Efficacy of an m-health physical activity and sleep intervention to improve sleep quality in middle-aged adults: The Refresh Study randomized controlled trial

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Abstract

Background

Poor sleep health is highly prevalent. Physical activity is known to improve sleep quality but not specifically targeted in sleep interventions.

Purpose

To compare the efficacy of a combined physical activity (PA) and sleep intervention with a sleep-only intervention and a wait-list control, for improving sleep quality in middle-aged adults *without* a diagnosed sleep disorder.

Methods

Three-arm randomized controlled trial (Physical Activity and Sleep-Health (PAS), Sleep-Health-Only (SO), Wait-list Control (CON) groups; 3-month primary time-point, 6-month follow-up) of 275 (PAS=110, SO=110, CON=55) inactive adults (40-65 years) reporting poor sleep quality. The main intervention component was a smartphone/tablet "app" to aid goal-setting and self-monitoring PA and/or sleep-hygiene behaviors (including stress management), and a pedometer for PAS group. Primary outcome was Pittsburgh Sleep Quality Index (PSQI) global score. Secondary outcomes included several self-reported PA measures and PSQI sub-components. Group differences were examined stepwise, first between pooled intervention (PI=PAS+SO) and CON groups, then between PAS and SO groups.

Results

Compared with CON, PI groups significantly improved PSQI global and sub-components scores at 3 and 6 months. There were no differences in sleep quality between PAS and SO groups. The PAS group reported significantly less daily sitting time at 3 months and were significantly more likely to report ≥2 days/week resistance training and meeting PA guidelines at 6 months than the SO group.

Conclusion

Pooled interventions had statistically significantly improved sleep quality among middle-aged adults with poor sleep quality without a diagnosed sleep disorder. The adjunctive PA intervention did not additionally improve sleep quality.

Trial Registration: Australian New Zealand Clinical Trial Registry: ACTRN12617000680369; Universal Trial number: U1111-1194-2680; Human Research Ethics Committee, Blinded by request of journal: H-2016-0267

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Poor sleep health is highly prevalent (1, 2), with 30-50% of the global population, including 30-45% of Australians, reporting some indicator of poor sleep health (1, 3, 4). Poor sleep health increases with age (5) and may be characterised by: short or long sleep duration; poor sleep quality; sleep disturbance; irregular sleep timing; and/or daytime dysfunction (6). The consequences of poor sleep health include increased risk of several non-communicable diseases (e.g., cardiovascular disease, type 2 diabetes) (7, 8), poor mental (9), and self-rated health, (10) and a considerable economic cost (11, 12).

Only about half of reported sleep problems are due to a specific sleep disorder (13). However, most sleep health interventions target clinical insomnia, with fewer interventions directed towards adults with poor sleep but *without* a diagnosed sleep disorder (14). Therefore, many people with poor sleep health may not be accessing resources to improve their sleep health (14). Cognitive Behavioral Therapy for Insomnia (CBTi) improves sleep quality in people with insomnia (d~0.41) (15-19). Of the limited research available, it appears that cognitive and behavioral interventions are also effective at improving sleep quality in people without a diagnosed sleep disorder (14). Over 50% of the worldwide population, including nearly 90% of Australians, used mobile internet in 2017 (20, 21). Consequently, mobile health (m-health) interventions have the potential to provide wide-reaching, large-scale, accessible delivery of cost-effective behavior change interventions relative to face-to face interventions (22). They are known to improve symptom severity among those with sleep disorders (23) and physical activity levels (24) but little research exists regarding the efficacy of m-health sleep interventions among adults *without* sleep disorders (14). Additionally, due to the high proportion of people reporting *both* low levels of physical activity and poor sleep quality (25), using m-health may be useful to provide wide availability of interventions.

Physical activity is also key to reducing the risk of many non-communicable diseases (e.g., cardiovascular disease, type 2 diabetes) (26). Additionally, several meta-analyses have demonstrated that regular physical activity, including resistance training (RT) (27), improves sleep quality relative to control group participants (d = ~0.74) (28-30) and there is some evidence that a bidirectional relationship exists between physical activity and sleep, whereby improvement in one behavior leads to improvement in the other (4, 31). However, only approximately 23.3% (range 4.1 to 65.0) of adults worldwide, and 52.6% of Australian adults meet aerobic physical activity guidelines (≥150 minutes/week moderate-to-vigorous-intensity physical activity) (32, 33) and only 19% meet resistance training guidelines (≥2 sessions/week) (33). Furthermore, physical activity levels decline with increasing age which, in combination with age related declines in sleep health, suggests that middle-aged and older adults are an important intervention target-group to prevent the associated negative health effects of physical inactivity and poor sleep health (32). Whilst "regular exercise" is frequently recommended as a component of sleep hygiene behaviors in sleep interventions (34), none of the studies included in a review of sleep health interventions provided participants with specific strategies and behavior change techniques to promote changes in physical activity (35). This is despite strong evidence showing that specific behavior change techniques (e.g., self-monitoring, action planning) are required to change each target behavior in multiple health behavior change interventions (36). Consequently, sleep interventions may fail to leverage the potential additional benefit to sleep health which could be gained from an improvement in physical activity.

Given the high prevalence of poor sleep health in people without a diagnosed sleep disorder (3, 13), and the associated health consequences (7-10, 37), there is a clear need for broad-reaching, effective interventions to improve sleep quality in subclinical populations (38). Adding a dedicated physical activity component to sleep interventions has the potential

to improve their efficacy. The primary aim of the Refresh Study (REsearch FoR Exercise, Sleep and Health), was to compare the efficacy of a combined physical activity and sleep health intervention with a sleep health-only intervention and a wait-list control, for improving sleep quality in middle-aged adults *without* a diagnosed sleep disorder. This study also assessed the secondary outcome measures of the intervention on physical activity, resistance training, meeting physical activity guidelines, sitting time and PSQI sub-components.

Methods

Study Sample

The Refresh Study was a three-arm randomized controlled trial with assessments at baseline, 3 months (primary time-point) and 6 months (follow-up time-point) post-baseline. A detailed description of The Refresh Study Protocol is available elsewhere (39). Briefly, rolling recruitment of participants from across Australia occurred between May and September 2017, using primarily Facebook advertising. Participants were eligible if, in the screening survey, they reported being aged 40 to 65 years, reported fairly bad or very bad sleep quality (as per the single sleep quality item of the Pittsburgh Sleep Quality Index), less than 90 minutes/week of moderate-to-vigorous-intensity physical activity (MVPA) (as indicated by response to a single item 'As a rule, do you engage in at least half an hour of moderate or vigorous exercise (such as walking or a sport) on three or more days of the week (yes/no)?') (39), had a body mass index (BMI) between 18.5 and 35.0, and had access to the internet with a device compatible with the intervention mobile app (iOS or Android). Exclusion criteria were: a previously diagnosed sleep disorder; use of sleep medication, pregnancy or having a child aged less than 12 months; having a condition which would contraindicate participation in physical activity or a change in sleep habits, current shift-work, plans to travel three or more hours outside their usual time zone during the first three

months of the study period; and, current use of a device for tracking physical activity and/or sleep.

After completing online eligibility screening and providing informed consent, eligible participants completed the baseline survey and were subsequently randomized into either the Physical Activity and Sleep Health intervention group (PAS), Sleep Health Only intervention group (SO) or waitlist-control group (CON), at a ratio of 2:2:1. Permuted block randomization was used with random blocks of sizes of 10 and 15, with the allocation sequence generated using SAS V9.4 (SAS Institute, Cary, North Carolina, USA). Group allocation was concealed in sequentially numbered envelopes. The Refresh Study received approval from the Human Research Ethics Committee, blinded by request of journal (reference number: H-2016-0267) and was prospectively registered with the Australian and New Zealand Clinical Trials Registry (ACTRN12617000680369; Universal Trial number: U1111-1194-2680).

