, et al., 2020).

These models serve as a theoretical foundation for deploying shift work interventions, such as implementing optimal shift schedules or using recommendations for sleep or light exposure to minimise alertness impairment on shifts. Using environmental constraints such as shift information, and lifestyle factors such as personal commitments, these models can generate individualised sleep schedules to optimise sleep and alertness in shift workers (Knock et al., 2021; Postnova et al., 2013). However, whether recommendations from these models can be followed and if this can yield a positive impact on the user is unexamined. Documenting whether sleep recommendations generated by these models can be practically implemented in real-world contexts, can help identify their utility and potential for supporting sleep interventions in shift workers.

To address these gaps, this implementation study provided shift-working nurses with model recommendations for sleep timing for one week using one of two established biomathematical models of sleep–wake: (i) the Phillips–Robinson Model (Phillips et al., 2017; Phillips & Robinson, 2007); and (ii) the Model of Arousal Dynamics (Abeysuriya et al., 2018; Postnova et al., 2016; Postnova et al., 2018). Sleep recommendations were optimised for alertness during shifts. The study evaluated the following: (i) the overlap between model recommendations and sleep behaviour (sleep and state percentage overlap); (ii) adherence between model recommendations and sleep onset and offset times; and (iii) changes in sleep duration, insomnia symptoms and sleep-related impairments after following the recommendations. Participants' feedback for improving the practicality and implementation of these recommendations are also reported.

## 2 | METHODS

### 2.1 | Participants

Expressions of interest were solicited through online advertisements on social media and advertisements shared via the national professional association, the Australian Nursing and Midwifery Federation. Participants were included if they met the following criteria: (i) nurse undertaking shift work, defined as work outside of 7:00 a.m. to 6:00 p.m.; (ii) aged ≥ 21 years; and (iii) no diagnosed sleep disorder other than insomnia. Participants were excluded if they: (i) undertook transmeridian travel in the past month; (ii) consumed > 400 mg caffeine/day; or (iii) consumed >14 alcoholic drinks/week. Eligible participants were contacted via telephone or email to discuss study procedures and determine shift schedules and personal commitments for the upcoming 3 weeks. Personal commitments were defined as social or individual events that the participant usually undertakes, such as meeting with friends, or going to a gym at specific times of the week. Participants provided informed consent prior to participation. The study protocol was approved by the Monash University Human Research Ethics Committee (#29474) and carried out in accordance with the standards set by the latest revision of the Declaration of Helsinki.

### 2.2 | Study procedure

The study was conducted across two weeks. Week 1 included monitoring of habitual sleep, where participants were instructed to follow their usual sleep patterns. In Week 2, participants were sent their sleep recommendations via email and instructed to follow these recommendations during the week. Participants were requested to contact the research team to receive updated recommendations if their shift schedule(s) changed. Across both weeks, sleep was monitored using an online sleep diary. The sleep diary used in this study was adapted from the standard Consensus Sleep Diary, using questions from the section that are to be completed upon awakening

(Questions 1–6 and 9; Carney et al., 2012). Participants were encouraged to use a free-text response section in the sleep diary to record any general comments from the last 24 h or provide any specific comments regarding the practicality or implementation of their recommendations. A text reminder was sent to participants daily to complete their sleep diary.

Before and after the study, the participants completed a questionnaire through Qualtrics (Qualtrics, Provo, UT, USA) including demographic information and the following instruments: (i) Insomnia Severity Index (ISI; Bastien et al., 2001), a clinically validated, brief screening measure of insomnia; (ii) Patient-Reported Outcomes Measurement Information System-Sleep Disturbance (PROMIS-SD) scale; (iii) PROMIS-Sleep-Related Impairment Scale (PROMIS-SRI, short form) that measures daytime impairment due to sleep disturbances (Yu et al., 2011); and (iv) reduced Morningness–Eveningness Questionnaire (rMEQ; Danielsson et al., 2019) to measure diurnal preference and timing for undertaking daily activities. In the post-study survey, participants provided further feedback and suggestions for improving the practicality and implementation of the recommendations.

## 2.3 | Biomathematical models

Participants were assigned to receive recommendations from one of the models after rosters were reviewed at the start of their study. Prior to the study start, rosters for each participant were reviewed to match the number of shifts and shift rotations across both models. Most participants were perfectly matched across each model, but because of changes in shift scheduling due to the COVID-19 pandemic, participants' shifts changed or were swapped during the study. Hence, five pairs across both models were perfect matches for the number of shifts and shift rotations, the remaining eight pairs were aligned for the type of shift rotation but had differences in the number of shifts and off-days between shifts during the recommendation week.

Sleep recommendations were provided from one of two models:

i. Phillips–Robinson Model (Phillips et al., 2010; Phillips & Robinson, 2007) is an ascending arousal system model that includes the effects of circadian and homeostatic drives and predicts hysteresis in the sleep–wake cycle with a region of bistability where sleep and wake states coexist; and
ii. Model of Arousal Dynamics is originally based on the Phillips–Robinson Model but incorporates a revised circadian input to the sleep–wake switch to produce the sleep propensity profile, as well as dynamics of melatonin and objective and subjective performance (Postnova et al., 2016).