Interventions

The Refresh intervention included access to a specifically designed *app* (40, 41), a participant handbook, text messages/SMS and emails (39). The intervention was guided by social cognitive theory and operationalized behavior change techniques which have been found to be effective across multiple health behaviors (42, 43). The intervention implemented key behavior change techniques including self-monitoring, goal setting and feedback that have been shown to be effective in several meta-analyses and reviews of m-health and website interventions (42-45). An intervention overview is shown in Supplementary Table 1. Participants only received intervention content specific to their group allocation, including in the app. The sleep intervention components were the same for the PAS and SO groups. The sleep intervention targeted reducing bed and wake time variability, engaging in a number of sleep hygiene behaviors (as chosen by participants) and stress management (e.g., progressive

muscle relaxation, deep breathing exercises, mindfulness). The PAS group also received a physical activity component which involved increasing their daily minutes of MVPA and step counts and weekly resistance training through goal setting and action planning. Participants used the app to access educational material, set physical activity and/or sleep goals, enter data daily to self-monitor their physical activity and/or sleep behaviors and to receive graphical feedback in relation to their progress towards these goals. Participants were mailed a *participant handbook*, containing an app installation and use guide, "*tools*" for stress management techniques and setting goals and action planning. PAS group participants were mailed a *pedometer* (Yamax SW200) to keep, for assistance with step count self-monitoring. During the 3 month intervention period, participants received an emailed weekly summary of their physical activity and/or sleep behaviors and progress in relation to goals, based on their app entries, as well as weekly educational facts via SMS. If participants stopped logging behaviors in the app (≥4/7 days/week), an SMS was sent to prompt re-engagement. At weeks 3, 6 and 9, participants were emailed a copy of the stress management, goal setting and action planning "*tools*" to reinforce these strategies. The CON group was offered the Physical Activity and Sleep Health intervention upon completion of the 6 month assessment.

Measures

Participants completed all online assessments using the Qualtrics® survey platform, at baseline, after 3 months (primary time-point) and 6 months (follow-up). All data were collected between May 2017 and April 2018. Sleep quality was measured using the Pittsburgh Sleep Quality Index (PSQI), a 19-item survey that assesses seven components of sleep comprising subjective sleep quality, sleep onset latency, sleep duration, sleep efficiency, sleep disturbances, use of sleep medication and daytime dysfunction. The scores (0-3) for each component are summed to provide a global sleep quality score (range 0-21). Scores above five indicate poor quality sleep, and higher scores signify progressively poorer

sleep (46). The PSQI has been found to have good validity and reliability (Cronbach α=0.83) (46, 47), including within non-clinical populations (48).

Physical activity was measured using the Active Australia Questionnaire (AAQ), which assesses time spent walking, and in moderate and vigorous intensity activities (with vigorous intensity physical activity time weighted by two) during the previous 7 days. The AAQ has adequate test-re-test reliability and validity (49, 50) and is sensitive to change (51). Total duration of weekly MVPA was calculated using established scoring protocols (52). Resistance training (RT) was measured by asking participants the total minutes/week (dichotomised as; <10 minutes/week or ≥10 minutes/week) and number of days/week (dichotomised as; <2 days/week or 2-7 days/week) they engaged in RT (53). Meeting of physical activity guidelines was assessed by combining total weekly MVPA and days/week of RT (dichotomised as; meeting physical activity guidelines (≥150 minutes/week MVPA and 2-7 days/week of RT) or not meeting physical activity guidelines) (54).

Average daily sitting time was assessed using the Workforce Sitting Questionnaire (WSQ) which assesses total and domain specific time spent sitting on week days and weekends. The WSQ has acceptable test-retest reliability (ICC = 0.46-0.90) and acceptable criterion validity compared with accelerometry (r = 0.18-0.46) (55).

Satisfaction with the app usability was assessed at the 3 month primary time-point using the System Usability Scale (SUS). SUS scores range from 0 to 100, with a higher score indicating greater usability (56). App usage, including average number of days of data logging and time to non-usage attrition (classified as no data-entry for 14 consecutive days), was calculated using data exported from the app similar to previous studies (57).

Power and Sample Size

The study was powered to detect baseline-adjusted group differences in the primary outcome of sleep quality measured using the PSQI at the three month primary time-point.

The familywise error rate was controlled using a stepwise multiple testing procedure. The first test planned to compare the pooled intervention (PI=PAS + SO) and the CON groups, (assuming mean PSQI = 6.85 and 8.00 for PI and CON groups respectively; SD = 2.42: two-sided $\alpha = 0.05$; power = 0.80), assuming an allocation ratio of 4:1. This resulted in a required sample size for the first comparison of PI group = 112, CON group = 28. If this null hypothesis was rejected, the two intervention groups were then planned to be compared with each other (assuming mean PSQI = 6.42 and 7.27 for PAS and SO groups respectively; SD = 2.42; two-sided $\alpha = 0.05$; power = 0.80, resulting in a required sample size for the second comparison of 82 per intervention group. The smallest specified difference was between the two intervention groups which thus determined the sample size for the study. The sample size was inflated to account for 25% attrition and allocation using a 2:2:1 ratio, resulting in a total sample size of 275 (40, 58).

Statistical Analyses

T-tests (continuous data) and chi-square analyses (categorical data) were employed to compare sample characteristics between survey completers and non-completers. Independent t-tests were used to compare average System Usability Scale ratings between intervention groups at 3 months only. Kaplan Meier survival estimates for time to non-usage attrition were plotted and Cox proportion hazards regression was used to examine between intervention group differences in time to non-usage attrition. Results were expressed as differences in least square group means with 95% CIs, and ORs with 95% CIs.

Minutes/week of MVPA were log-transformed due to right skew. Between-group differences at three months in PSQI, MVPA (log minutes/week) and sitting time were examined using generalized linear models (GLM) using an ANCOVA (baseline-adjusted) approach, including fixed-effects for study group and the baseline value of the outcome. Logistic regression was used to assess group differences in days/week of RT, minutes/day of

RT, meeting physical activity guidelines and ordered logistic regression was used to examine group differences in PSQI sub-component scores at three months. Logistic regression and ordered logistic regression models were adjusted for the baseline value of the outcome.

To examine differences between groups at six months in PSQI, MVPA (log minutes/week) and sitting time, generalized linear mixed models (GLMM) were used. To examine differences between groups at six months in days/week of RT, minutes/day of RT, meeting physical activity guidelines, mixed effects logistic regression was used, and mixed effects ordered logistic regression was used to examine differences in PSQI sub-component scores. All models specified 3 and 6 month data as outcomes and including fixed effects for study group, time, the group-by-time interaction and baseline values, and a random intercept to account for repeated measures of participants.

Analyses were conducted according to the intention-to-treat principle including all available data. Sensitivity analyses used multiply imputed (MI) data (25 imputations) with predictive Mean Matching (PMM) including all primary and secondary outcome variables in the MI model, based on a missing at random assumption (MAR). Alpha was set at 0.05 for all analyses, which were conducted using Stata V15.1. in May 2018 (59).

Results

Of the 275 participants who enrolled and completed the baseline survey, 240 (87.3%) completed the 3-month survey (PAS group: n = 102 (92.7%); SO group: n = 88 (80.0%); CON group: n = 50 (90.9%)), whilst 201 (73.1%) completed the 6-month survey (PAS group: n = 83 (75.5%); SO group: n = 74 (67.3%); CON group: n = 44 (80.0%)) (Figure 1). Characteristics of participants at baseline, by study group, are shown in Table 1. The mean participant age was 52 years (range 40-65 years) and 83% were female. Almost all (98%) participants were classified as having poor sleep quality (global PSQI score ≥5; despite 100% reporting fairly bad or very bad sleep quality when answering the single item eligibility

question), 55% reported <150 minutes/week of MVPA (despite indicating <90 minutes/ week of MVPA when answering the single item eligibility question) and about 90% reported <2 days/week of resistance training. There were no significant differences between completers and non-completers of the 3 month survey, however it was completed by a lower proportion of the SO group than the PAS and CON groups (80% SO, 93% PAS and 91% CON; p=0.012). Descriptive data for sleep and physical activity outcomes by study group at each time point are detailed in Supplementary Table 2.

Between Group Differences in Overall Sleep Quality

The baseline-adjusted mean PSQI total score at 3 months was significantly lower (improved) in the PI groups compared with the CON group (7.84 vs 9.81, p <0.001) and the difference was maintained at 6 months (7.64 vs 9.72, p <0.001) (Table 2). Relative to the CON, the PI groups were significantly less likely to have poorer PSQI sub-component scores for subjective sleep quality, sleep onset latency, sleep duration, sleep efficiency, and daytime dysfunction at 3 and 6 months (Table 3). Though the PAS scores were higher, there were no significant differences between the PAS and SO groups in mean baseline-adjusted PSQI total scores at 3 or 6 months (Table 2). The PAS group had higher odds of having a higher sleep medication PSQI sub-component score at 3 months (OR = 2.55, p = 0.026) but not at 6 months (Table 3). These results remained robust after sensitivity analyses using multiple imputation for missing data (Supplementary Tables 3 and 4), except for the 6-month sleep duration outcome between the PI and CON groups, which was no longer significant in analyses of imputed data (Supplementary Table 4).

Between Group Differences in Physical Activity

All groups reported increased minutes/week of MVPA at 3 and 6 months compared with baseline (Supplementary Table 2). There were no significant differences between the PI and CON groups for log-minutes/week of MVPA, minutes/week of RT, days/week of RT,

meeting physical activity guidelines or daily sitting time at 3 or 6 months (Tables 2 and 3). The PAS group was significantly more likely than the SO group to report ≥10 minutes/week of RT at 3 months (OR = 2.34, $p = 0.010$) and 6 months (OR = 10.60, $p = 0.003$) (Table 3). The PAS group reported significantly less sitting time (48.3 fewer minutes/day, $p = 0.042$), than the SO group at 3 months but not at 6 months (Table 2). There were no significant differences between the PAS and SO groups for days/week of RT or meeting physical activity guidelines at 3 months. However, at 6 months, the PAS group was significantly more likely than the SO group to report 2-7 days/week of RT (OR = 6.54, $p = 0.016$) and also to meet physical activity guidelines (OR = 5.38, $p = 0.023$) (Table 3). There were no significant differences between the PAS and SO groups in log-minutes/week of MVPA at 3 months or 6 months (Table 2). These results remained robust after sensitivity analyses using multiple imputation for missing data (Supplementary Tables 3 and 4) except for daily sitting time at 6 months, where complete case analysis was not significant but analysis of multiply-imputed data showed significantly less daily sitting time (51.3 fewer minutes/day, $p = 0.041$) for the PAS group compared with the SO group (Supplementary Table 3).

App usage and participant satisfaction

Throughout the 3-month intervention period (84 days), 65 (29.6%) participants logged data regularly across the entire 84 days (PAS = 35 (31.8%); SO = 30 (27.3%)), whereas 52 (23.6%) participants never logged data (PAS = 17 (15.5%); SO = 35 (31.8%)). Overall, 155 (70.5%) participants succumbed to non-usage attrition (PAS = 75 (68.2%), SO = 80 (72.7%)) with the average time to attrition being 46 (± 36) days (PAS = 51 (± 34); SO = 41 (± 36)). There was no statistically significant difference between intervention groups in time to non-usage attrition (HR = 0.80; $p = 0.175$). Kaplan-Meier survival estimates for app usage are shown in Figure 2. The mean System Usability Score at 3 months was 67.62 (SD 16.77), with no difference between the PAS and SO groups (67.94 vs 67.52; $p = 0.867$), indicating

reasonable usability (60). A summary of proportions of responses to individual System Usability Scale items is shown in Supplementary Table 5.

Discussion

The primary aim of the Refresh Study was to compare the efficacy of a combined physical activity and sleep health intervention with a sleep health-only intervention and a wait-list control, to improve sleep quality in middle-aged adults *without* a diagnosed sleep disorder. This study demonstrated a significant improvement in sleep quality in both intervention groups compared to the control condition after three months, which was maintained at six months. However, there was no significant difference in sleep quality between intervention groups.

In populations with insomnia, a reduction in PSQI score of ≥3 points is considered a meaningful response to treatment (61). At 3 and 6 months, the PI groups had a reduction in mean PSQI of >2 points, and 20% more participants than at baseline with a global PSQI score <5 (Supplementary Table 2), indicating remission of sleep problems (46). The current sample reported subclinical insomnia symptoms, as evidenced by the average baseline Insomnia Severity Index scores (Table 1). As such, this subclinical sample was likely to have a lower baseline PSQI score, and therefore a lower margin for improvement than those with insomnia. Despite this the reduction in PSQI scores in this study are larger than those observed in meta-analyses of the effect of exercise on sleep quality and insomnia in middle-aged women which observed significant reductions in PSQI scores for both low-moderate physical activity (MD = -1.34; 95% CI: -2.67, 0.00) and moderate physical activity (MD = -1.85; 95% CI: -3.63, -0.07), compared with controls (62, 63). Thus the improvement in sleep quality in this study is likely to be meaningful. Previous interventions for poor sleep health have focussed on clinical treatment for insomnia (17). However, few interventions (including internet-delivered) have targeted adults with poor sleep but *without* a diagnosed sleep

disorder (14). The current study improves our understanding by demonstrating that an m-health sleep intervention for poor sleep health is effective in populations reporting poor quality sleep but who do not have a diagnosed sleep condition.

It was anticipated that, by adding a dedicated physical activity component to the sleep health intervention, a superior improvement in sleep quality would be achieved. However, there was no significant difference in sleep quality between the two intervention groups. Although the SO and CON groups were expected to maintain MVPA at levels similar to their low baseline levels, all three groups substantially increased their weekly minutes of MVPA between baseline and the 3 month primary time-point. Additionally, there was considerable variation in these changes (Supplementary Table 2). This attenuated the ability to determine if adding a dedicated physical activity intervention component would increase physical activity relative to the sleep-only intervention and further improve sleep quality.

The observed increases in physical activity by all groups may in part be due to having attracted already motivated participants who responded to recruitment advertising which indicated an opportunity to increase physical activity (e.g., advertisements included the slogan “Sleep better. Move more.”), and then increased physical activity regardless of group allocation which is commonly observed among control group participants in physical activity interventions (64). It may also have been a function of self-reported physical activity which is prone to bias and overestimation and future studies would benefit from objective measures.

Although the PAS group was significantly more likely to be participating in RT and meeting physical activity guidelines by 6 months (Supplementary Table 4), no difference between the intervention groups in overall sleep quality emerged. These findings do not align with the considerable evidence indicating that physical activity interventions improve sleep quality. For example, three meta-analyses of the effects physical activity on sleep found that sleep quality was improved by regular exercise (d = 0.74; 95% CI: 0.48, 1.00) (28) and by

participation in 10 to 16 weeks of supervised exercise training (SMD = 0.47; 95% CI: 0.08, 0.86) (29); MD = −1.85; 95% CI: −3.62, −0.07) (62). In our study participants' physical activity was self-driven and not dictated by a prescriptive or supervised exercise programme with more intensive support, such as those examined in the meta-analyses. Furthermore, most of the physical activity interventions included in the reviews were compared to control groups only. These factors, combined with a possible ceiling effect of exercise on sleep in this population *without* a diagnosed sleep disorder (65), may have rendered participants less sensitive, or requiring a longer time-frame, to obtain any benefits of physical activity on sleep quality (30).

Despite similar improvements in sleep quality in both intervention groups, the improvements in RT and meeting physical activity guidelines by the PAS group have other interesting implications. These improvements may be a response to the specific instructions regarding how to increase physical activity levels, perform RT exercises and provision of a pedometer to track step-count, which aligns with previous research indicating that, in multi-behavior interventions, specific behavior change techniques for each target behavior are required to maximise change in each behavior (36, 66). Furthermore, the PAS group successfully improved two behaviors simultaneously. This indicates participants were unlikely to have been overburdened by the multiple behavior nature of their intervention (67), which is further supported by a much longer time (albeit non-significant) to app non-usage attrition by the PAS group. This is useful information for the development future multiple health behavior change interventions which have the potential to maximize health benefits in a time and cost efficient manner (68, 69). The apparent suitability of the combination of physical activity and sleep demonstrated in this study is important since targeting some combinations of behaviors is more successful than others (70).

The proportional increases within the PAS group, from baseline to the 6-month follow-up, in RT participation (from 10.9% to 28.9%) and meeting physical activity guidelines (≥150 minutes/week MVPA and 2-7 days/week of RT) (from 6.4% to 25.3%) are promising, given only 18.6% and 15.0% of the Australian population meet recommendations for these behaviors respectively (33). MVPA and RT each reduce the risk of many non-communicable diseases (26, 71). In addition, physical activity and muscle mass and quality decline with age (32, 72), so the impact of this intervention on this sample of middle-aged adults has important implications for promoting healthy aging.

The PAS group reported significantly less sitting time (48.29 fewer minutes/day) at 3 months than the SO group. This aligns with findings of a meta-analysis of physical activity interventions which reported modest reductions in sitting time (SMD: -0.22 minutes/day; 95% CI: -0.35, -0.10) (73). The improvement in sleep, MVPA, RT and sitting time observed in the PAS intervention group have the potential to have conferred greater overall benefits to health given that the higher the number of healthy lifestyle behaviors the lower the risk of all-cause mortality (74). Quantifying how the behavioral changes elicited during the intervention influence chronic disease risk factors (e.g., blood pressure, triglycerides, insulin) will be useful to examine in future studies.