The Phillips–Robinson Model with default parameter values (Phillips et al., 2010) generated sleep recommendations that were considered too short for non-daytime shifts, so parameter D0 was adjusted from its original value of $-10.2$ mV to $-7.8$ mV to enable longer sleep recommendations. All other parameters were kept at default values. With this modification, the Phillips–Robinson Model predicted typical sleep between 9:10 p.m. and 7:44 a.m., and sleep duration of 10.6 h. The Model of Arousal Dynamics was used with the default parameters as previously published (Abeysuriya et al., 2018;

**TABLE 1** Participant characteristics ($N = 28$).

| Characteristic | Overall sample ($N = 28$) | Phillips–Robinson Model ($n = 14$) | Model of Arousal Dynamics ($n = 14$) |
|---|---|---|---|
| Age, years, mean (SD; range) | 37.21 (9.61; 23–57) | 35.02 (9.15; 25–53) | 38.23 (10.45; 23–57) |
| Gender, female/male, *n* | 25/3 M | 12/2 | 13/1 |
| Marital status, *n* | 16 | 7 | 9 |
| Married | 9 | 6 | 3 |
| Single | 3 | 1 | 2 |
| Separated | | | |
| Years of experience in shift work, mean (SD) | 6.22 (3.71) | 5.80 (3.46) | 6.61 (4.03) |
| Reduced Morningness–Eveningness Questionnaire score, mean (SD) | 14.04 (3.64) | 14.33 (3.82) | 15.00 (3.43) |

**TABLE 2** Overlap between participants sleep windows and recommendations from biomathematical models.

| Overlap, mean (SD; range) | Overall sample ($N = 28$) | Phillips–Robinson Model ($n = 14$) | Model of Arousal Dynamics ($n = 14$) | *p* |
|---|---|---|---|---|
| Sleep percentage overlap | 73.62 (10.24; 53–93) | 69.01 (9.91; 53–89) | 79.16 (8.14; 68–93) | <0.020 |
| Wake percentage overlap | 91.76 (4.22; 84–97) | 90.93 (5.27; 84–97) | 92.52 (2.91; 88–97) | 0.442 |
| State percentage overlap | 87.37 (5.43; 76–97 | 85.24 (5.50; 76–94) | 90.33 (3.93; 84–97) | 0.032 |

*Note*: *p* values based on Mann–Whitney *U* tests examining the differences between the Phillips–Robinson Model and the Model of Arousal Dynamics for: (i) Sleep percentage, and (ii) State percentage overlap.