The m-health delivery of this intervention enabled wide accessibility and reached across Australia, with more than a third of participants living outside major cities. This is beneficial given that access to physical activity infrastructure and access to medical care is lower in non-metropolitan areas (75, 76). Average time to non-usage attrition of the app was 46 days which is better than several other web and/or app based interventions (46 versus 11 days; >25% still using the app at 80 days versus 21 days) (77, 78). Whilst, better engagement is likely to be associated with better outcomes, there is still limited understanding of how app usage is related to behavior change (e.g., the impact of continuous versus intermittent app

usage on behavior change or the minimum ‘dose’ of app usage required) (77). In the current study, around 75% of participants made a self-monitoring entry and 30% were still using the app at the primary time point. The interaction between intervention usage, as quantified by the number and pattern of self-monitoring entries, and behavior change is likely to vary between individuals. For instance for some users, a short period of engagement may be sufficient to change behaviors over the period assessed in the current study, whilst for other longer more prolonged engagement may be necessary.

Among the strengths of the study is the sample of participants without diagnosed sleep disorders. This is important as most interventions target those with insomnia, even though only half of those reporting sleep problems have a sleep disorder (13), indicating the remaining half are under-supported. The sleep intervention did not include all elements of CBTi, however it included several behavioral components (e.g., stress management/relaxation, sleep hygiene) that appear to be useful for people who have poor sleep quality but no diagnosed disorder to improve their sleep (14). Other strengths include the sample size, length of intervention and follow-up relative to other sleep interventions in non-clinical samples (mean intervention duration of five weeks) (14, 62), the high retention rate (87.3%), and relatively lower numbers succumbing to non-usage attrition compared with previous m-health interventions .

Study limitations included the use of self-reported physical activity measures, as previously mentioned. Future studies would benefit from objectively measured sleep and physical activity. However, whilst some components of sleep can be objectively measured using polysomnography and actigraphy, subjective satisfaction with sleep cannot be captured in this manner, requiring self-report regardless (6). Although improvements in sleep quality were maintained between 3 and 6 months, the lack of further improvement in sleep quality indicates that research of long term m-health-delivered behavior change is required (22).

Another limitation relates to the potential presence of undiagnosed sleep disorders among participants, such as sleep apnoea, which may benefit less from the intervention approach used and may have attenuated the results. Future research would benefit from the use of assessment tools to evaluate the presence of undiagnosed sleep disorders and examine these as potential moderators of intervention efficacy.

The significant finding of higher PAS group sleep medication use at 3 months may be due to a higher number of participants (15 versus 5) reporting using sleep medication less than once per week and is unlikely to be meaningful. Another limitation is a higher than anticipated baseline MVPA and large variability in MVPA at all time-points. These factors may have obscured the ability to detect a relationship between increased MVPA and improvement in sleep quality if it existed.

Conclusion

This study demonstrated a statistically significant improvement in sleep quality among middle-aged adults with poor sleep quality *without* a diagnosed sleep disorder. Additional improvement in sleep quality associated with an adjunctive physical activity intervention was not detected. The increases in MVPA in all study groups likely reduced the ability of the study to examine this adjunctive effect of physical activity. However, given the large proportion of the population with poor sleep health and its associated burden of disease (6, 11), the current interventions have the potential to provide effective and broad-reaching opportunities to reduce reducing the burden of disease associated with poor sleep quality.

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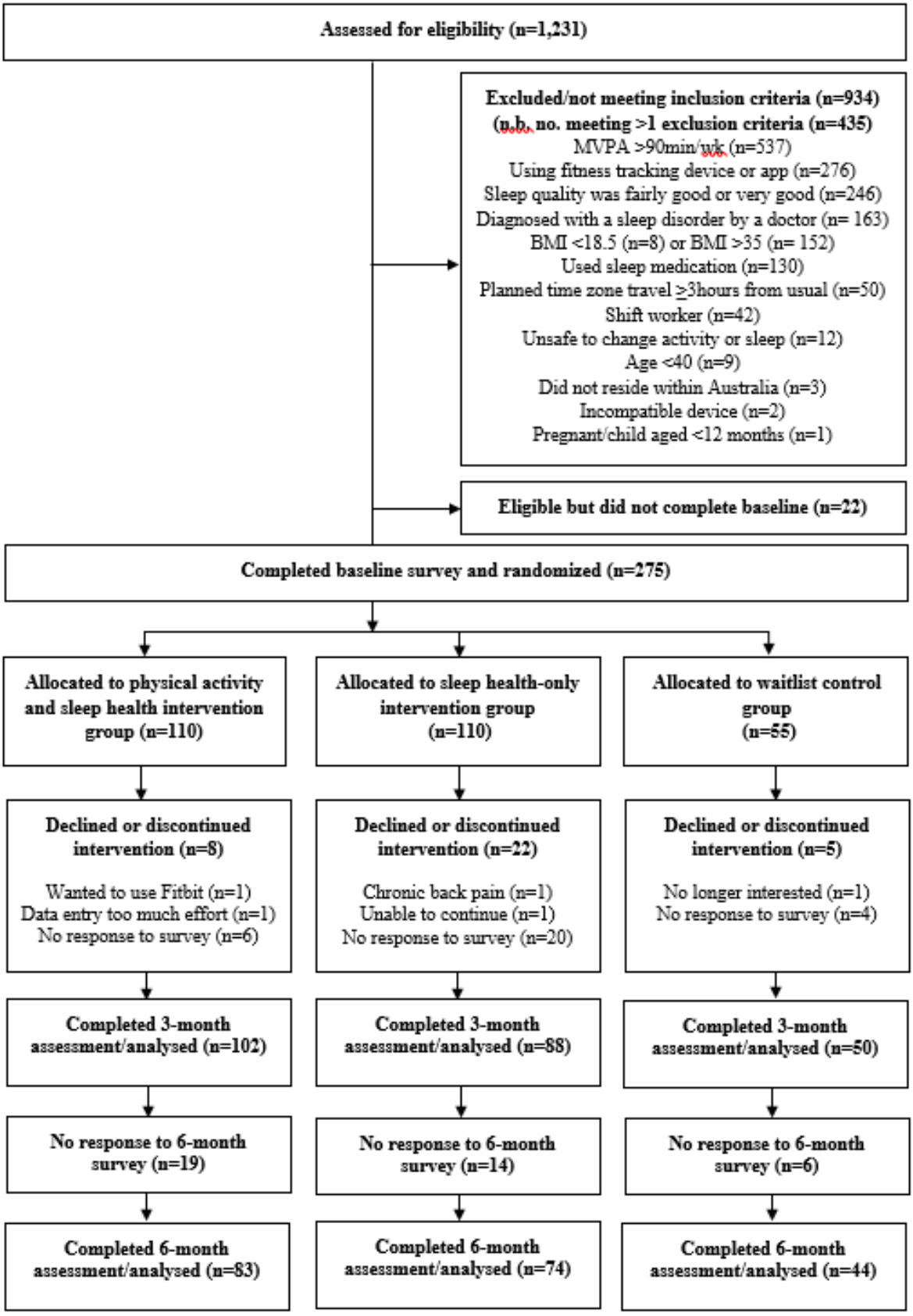

Figure 1. CONSORT diagram describing participant flow to the 6-month time point

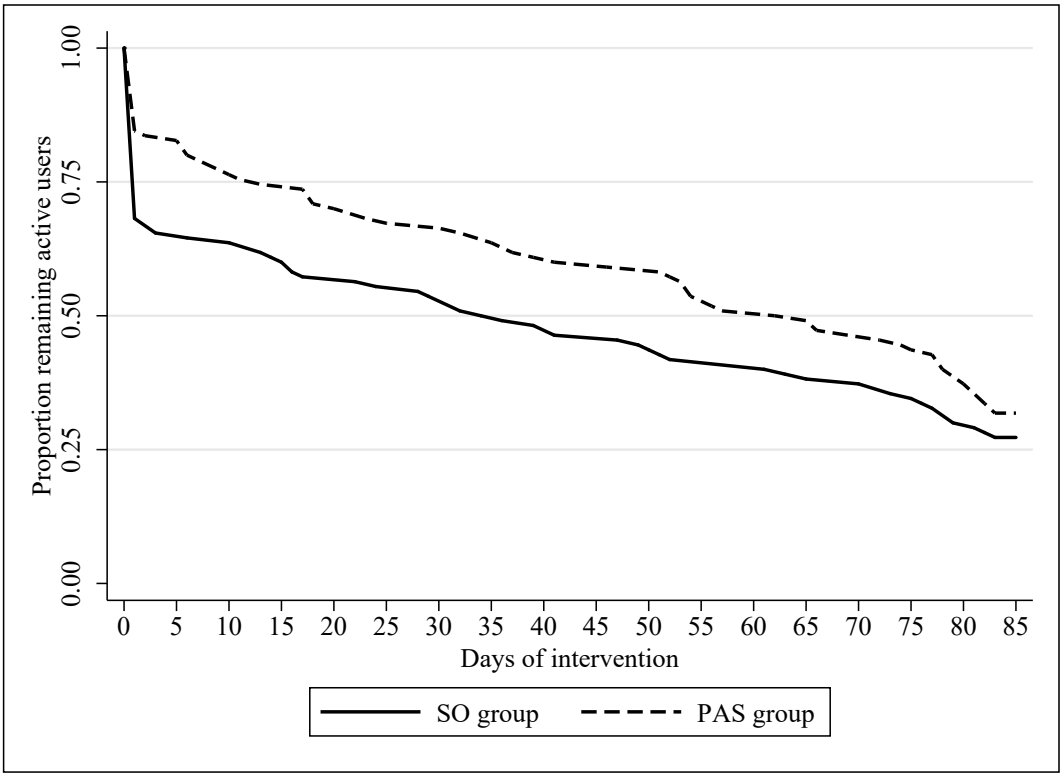

Figure 2. Kaplan Meier estimates of the survival distribution for time to non-usage attrition by group

Note: 75% of PAS group were still using the app at day 13. 75% of SO group were still using the app at day 1. 50% of PAS group were still using the app at day 62. 50% of SO group were still using the app at day 34. Greater than 25% of participants in both intervention groups were still using the app at the 3-month primary time point.