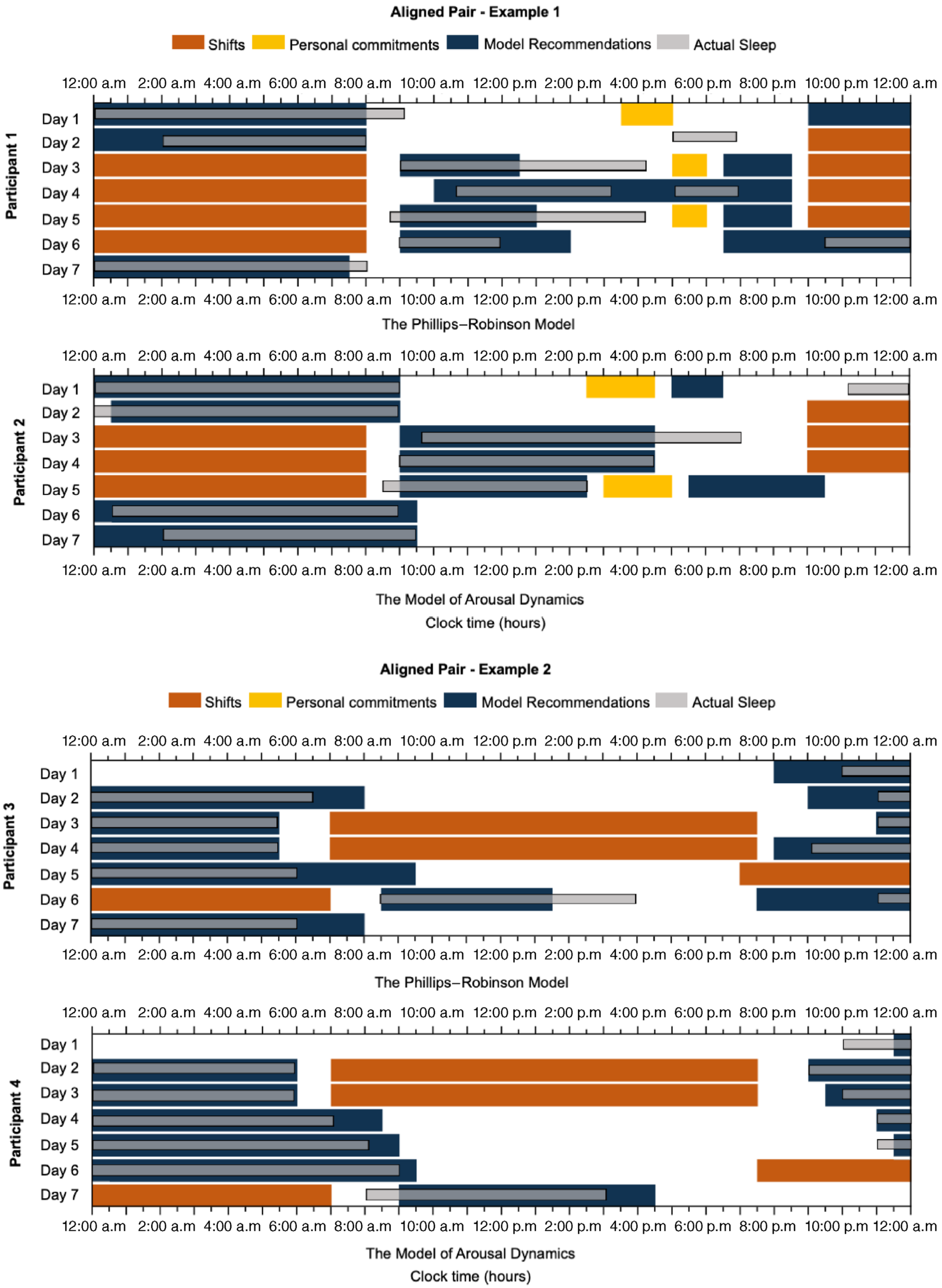

**FIGURE 1** Example raster plots showing recommendations (dark blue) and actual sleep (grey) of participants assigned to the Phillips–Robinson Model and the Model of Arousal Dynamics. Shift rotations for participants in both examples were aligned, illustrated in orange, and personal commitments are in yellow.

Postnova et al., 2016; Postnova et al., 2018). Without any constraints, the model predicts normal sleep–wake cycles with sleep between 11:30 p.m. and 8:00 a.m., and total sleep time of 8.5 h. Ambient light in both models was set to 250 lux between 8:00 a.m. and 8:00 p.m., 40 lux between 8:00 p.m. and 8:00 a.m., and 0 lux during sleep.

For both models, the optimisation algorithm was set to use *average alertness* on shift as a goal function. Within this optimisation, a large set of possible sleep–wake schedules are defined and constrained by physiology. For all possible solutions (i.e., sleep–wake schedules), the model's response was evaluated to calculate the value of the goal function. The solution with maximum alertness on shift was selected as a recommendation for a given participant. For both models, predicted alertness on shift was measured as visual lapses on the 10-min Psychomotor Vigilance Task. The models did not have fixed targets for sleep–wake schedule samples or the number of naps.

Both models were accessed using a web-interface at www.alertnessapi.com, which allows the evaluation of model dynamics on different shift schedules and the generation of recommendations for sleep, lighting, and shift times (only sleep recommendations were used in this study). Shifts, commute times and personal commitments were entered as constraints (inputs) to the models representing times a person is forced to be awake. Preparation and commute times were set at 1.5 h before and after any shift (i.e., 3 h in total) and 0.5 h for any personal commitments (i.e., 1 h in total) for all participants.

## 2.4 | Data analysis

Data were analysed using R version 4.1.2. Summary data are presented as means and standard deviations (SDs), where appropriate. Based on Knock et al. (2021), the overlap between participants' self-reported sleep and model recommendations was examined as: (i) sleep percentage overlap (sensitivity), which considers anytime both the model and participant report sleep and converts it into a percentage with maximum total sleep time (e.g., if the model recommended sleep from 12:00 a.m. to 8:00 a.m. and a participant slept from 11:00 p.m. to 6:00 a.m., the sleep percentage overlap would be 75%); (ii) wake percentage overlap (specificity), which considers anytime both the model and participant report wake and converts it into a percentage; and (iii) state percentage overlap (accuracy), which considers any time both model and participant report the same state of either being asleep or awake. Mann–Whitney *U* tests were used to compare differences between both models for percentage overlap.

Sleep and state percentage overlap can potentially produce biased results (Knock et al., 2021). For this reason, we also examined adherence between model recommendations and sleep onset and offset times was also calculated by subtracting participants' sleep onset and offset times from their model recommended sleep timings. This was done to examine proportion of bedtimes and waketimes that were within 30, 60, 90, 120, >120 min of their recommendations. Linear mixed models were used to compare adherence between both models, with fixed effects: (i) model type (i.e. Phillips–Robinson Model, Model of Arousal Dynamics); and (ii) shift type (i.e. morning, afternoon, night shift), with each participant added to the model as a random effect intraclass correlation coefficients (ICCs) were calculated to examine between and within-person variability in adherence with model recommendations. Sleep onset and offset times were also categorised in 30-min bins in relation to model recommendations when participants recorded their habitual sleep patterns in Week 1 (Habitual Week) and when they were exposed to recommendations in Week 2 (Recommendation Week) to visualise adherence with recommendations. Differences in sleep duration, insomnia, sleep-related impairments, and sleep disturbance pre- and post-study were assessed using paired-sample *t* tests. Free-text responses by participants in sleep diaries and the survey at the end of the study were analysed for any content regarding implementation or practicality of recommendations using Microsoft Excel.

## 3 | RESULTS

Overall, 153 eligible nurses were provided with information about the study. Sample size was capped at 30, with 12–15 participants per model based on the criteria set by Browne (1995) and Julious and Owen (2006) for pilot studies. A total of 28 participants from

**TABLE 3** Alignment between model recommendations and sleep onset and offset times (min) for sleep in the 24-h prior to shifts. Lower number of minutes indicates better alignment with model recommendations.

| | Alignment with the Phillips–Robinson Model, mean (SD) | | Alignment with the Model of Arousal Dynamics, mean (SD) | | | |
|---|---|---|---|---|---|---|
| Variable | Sleep onset times, min | Sleep offset times, min | Sleep onset times, min | Sleep offset times, min | *p* (sleep onset) | *p* (sleep offset) |
| All shifts combined | 106.77 (95.06) | 88.71 (76.94) | 61.98 (45.88) | 71.99 (60.09) | 0.012 | 0.042 |
| Morning shift | 141.00 (99.89) | 66.12 (80.77) | 38.46 (23.39) | 45.31 (33.83) | 0.001 | 0.861 |
| Afternoon shift | 56.03 (59.91) | 71.33 (44.63) | 21.71 (20.70) | 104.94 (78.69) | 0.113 | 0.010 |
| Night shift | 51.67 (32.67) | 196.00 (60.59) | 52.47 (30.65) | 107.93 (81.51) | 0.336 | 0.040 |

*Note*: Total number of observations for all shifts = 98. The *p* values are based on linear mixed models that examined differences in alignment between both models. Referent categories: (i) Model: The Phillip Robinson Model, (ii) Shift: Morning Shift.