Table 1. *Baseline socio-demographic, health and behavioral characteristics of participants by group*

	Physical Activity and Sleep Health Group (n=110)	Sleep Health Only Group (n=110)	Pooled Intervention Groups (n=220)	Control (n=55)	Overall (n=275)
Age (Range 40-64), M[a] (SD)	51.7 (6.7)	52.2 (7.0)	51.9 (6.9)	52.4 (7.3)	52.0 (6.9)
Female, n (%)	89 (80.9)	92 (83.6)	181 (82.3)	47 (84. 5)	228 (82.9)
Race, n (%)					
Caucasian	103 (93.6)	106 (96.4)	209 (95.0)	54 (98.2)	263 (95.6)
Non-Caucasian[b]	7 (6.4)	4 (3.6)	11 (5.0)	1 (1.8)	12 (4.4)
Area of Residence[c], n (%)					
Major city	69 (62.7)	73 (66.4)	142 (64.6)	33 (60.0)	175 (63.6)
Regional or remote	41 (37.3)	37 (33.6)	78 (35.4)	22 (40.0)	100 (36.4)
Marital status, n (%)					
Married/defacto	85 (77.3)	80 (72.7)	165 (75.0)	38 (69.1)	203 (73.8)
Not married[d]	21 (19.2)	30 (27.3)	51 (23.2)	16 (29.1)	67 (24.4)
No response	4 (3.6)	0 (0.0)	4 (1.8)	1 (1.8)	5 (1.8)
Education (years), M[a] (SD)	15.96 (2.81)	16.64 (3.12)	16.30 (2.97)	16.94 (2.93)	16.43 (2.95)
Annual Income[e], n (%)					
<$30,000	17 (15.5)	16 (14.6)	33 (15.0)	12 (21.8)	45 (16.4)
$30,001-$70,000	28 (25.5)	26 (23.6)	54 (24.5)	14 (25.5)	68 (24.7)
$70,001-$150,000	46 (41.8)	50 (45.5)	96 (43.6)	21 (38.2)	117 (42.5)
>$150,000	8 (7.3)	1 (0.9)	9 (4.1)	5 (9.1)	14 (5.1)
Don't know/don't want to answer	11 (10.0)	17 (15.5)	28 (12.7)	3 (5.5)	31 (11.3)

Employment Situation, n (%)					
Employed[f]	91 (82.7)	93 (84.6)	184 (83.6)	46 (83.6)	230 (83.6)
Retired	5 (4.5)	6 (5.5)	11 (5.0)	3 (5.5)	14 (5.1)
Not in paid employment[g]	11 (1.0)	9 (8.2)	20 (9.1)	4 (7.3)	24 (8.8)
Other	3 (2.7)	2 (1.8)	5 (2.3)	2 (3.6)	7 (2.6)
Work duration (hh:mm) M[a] (SD)	7:33 (1.5)	8:07 (2.3)	7:50 (2.1)	7:40 (2.5)	7:48 (2. 2)
BMI (kg/m^2), M[a] (SD)	28.40 (4.0)	28.52 (4.4)	28.46 (4.2)	28.29 (4.1)	28.42 (4.2)
Chronic conditions, n (%)					
No chronic conditions	40 (36.4)	38 (34.6)	78 (35.5)	17 (30.9)	95 (34.5)
1-2 chronic conditions	52 (47.3)	50 (45.5)	102 (46.4)	26 (47.3)	128 (46.5)
≥3 chronic conditions	18 (16.4)	22 (20.0)	40 (18.2)	12(21.8)	52 (18.9)
Non-smoker, n (%)	104 (94.6)	104 (94.6)	208 (94.6)	54 (98.2)	262 (95.3)
Insomnia Severity Score[h], n (%)	13.51 (4.19)	14.13 (4.24)	13.82 (4.21)	14.12 (3.85)	13.88 (4.14)
PSQI total score[i] (0-21), M[a] (SD)	9.84 (3.06)	10.39 (3.11)	10.11 (3.09)	10.67 (3.05)	10.23 (3.08)
Sleep quality category, n (%)					
Good quality sleep	2 (1.8)	3 (2.7)	5 (2.3)	1 (1.8)	6 (2.2)
Poor quality sleep	108 (98.2)	107 (97.3)	215 (97.7)	54 (98.2)	269 (97.8)
PSQI Sub-scores[j], M[a] (SD)					
Subjective sleep quality	1.94 (0.55)	1.93 (0.46)	1.93 (0.51)	2.02 (0.49)	1.95 (0.50)
Sleep onset latency	1.67 (1.12)	1.84 (1.11)	1.75 (1.11)	1.82 (1.09)	1.77 (1.11)
Sleep duration	1.19 (0.86)	1.31 (0.88)	1.25 (0.87)	1.36 (0.97)	1.27 (0.89)

Sleep efficiency	1.62 (1.13)	1.65 (1.09)	1.63 (1.10)	1.69 (1.17)	1.64 (1.12)
Sleep disturbances	1.55 (0.55)	1.60 (0.58)	1.58 (0.56)	1.58 (0.57)	1.58 (0.56)
Sleep medication use	0.31 (0.74)	0.42 (0.93)	0.36 (0.84)	0.42 (0.81)	0.37 (0.83)
Daytime dysfunction	1.55 (0.77)	1.65 (0.76)	1.60 (0.77)	1.78 (0.85)	1.64 (0.79)
MVPA[k] (min/week), median (IQR)	120 (50-210)	105 (60-180)	120 (60-205)	180 (60-320)	120 (60-240)
RT[l] minutes/week, n (%)					
<10 minutes/week	91 (82.7)	91 (82.7)	182 (82.7)	45 (81.8)	227 (82.6)
≥10 minutes/week	19 (17.3)	19 (17.3)	38 (17.3)	10 (18.2)	48 (17.4)
RT[l] Frequency, n (%)					
0-1 days/week	98 (89.1)	99 (90.0)	197 (89.5)	50 (90.9)	247 (89.8)
2-7 days/week	12 (10.9)	11 (10.0)	23 (10.5)	5 (9.1)	28 (10.2)
Meeting Guidelines for both RT and aerobic PA[m], n (%)					
Not meeting	103 (93.6)	102 (92.7)	205 (93.2)	51 (92.7)	256 (93.1)
Meeting	7 (6.4)	8 (7.3)	15 (6.8)	4 (7.3)	19 (6.9)
Sitting time minutes/day, M[a] (SD)	665.86 (195.71)	656.58 (184.71)	661.22 (189.91)	652.86 (176.47)	659.55 (187.02)

Notes: a. M = mean; b. Non-Caucasian = Aboriginal, Torres Strait Islander or Pacific Islander, African, Asian or other; c. Area of residence as classified by Australian Bureau of Statistics classifications for remoteness; d. Not married = single, divorced, or widowed; e. Individual pre-tax annual income; f. Employed (Full time, part time, casual); g. Not in paid employment = Home duties, student, permanently unable to work, unemployed; h. Insomnia Severity Index Score categories: 0-7 = no clinically significant insomnia; 8-14 = subthreshold insomnia; 15-21 moderate severity clinical insomnia; 22-28 sever clinical insomnia; i. Pittsburgh Sleep Quality Index (PSQI): scores range from 0-21 with scores >5 indicating poor quality sleep; j. PSQI component scores range from 0-3, lower score is better; k. Moderate-to-vigorous-intensity physical activity, l. Resistance training, m. ≥150 minutes/week MVPA and 2-7 days/week of RT

Table 2. Adjusted *post-test means and group differences for Pooled Intervention groups (PI groups) vs Control group (CON) and Physical Activity and Sleep Health Group (PAS) vs Sleep Health Only Group (SO); At 3 months and 6 months*

	3 Months				3 Months			
	PI groups (n = 190) M (95% CI)	CON (n = 50) M (95% CI)	Between group co-efficient (95% CI)	*p*	PAS (n = 102) M (95% CI)	SO (n = 88) M (95% CI)	Between group co-efficient (95% CI)	*p*
Sleep quality PSQI	7.84 (7.41, 8.26)	9.81 (9.02, 10.59)	-1.97 (-2.87, -1.07)	<0.001	7.80 (7.17, 8.43)	7.71 (7.17, 8.26)	0.08 (-0.75, 0.92)	0.849
MVPA[ab] log min/wk	5.20 (5.01,5.39)	5.24 (4.93, 5.54)	-0.04 (-0.39, 0.32)	0.844	5.21 (4.95, 5.48)	5.13 (4.86, 5.40)	0.08 (-0.30, 0.46)	0.664
Sitting min/day	641.32 (617.14, 665.50)	643.57 (595.98, 691.17)	-2.25 (-55.63, 51.13)	0.934	619.18 (587.57, 650.80)	667.77 (633.31, 702.23)	-48.59 (-95.36, -1.81)	0.042
	6 Months				6 Months			
	PI groups (n = 157) M (95% CI)	CON (n = 44) M (95% CI)	Between group co-efficient M (95% CI)	*p*	PAS (n = 83) M (95% CI)	SO (n = 74) M (95% CI)	Between group co-efficient (95% CI)	*p*
Sleep quality PSQI	7.64 (7.18, 8.10)	9.72 (8.85, 10.60)	-2.08 (-3.07, -1.09)	<0.001	7.83 (7.19, 8.47)	7.23 (6.55, 8.38)	0.60 (-0.33, 1.53)	0.203
MVPA[ac] log min/wk	5.16 (4.94, 5.37)	5.10 (4.68, 5.51)	0.06 (-0.41, 0.53)	0.797	5.17 (4.86, 5.48)	5.11 (4.78, 5.44)	0.06 (-0.39, 0.51)	0.797
Sitting min/day	589.73 (564.06, 615.40)	602.37 (553.55, 651.19)	-12.64 (-67.80, 42.52)	0.653	572.62 (539.22, 606.02)	609.71 (574.27, 645.15)	-37.09 (-85.78,11.61)	0.136

Notes: a. Log min/wk MVPA = natural logarithm of total minutes/week of MVPA +1 (to permit logarithmic transformation of 0 values); b.3 month back-transformed (exponentiated) values (minutes/week) of estimated marginal means log (minutes/week) of MVPA from GLM models: PI groups =181.53 (95% CI=150.48, 218.23), CON=187.78 (95% CI=138.34, 254.90), PAS=183.91 (95% CI=141.23, 239.47), SO=169.16 (95% CI=29.31, 221.30); c. 6 month back-transformed (exponentiated) values (minutes/week) of estimated marginal means log (minutes/week) of MVPA from GLM models: PI groups =173.55 (95% CI=139.70, 215.59), CON=163.22 (95% CI=108.01, 246.64), PAS=175.92 (95% CI=129.08, 239.76), SO=165.81 (95% CI=119.41, 230.24)

Table 3. *Associations between Pooled Intervention groups (PI groups) vs Control group (CON) and Physical Activity and Sleep Health Group (PAS) vs Sleep Health Only Group (SO) for days/week of resistance training, minutes/week of resistance training, meeting activity guidelines and having higher vs lower PSQI sub-component scores; At 3 months and 6 months*

	3 Months			
	PI groups (n=190) vs CON (n=50) (Reference category)		PAS (n=102) vs SO Group (n=88) (Reference category)	
	OR (95% CI)	p	OR (95% CI)	p
Resistance training ≥ 10 min/week (Reference category: < 10 min/week)	1.47 (0.72, 3.02)	0.292	2.34 (1.23, 4.48)	0.010
Resistance Training 2-7 days/week (Reference category: 0-1 days/week)	0.71 (0.33, 1.49)	0.363	1.51 (0.73, 3.11)	0.267
Meeting Activity Guidelines[a] (Reference category: Not Meeting Activity Guidelines)	0.72 (0.35, 1.47)	0.371	1.43 (0.70, 2.90)	0.327
Subjective Sleep Quality	0.29 (0.15, 0.56)	<0.001	0.81 (0.46, 1.42)	0.457
Sleep Onset Latency	0.48 (0.27, 0.88)	0.017	0.99 (0.56, 1.74)	0.972
Sleep Duration	0.52 (0.28, 0.98)	0.042	1.09 (0.62, 1.92)	0.766
Sleep Efficiency	0.39 (0.21, 0.72)	0.003	0.92 (0.52, 1.62)	0.768
Sleep Disturbance	0.89 (0.45, 1.79)	0.752	0.68 (0.36, 1.31)	0.248
Sleep Medications	0.64 (0.31, 1.30)	0.218	2.55 (1.12, 5.81)	0.026

Daytime Dysfunction	0.32 (0.19, 0.56)	<0.001	0.88 (0.50, 1.53)	0.649

	6 Months			
	PI groups (n=157) vs CON (n=44) (Reference category)		PAS (n=83) vs SO Group (n=74) (Reference category)	
	OR (95% CI)	p	OR (95% CI)	p
Resistance training ≥ 10 min/week (Reference category: < 10 min/week)	3.27 (0.68, 15.64)	0.138	10.60 (2.20, 51.09)	0.003
Resistance Training 2-7 days/week (Reference category: 0-1 days/week)	1.78 (0.41, 7.70)	0.441	6.54 (1.42, 30.15)	0.016
Meeting Activity Guidelines[a] (Reference category: Not Meeting Activity Guidelines)	1.77 (0.39, 7.99)	0.456	5.38 (1.25, 23.09)	0.023
Subjective Sleep Quality[b]	0.21 (0.08, 0.57)	0.002	1.22 (0.51, 2.94)	0.656
Sleep Onset Latency[b]	0.19 (0.06, 0.60)	0.005	1.52 (0.55, 4.25)	0.420
Sleep Duration[b]	0.28 (0.09, 0.85)	0.025	2.46 (0.89, 6.76)	0.082
Sleep Efficiency[b]	0.35 (0.14, 0.85)	0.021	1.06 (0.45, 2.49)	0.893
Sleep Disturbance[b]	0.33 (0.10, 1.05)	0.060	2.24 (0.66, 7.54)	0.194
Sleep Medications[b]	0.72 (0.13, 4.05)	0.712	1.67 (0.36, 7.88)	0.515
Daytime Dysfunction[b]	0.16 (0.06, 0.41)	<0.001	1.04 (0.44, 2.45)	0.932

Note: a. meeting activity guidelines: ≥150 minutes/week MVPA and 2-7 days/week of RT; b. For all PSQI subcomponent scores, lower scores indicate a better outcome and, as such, an OR <1 indicates that a group is less likely to have a higher (worse) score relative to the reference group.

Supplementary Table 1. *Operationalisation of social cognitive factors and behaviour change strategies for sleep and physical activity intervention components.*

Theoretical Construct	Behaviour Change Technique	Intervention Components	Operationalization of sleep intervention components received by both SO[a] and PAS[b] groups	Operationalization of physical activity components received PAS[b] group only
Self-efficacy				
Confidence in one's ability to engage in a behaviour (physical activity or sleep) (task self-efficacy) and to overcome barriers to engaging in these behaviours (barrier self-efficacy)	Setting graded tasks/ incremental challenges	Setting achievable goals and regular revision of goals	Participants will be encouraged to set realistic sleep goals (Bed time, wake time and sleep hygiene goals) which can be adjusted at any time.	Participants will be encouraged to gradually increase the number of sessions, duration and intensity of physical activity.
	Self-monitoring/ Self-re-evaluation	Daily logging of activity into Balanced app	Participants will log: - Bed time - Wake time - Sleep hygiene goals achieved (from checklist of 10) - Sleep quality rating (1-5 stars) Graphical feedback in the form of bar charts and a colour coded traffic light display relating	Participants will log: - Minutes of daily physical activity - Daily step count (pedometer provided) - Muscle strengthening sessions – 'yes' or 'no' each day. Graphical feedback in the form of bar charts and a colour coded traffic light display relating to their progress towards set goals will be provided.

		to their progress towards set goals will be provided.	
Goal review/feedback/ positive reinforcement	Dashboard -Traffic lights	The dashboard will be divided into tiles. The sleep tile will relate to nightly sleep duration; A green light indicates a participant is meeting, exceeding or close to their goal; an orange light indicates they are progressing toward their goal although are not close; and a red light indicates they are markedly below their goal.	The dashboard will be divided into tiles. The physical activity tile will relate to minutes of physical activity based on daily entries (24h); A green light indicates a participant is meeting, exceeding or close to their goal; an orange light indicates they are progressing toward their goal although are not close; and a red light indicates they are markedly below their goal.
	Bar graphs	Bar Graphs will show progress in relation goals for bed time/wake time, sleep duration, sleep hygiene and sleep quality over four time points; one day, week, three-months and all.	Bar Graphs will show progress in relation goals for minutes of physical activity, step count and days including muscle strengthening sessions, over four time points; daily, weekly, three-month and all.
	Email messages	Weekly personalised summary email with information about personal sleep goals progress will be sent to participants.	Weekly personalised summary email with information about personal activity goal progress will be sent to participants.