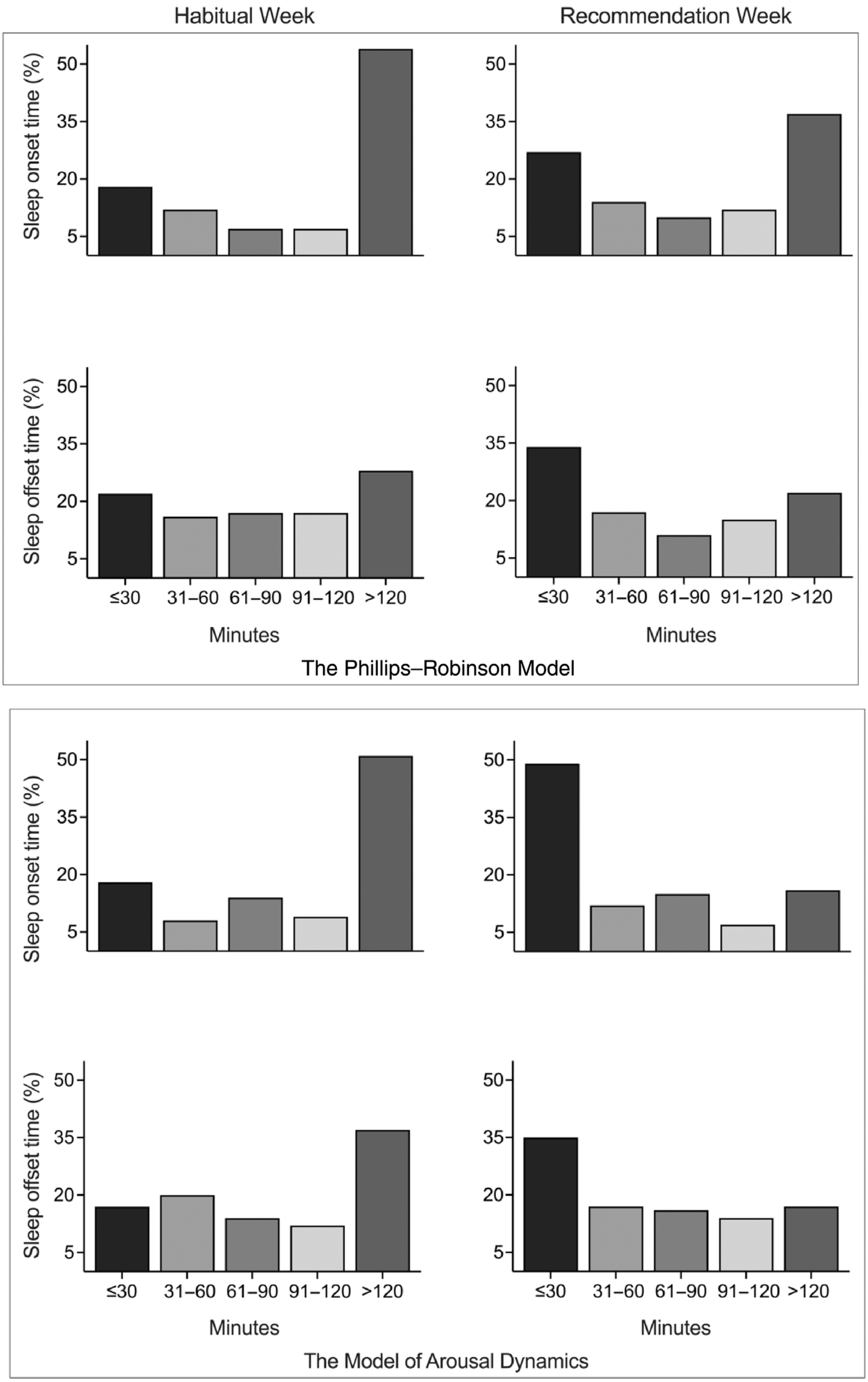

**FIGURE 2** The proportion of sleep onset and offset times between ≤30, 31–60, 61–90, 91–120, >120 min of model recommendations during the Habitual Week and Recommendation Week for both models.

multiple healthcare sectors, such as emergency care, critical care, aged care, and paediatrics were recruited (mean [SD] age 37.2 [9.7] years). Where possible, an attempt was made to have comparable shift types and rotations across each model. There were no significant differences in demographics, sleep duration, ISI, PROMIS-SRI, and PROMIS-SD scores between participants allocated to each biomathematical model group.

All participants had a minimum of three shifts during both weeks of the monitoring period (range three to five shifts). In all, 20 participants had different shift schedules during the Habitual and

Recommendation Week, but similar start and end times for each shift type. Participant characteristics are presented in Table 1.

### 3.1 | Sleep and state percentage overlap

During exposure to recommendations, the mean (SD) sleep percentage overlap was 73.62% (1.93%) and the state overlap was 87.37% (5.43%) for the overall sample. The sleep and state percentage overlaps were significantly larger with the Model of Arousal Dynamics compared to the Phillips–Robinson Model (Table 2). Example raster plots showing shift types, personal commitments and overlap between recommendations and sleep for four participants matched across both models are presented in Figure 1.

### 3.2 | Adherence between model recommendations and sleep onset and offset times

Linear mixed models showed significantly better adherence between sleep onset and offset times and recommendations from the Model of Arousal Dynamics compared with the Phillips–Robinson Model for all shift types: (i) sleep onset times (Intercept = 104 min, Model of Arousal Dynamics = −54 min, ICC = 0.27; *p* = 0.012); (ii) sleep offset times (Intercept = 91 min, Model of Arousal Dynamics = −28.5 min, ICC = 0.14; *p* = 0.04; Table 3). ICCs suggested that 27% and 14% of variance in adherence between model recommendations and sleep onset and offset, respectively, was due to between-individual differences.

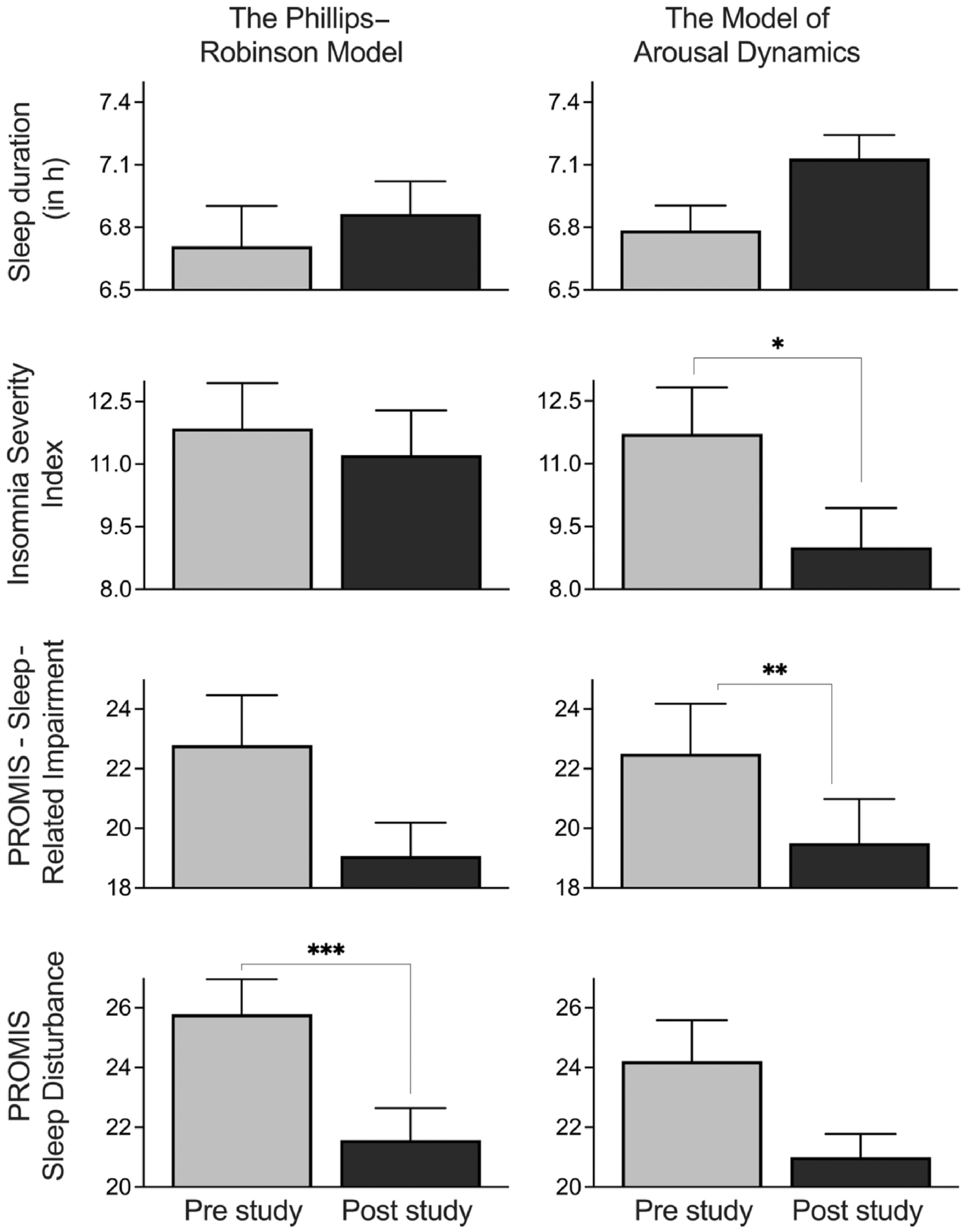

**FIGURE 3** Differences in sleep duration, insomnia symptoms, sleep-related impairment, and sleep from pre- and post-study across both models. *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$.

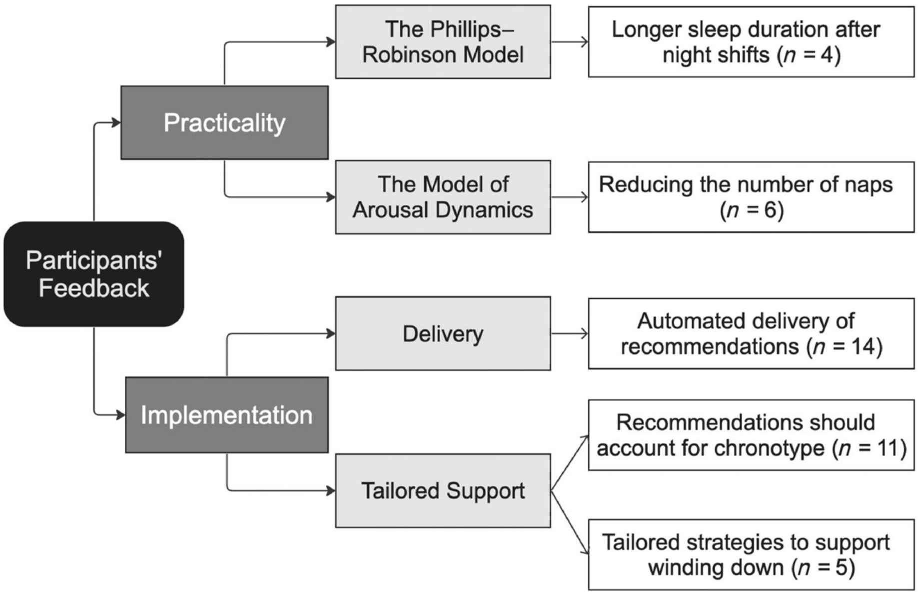

**FIGURE 4** Themes from participants' feedback to improve the practicality and implementation of sleep recommendations from models.

Adherence between sleep onset and offset times and model recommendations significantly differed for sleep in 24 h prior to morning, afternoon, or night shifts. Adherence between sleep onset and model recommendations was significantly better with the Model of Arousal Dynamics than the Phillips–Robinson Model for morning and afternoon shifts, but not for sleep recommendations prior to night shifts (Table 3). Adherence between sleep offset times and model recommendations was significantly better for the Phillips–Robinson Model than the Model of Arousal Dynamics for afternoon shifts.

Sleep onset and offset times were also categorised in 30-min bins to identify the proportion of occasions where sleep aligned within 30, 60, 90, 120 and > 120 min of model recommendations. When participants followed their Habitual Week patterns, the majority of sleep onset and offset times were > 120 min beyond recommendations generated by their respective models. During the Recommendation Week, sleep onset times were within 30 min of recommendations for 27% of sleeps for the Phillips–Robinson Model and 49% of sleeps for the Model of Arousal Dynamics. Sleep offset times were within 30 min of recommendations for 35% of sleeps for both models (Figure 2).