	Relapse prevention	Use of prompts	Participants will receive text prompts to remind them to log sleep behaviours if they have not logged for any four of seven consecutive days.	Participants will receive text prompts to remind and encourage them to log physical activities if they have not logged for any four of seven consecutive days.
			Text messages including useful facts about sleep and information about overcoming barriers.	Text messages including useful facts about physical activity and information about overcoming barriers.
	Knowledge/ education	Educational information in the "Resources" section of the Balanced app and the Goal Setting, Action Planning and Stress Management Tools	Advice including national recommendations for sleep duration and about the how much, why and how of engaging in sleep promoting behaviours (sleep hygiene) will be provided.	Australian physical activity recommendations will be provided.
			Health benefits of good sleep (e.g., reducing the risk of heart disease, diabetes, depression and anxiety as well as feel more energised) will be provided.	Health benefits of physical activity (e.g., reducing the risk of heart disease, diabetes, depression and anxiety as well as feel more energised) will be provided.
			Information about environmental restructuring and how to manage the bedroom environment as part of good sleep hygiene will be provided.	Overcoming barriers; participants will be provided with information about overcoming barriers.

			The action planning tool will provide information about the how, why, when, where, who with and what of achieving sleep goals.	Tips for creating an action plan outlining type of activity, intensity, duration, where, when, who with and some problem-solving strategies, will be provided to inform participants how to go about being physically active.
			The stress management tool will provide links to relaxation podcasts and videos, as well as step-by-step guides to progressive muscle relaxation, deep breathing exercises and mindfulness exercises which are commonly accepted techniques incorporated into interventions for sleep.	Social support; participants will be encouraged to find friends and family to be physically active with.
Outcome Expectations/Expectancies				
An individual's anticipated outcome of sleep and physical activity behaviours and the	Information on consequences of behaviour	Educational information in the "Resources" section of the Balanced app and in the Handbook	Health benefits of good sleep (e.g., reducing the risk of heart disease, diabetes, depression and anxiety as well as feel more energised) and the current national guidelines on how much sleep is needed, will be provided.	Health benefits of physical activity (e.g., reducing the risk of heart disease, diabetes, depression and anxiety as well as feel more energised) will be provided.

value they place upon that outcome				
		Action Planning Tool	As part of the intervention materials, reasons why they wish to improve their sleep behaviour and what they anticipate as personal benefits, following improved sleep (examples will be provided	As part of the intervention materials, reasons why they wish to improve their physical activity and what they anticipate as personal benefits, following improved physical activity (examples will be provided).
Socio-structural				
The creation of supportive relationships which reduce vulnerability to stress	Mobilise social support	Information in the "Resources" section of the Balanced app and in the example action plan	Information on seeking support from those in the same household (housemates, partner, and family members) will be provided.	Participants will be encouraged to engage with family members, friends and peers to assist them achieve their physical activity goals by joining in or encouraging them to do so.
	Environmental restructuring	Educational information in the "Resources" section of the app and in the Action Planning tool.	Environmental restructuring as part of good sleep hygiene will be highlighted in the resource section and include details on how to manage the bedroom environment	The example action plan will provide ideas to assist participants make the most of their environment to improve their physical activity such as: "I'll park the car further away so I can walk.", "Use the steps and the bench in the park".

Intentions and Goals				
Intentions and goals refer to what a person proposes to do	Use of prompts	Text messages	Participants will receive text prompts to remind them to log sleep if not logged for any 4 of 7 consecutive days.	Participants will receive text prompts to remind them to log physical activities if have not logged for any 4 of 7 consecutive days.
	Action plan	Development of action plan	Participants will receive a guide to assist them develop action plan based on sleep hygiene recommendations, which fosters engagement in sleep promoting behaviours.	The Action Planning Tool will assist in the creation of an action plan, outlining type of activity, intensity, duration, where, when, who with and some problem-solving strategies, will be provided to inform participants how to go about being physically active.
	Graded tasks	Action plan revision	Participant's action plans will be revised/updated as required intermittently	Participant's action plans will be revised/updated as required intermittently
	Goal setting	Setting of proximal and distal goals	Participants will set personal bedtime and wake time goals; number of sleep hygiene behaviours will be set as a sleep hygiene goal.	Participants will set daily goals with an action plan. Additionally, participants will be asked to set a longer term goal to keep in mind for the end of the intervention (e.g., "I will run a Park Run without stopping").

	Review of goals	Graphical feedback: bar charts	Bar Graphs will show progress in relation goals for bed time/wake time, sleep duration, sleep hygiene and sleep quality over four time points; one day, one week, three-months and all.	Participants will receive on-screen feedback on their progress in the form of a bar chart which displays their progress towards their goals.
		Graphical feedback: traffic lights	The dashboard will be divided into tiles. The sleep tile will relate to nightly sleep duration; entries within 20%, meeting or exceeding goals will generate a green light; entries between 20% and 35% of goal will generate an orange light; entries more than 35% below goal will generate a red light.	Participants will receive graphical on-screen feedback on their progress in relation to their goals in the form of a traffic light system display; within 20%, meeting or exceeding goals will generate a green light; entries between 20% and 35% of goal will generate an orange light; entries more than 35% below goal will generate a red light. This feedback will be used to assist participants in reviewing their goals.
	Time management	Educational information in the Action Planning tool.	Tips for regulating bed and wake times, and timing of sleep-promoting behaviours will be provided in the action planning tool.	Participants will be provided with information about scheduling physical activity sessions in the example action plan.

Notes: a. SO = Sleep Health-Only; b. PAS = Physical Activity and Sleep Health

Supplementary Table 2. *Baseline, 3 month and 6 month health and behavioral characteristics of participants by group*

	Control Group			Pooled Intervention Groups			PAS[a] Group			SO[b] Group		
	Baseline (n=55)	3 months (n=50)	6 months (n=44)	Baseline (n=220)	3 months (n=190)	6 months (n=157)	Baseline (n=110)	3 months (n=102)	6 months (n=83)	Baseline (n=110)	3 months (n=88)	6 months (n=74)
PSQI[c] total score (0-21), M[d] (SD)	10.67 (3.05)	10.10 (3.54)	9.91 (3.99)	10.11 (3.09)	7.76 (3.53)	7.39 (3.77)	9.84 (3.06)	7.68 (3.83)	7.53 (3.92)	10.39 (3.11)	7.85 (3.17)	7.23 (3.61)
Sleep quality category, n (%)												
Good quality	1 (1.8)	3 (6.0)	5 (11.4)	5 (2.3)	43 (22.6)	37 (23.6)	2 (1.8)	25 (24.5)	18 (21.7)	3 (2.7)	18 (20.5)	19 (25.7)
Poor quality	54 (98.2)	47 (94.0)	39 (88.6)	215 (97.7)	147 (77.4)	120 (76.4)	108 (98.2)	77 (75.5)	65 (78.3)	107 (97.3)	70 (79.6)	55 (74.3)
PSQI sub-scores, M (SD)												
Subjective sleep quality	2.02 (0.49)	1.82 (0.69)	1.73 (0.69)	1.93 (0.51)	1.41 (0.62)	1.37 (0.72)	1.94 (0.55)	1.39 (0.65)	1.41 (0.75)	1.93 (0.46)	1.43 (0.58)	1.32 (0.68)
Sleep onset latency	1.82 (1.09)	1.68 (1.04)	1.77 (1.24)	1.75 (1.11)	1.31 (1.00)	1.28 (1.09)	1.67 (1.12)	1.26 (0.99)	1.31 (1.05)	1.84 (1.11)	1.35 (1.02)	1.24 (1.14)
Sleep duration	1.36 (0.97)	1.22 (1.04)	1.11 (1.04)	1.25 (0.87)	0.84 (0.89)	0.79 (0.93)	1.19 (0.86)	0.84 (0.95)	0.87 (0.98)	1.31 (0.88)	0.84 (0.89)	0.70 (0.86)
Sleep efficiency	1.69 (1.17)	1.52 (1.09)	1.39 (1.17)	1.63 (1.10)	1.04 (1.07)	1.03 (1.09)	1.62 (1.13)	1.04 (1.12)	1.06 (1.15)	1.65 (1.09)	1.03 (1.02)	1.00 (1.03)