## 3.3 | Pre- and post-study differences in insomnia, sleep-related impairment, and sleep disturbance

Paired-sample *t* tests revealed significant improvements with small effect sizes for various sleep outcomes. Sleep duration increased across both groups, but this was not statistically significant: (i) with the Phillips–Robinson Model, the mean (SD) sleep duration before the study was 6.71 (0.15) h and 6.87 (0.24) h after ($p = 0.53$); and (ii) with the Model of Arousal Dynamics the mean (SD) sleep duration was 6.78 (0.34) h before the study and 7.13 (0.16) h after ($p = 0.05$). Scores on the ISI and PROMIS-SRI scale reduced significantly for participants in the Model of Arousal Dynamics group (Figure 3). Scores on the PROMIS-SD scale reduced significantly for participants in the Phillips–Robinson Model group.

## 3.4 | Participant feedback for improving the practicality and implementation of recommendations

Participants were instructed to provide comments related to their feedback or concerns regarding the recommendations using either the sleep diary free-text response section or the post-study survey. Overall, participants provided 259 free-text feedback comments, with 40 comments identified as including suggestions for the practicality and implementation of models. Each participant provided at least one comment related to their recommendations. Five primary themes were identified in these comments, including suggestions to tailor recommendations to suit individual diurnal preferences, and enable automated delivery of recommendations, such as through a smartphone application (Figure 4). Four participants receiving recommendations from the Phillips–Robinson Model reported that they exceeded their recommended sleep duration after all their night shifts (recommendations to sleep after night shifts were ~4 h). Six comments suggested that the nap recommendations provided by the Model of Arousal Dynamics were difficult to follow due to inconvenient timing of the naps or personal preferences around taking naps.

## 4 | DISCUSSION

This study examined the implementation of two evidence-based biomathematical models for providing sleep recommendations based on shift schedules and personal commitments in shift workers. For both models combined, there was a 73% overlap between model recommendations and participants' sleep. There were modest but significant improvements in sleep outcomes after use of the recommendations. These findings collectively highlight the feasibility of using biomathematical models in real-world shift work contexts to deliver personalised recommendations. Randomised controlled trials with longer follow-ups are recommended to examine whether biomathematical model recommendations can lead to sustained behaviour change, and improvements in health outcomes.

Significantly better adherence was observed between recommendations from the Model of Arousal Dynamics compared and the Phillips–Robinson Model for sleep onset times for sleep in the 24-h prior to the start of morning and afternoon shifts. These differences in adherence may be partly explained by how sleep propensity is predicted by the Model of Arousal Dynamics. While both models use both circadian and homeostatic processes to predict sleep timing, the Model of Arousal Dynamics has been further calibrated using forced desynchrony schedules to make better predictions of sleep propensity and the wake maintenance zone, particularly during circadian misalignment (Postnova et al., 2016). Thus, the model may facilitate more feasible recommendations for sleep in shift-work scenarios, where circadian misalignment is a common occurrence.

For both models, average adherence with sleep offset times was lower than adherence with sleep onset times. This may be due to shift workers experiencing more interrupted sleep and compensating for this by extending their sleep offset times (Shriane et al., 2020). Increasing model accuracy in predicting sleep needs and adapting recommendations by accounting for daily variations in sleep may improve future adherence.

Results from linear mixed models also showed potential inter-individual differences in adherence between model recommendations and sleep onset times. It is possible that inter-individual differences in sleep onset times is due to diurnal preference. Participants indicated that recommendations adapted to suit their diurnal preferences would make them more practical and encourage greater uptake. A systematic review has shown that diurnal preference, particularly individuals identifying as 'morning' types have poorer sleep quality and increased risk of shift-work disorder compared to 'evening' types (Booker et al., 2018). Biomathematical models can theoretically account for individual differences in physiology, which may underpin differences in diurnal preference (Phillips et al., 2010; Skeldon et al., 2016; Swaminathan et al., 2017). By mapping model parameters to diurnal preference or other indicators of individual differences (e.g., sleep timing or circadian phase assessment), these models could potentially be used to deliver tailored recommendations for sleep and alertness during shifts based on individual preference and variance in physiological response to shift work.

Our findings contribute to an emerging literature showing that manually delivered sleep recommendations can alter sleep–wake patterns in circadian misalignment, such as shift work, jetlag or a combination of the two (Åkerstedt et al., 2007; Booker et al., 2022; Flynn-Evans et al., 2020; Janse van Rensburg et al., 2021). This is the first study, however, to employ biomathematical models as a basis of delivering recommendations and addressing variability in shift hours. While these models have previously been used to simulate shift-work rosters under a variety of conditions (Fulcher et al., 2014; Knock et al., 2021; Postnova et al., 2012; Postnova et al., 2013; Postnova et al., 2016), this is the first attempt to use their recommendations in operational contexts.

The study examined overlap between participants' sleep and the recommendations and assessed potential enablers for the uptake of such interventions, which may be useful in future application of shift-work interventions. For instance, participants reported that automated or app-based delivery of recommendations can improve their usability. Previous research has shown that adherence for face-to-face or meeting-based interventions may be low due to limited time or resources and non-standard work hours in shift workers (Booker et al., 2022). App-based support may be more practical in such cases. Smartphone applications are being increasingly used to counter sleep disturbances due to circadian factors, delay or advance of circadian phase in non-shift-work populations (Inder et al., 2016; Lin et al., 2019; Rigney et al., 2021). Similar interventions may increase accessibility, promote positive health behaviours (Edwards et al., 2016), and allow shift workers to deploy these interventions at their convenience. Apps may also have the provision of using multi-modal intervention strategies, such as light therapy, cognitive behaviour therapy for insomnia and mindfulness, serving as a toolkit for lifestyle management in shift workers. Recent research by Booker et al. (2022) using individualised strategies for sleep and diet management showed that both interventions improved health outcomes, highlighting that multilevel support may be useful for shift workers.

This study is subject to the following limitations. First, data were collected during the COVID-19 pandemic, and multiple Australian states were in a 'lockdown', which was associated with most participants not reporting any personal or social commitments. In addition, the rostering practices and shift schedules during the pandemic changed rapidly, which led to difficulties in matching participants shift rotations and number of shifts across both models. We addressed this by aligning shift rotations to ensure comparability across models. Second, participants reported different rosters for Habitual and Recommendation Weeks, therefore direct comparisons for sleep onset times and sleep offset times before and during exposure to recommendations was not possible Third, given this was a pilot study, additional constraints were not used for producing recommendations. For instance, biomathematical models allow customised light exposure to be provided as an input as well as a factor to calibrate the parameters on the model to match an individual's sleep and circadian markers. Adding these would allow for more personalised recommendations. Fourth, while the optimisation target for recommendations was *average alertness* on shifts, alertness using a psychomotor vigilance task or standard measures of sleepiness was not measured to avoid participant burden. Future studies should systematically measure alertness during shifts and commute to examine potential implications in real-world situations. Further implementation studies can consider incorporating interviews and richer forms of qualitative data collection to identify factors that can impact uptake and use of personalised recommendations. Lastly, study participants were not blinded to recommendations, and self-report sleep diary data were used for measuring sleep overlap and adherence. While sleep diaries demonstrate strong correlation and agreement with actigraphy derived sleep outcomes (Billings, 2022), future studies should incorporate objective assessments, with double blinding procedures.

## 5 | CONCLUSION

Previous studies have shown that biomathematical models can help predict alertness in shift workers and determine optimal sleep timings in situations of circadian misalignment. This study demonstrated for the first time the application of biomathematical models to deliver personalised sleep recommendations in the real-world shift-work context. Randomised controlled trials with follow-up assessments of health outcomes are required to further examine compliance with and the effectiveness of recommendations. Personalising these models with additional information, and app-based delivery of recommendations can enable operational translation of biomathematical models to various shift-work settings.

## AUTHOR CONTRIBUTIONS

**Prerna Varma:** Conceptualization; investigation; methodology; validation; visualization; writing – review and editing; software; formal analysis; project administration; supervision; writing – original draft. **Svetlana Postnova:** Conceptualization; investigation; methodology; writing – review and editing; software; supervision. **Andrew J.K. Phillips:** Conceptualization; investigation; methodology; writing – review and editing; software; supervision. **Stuart Knock:** Methodology; investigation; software; writing – review and editing. **Mark E. Howard:** Methodology; writing – review and editing; supervision. **Shantha M.W. Rajaratnam:** Conceptualization; methodology; investigation; formal analysis; supervision; writing – review and editing. **Tracey L. Sletten:** Conceptualization; methodology; investigation; writing – review and editing; writing – original draft; formal analysis; supervision; resources.

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## CONFLICT OF INTEREST STATEMENT

Dr Varma has no conflicts of interest to declare. Dr Postnova was Theme and Project Leader and received grants for research from the Cooperative Research Centre for Alertness, Safety and Productivity. Dr Phillips has received research funding from Versalux and Delos, he was an investigator on projects under the Cooperative Research Centre for Alertness, Safety and Productivity, and he is co-founder/director of Circadian Health Innovations Pty Ltd. Dr Knock has no conflicts of interest to declare. Dr Howard was Theme Leader and received grants for research from the Cooperative Research Centre for Alertness, Safety and Productivity. Dr Rajaratnam has unpaid appointments at the CRC for Alertness, Safety and Productivity, Australia, and the Sleep Health Foundation. Dr Rajaratnam also is supported on grants from Vanda Pharmaceuticals, Philips Respironics, Cephalon, Rio Tinto, BHP Billiton, and Shell. Dr Rajaratnam also has received other support from Optalert, Compumedics, Teva Pharmaceuticals and Circadian Therapeutics, through his institution. He is a member of the National Sleep Foundation Sleep Timing Variability Consensus Panel, for which he was paid an honorarium through his institution. Dr Sletten was a Project Leader and received grants for research from the Cooperative Research Centre for Alertness, Safety and Productivity. [Correction added on 16 October 2023, after first online publication: Conflict of Interest Statement was updated in this version.]

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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