Sleep disturbances	1.58 (0.57)	1.44 (0.54)	1.52 (0.55)	1.58 (0.56)	1.39 (0.54)	1.36 (0.52)	1.55 (0.55)	1.34 (0.52)	1.39 (0.51)	1.60 (0.58)	1.44 (0.56)	1.32 (0.3)
Sleep medication use	0.42 (0.81)	0.58 (1.03)	0.55 (1.04)	0.36 (0.84)	0.38 (0.83)	0.32 (0.75)	0.31 (0.74)	0.43 (0.83)	0.28 (0.63)	0.42 (0.93)	0.33 (0.84)	0.38 (0.87)
Daytime dysfunction	1.78 (0.85)	1.84 (0.79)	1.84 (0.81)	1.60 (0.77)	1.39 (0.76)	1.24 (0.84)	1.55 (0.77)	1.36 (0.83)	1.22 (0.83)	1.65 (0.76)	1.42 (0.67)	1.26 (0.86)
MVPA[e] (min/week), median (IQR)	180 (60-320)	240 (120-400)	205 (90-465)	120 (60-205)	240 (90-430)	250 (90-520)	120 (50-210)	290 (100-480)	240 (90-540)	105 (60-180)	210 (90-420)	265 (90-520)
RT[f] min/week, n (%)												
<10 min/week	45 (81.8)	35 (71.4)	33 (75.0)	182 (82.7)	121 (63.7)	93 (61.2)	91 (82.7)	57 (55.9)	42 (50.6)	91 (82.7)	64 (72.7)	54 (73.0)
≥10 min/week	10 (18.2)	14 (28.6)	11 (25.0)	28 (17.3)	59 (36.3)	61 (38.9)	19 (17.3)	45 (44.1)	41 (49.4)	19 (17.3)	24 (27.3)	20 (27.0)
RT[f] days/week, n (%)												
0-1 days/week	50 (90.9)	36 (73.5)	37 (84.1)	197 (89.6)	149 (78.4)	122 (77.7)	98 (89.1)	77 (75.5)	59 (71.1)	99 (90.0)	72 (81.8)	63 (85.1)
2-7 days/week	5 (9.1)	13 (26.5)	7 (15.9)	23 (10.4)	41 (21.6)	35 (22.3)	12 (10.9)	25 (24.5)	24 (28.9)	11 (10.0)	16 (18.2)	11 (14.9)
Meeting Guidelines for both RT and aerobic PA[g],												

n (%)

Not meeting	51 (92.7)	36 (73.4)	38 (86.4)	205 (93.2)	150 (79.0)	127 (80.9)	103 (93.64)	78 (76.57)	62 (74.7)	102 (92.7)	72 (81.8)	65 (87.8)
Meeting	4 (7.3)	13 (26.6)	6 (13.6)	15 (6.8)	40 (21.0)	30 (19.1)	7 (6.36)	24 (23.5)	21 (25.3)	8 (7.3)	16 (18.2)	9 (12.2)
Sitting time	652.86	643.32	595.91	661.22	641.39	589.84	665.86	616.32	567.85	656.58	671.18	614.51
min/day, M (SD)	(176.47)	(207.06)	(203.29)	(189.91)	(207.41)	(189.68)	(195.71)	(203.01)	(190.13)	(184.71)	(209.83)	(187.39)

Notes: a. PAS = Physical Activity and Sleep Health intervention group, b. SO = Sleep Health Only intervention group, c. PSQI = Pittsburgh Sleep Quality Index, d. Mean e. MVPA = moderate-to-vigorous-intensity physical activity, f. RT = resistance training, g. Meeting Guidelines for both RT and aerobic PA = ≥150 min/week MVPA plus ≥2 days/week RT

Supplementary Table 3. Sensitivity analyses using multiply imputed data (25 imputations); Adjusted post-test means and group differences for Pooled Intervention groups (PI groups) vs Control group (CON) and Physical Activity and Sleep Health Group (PAS) vs Sleep Health Only Group (SO); At 3 months and 6 months

	3 Months				3 Months			
	PI groups (n = 220) M (95% CI)	CON (n = 55) M (95% CI)	Between group co-efficient (95% CI)	*p*	PAS (n = 110) M (95% CI)	SO (n = 110) M (95% CI)	Between group co-efficient (95% CI)	*p*
Sleep quality PSQI	7.87 (7.45, 8.29)	9.80 (9.00, 10.60)	-1.93 (-2.85, -1.01)	<0.001	7.86 (7.24, 8.48)	7.74 (7.18, 8.30)	0.12 (-0.73, 0.97)	0.786
MVPA[ab] log min/wk	5.18 (5.00, 5.37)	5.21 (4.88, 5.53)	-0.02 (-0.39, 0.35)	0.909	5.21 (4.95, 5.47)	5.12 (4.84, 5.39)	0.09 (-0.28, 0.47)	0.620
Sitting min/day	647.51 (624.63, 670.40)	642.47 (593.16, 691.79)	5.04 (-49.13, 59.20)	0.855	621.42 (589.60, 653.23)	675.79 (641.78, 709.80)	-54.37 (-102.30, -6.44)	0.026
	6 Months				6 Months			
	PI groups (n = 220) M (95% CI)	CON (n = 55) M (95% CI)	Between group co-efficient (95% CI)	*p*	PAS (n = 110) M (95% CI)	SO (n = 110) M (95% CI)	Between group co-efficient (95% CI)	*p*
Sleep quality PSQI	7.51 (7.04, 8.00)	9.67 (8.75, 10.58)	-2.15 (-3.20, -1.10)	<0.001	7.74 (7.04, 8.43)	7.29 (6.62, 7.96)	0.45 (-0.51, 1.41)	0.358
MVPA[ac] log min/wk	5.14 (4.90, 5.39)	5.08 (4.69, 5.47)	0.06 (-0.40, 0.52)	0.794	5.18 (4.85, 5.50)	5.12 (4.73, 5.50)	0.06 (-0.44, 0.56)	0.818

Sitting min/day	589.83 (563.31, 616.35)	601.51 (540.81, 662.21)	-11.68 (-78.64, 55.28)	0.732	564.13 (529.45, 598.81)	615.43 (578.00, 652.86)	-51.30 (-100.58, -2.03)	0.041

Notes: a. Log minutes/week of MVPA = log of total minutes/week of MVPA +1 (to permit logarithmic transformation of 0 values); b. 3 month back-transformed (exponentiated) values (minutes/week) of estimated marginal means log (minutes/week) of MVPA from GLM models: PI groups =178.43 (95% CI=148.15, 214.89), CON=182.33 (95% CI=132.03, 251.81), PAS=183.30 (95% CI=141.60, 237.28), SO=166.73 (95% CI=126.86, 219.09); c. 6 month back-transformed (exponentiated) values (minutes/week) of estimated marginal means log (minutes/week) of MVPA from GLM models: PI groups =171.39 (95% CI=133.76, 219.60), CON=161.20 minutes/week (95% CI=108.98, 238.42), PAS=176.81 (95% CI=127.48, 245.24), SO=166.66 (95% CI=113.85, 243.95)

Supplementary Table 4. *Sensitivity analyses using multiply imputed data (25 imputations); Associations of resistance training, minutes/week of resistance training, meeting activity guidelines and having higher vs lower PSQI sub-component scores; At 3 months and 6 months*

	3 Months			
	Pooled IG (n=220) vs CON (n=55) (Reference category)		PAS (n=110) vs SO Group (n=110) (Reference category)	
	OR (95% CI)	p	OR (95% CI)	p
Resistance training ≥ 10 min/week (Reference category: < 10 min/week)	1.47 (-0.37, 1.14)	0.318	2.15 (1.15, 4.01)	0.017
Resistance Training 2-7 days/week (Reference category: 0-1 days/week)	0.73 (0.35, 1.53)	0.410	1.47 (0.73, 2.97)	0.282
Meeting Activity Guidelines[a] (Reference category: Not Meeting Activity Guidelines)	0.72 (0.35, 1.47)	0.371	1.43 (0.70, 2.90)	0.327
Subjective Sleep Quality	0.29 (0.15, 0.56)	<0.001	0.82 (0.46, 1.45)	0.496
Sleep Onset Latency	0.49 (0.27, 0.90)	0.022	0.98 (0.57, 1.67)	0.931
Sleep Duration	0.52 (0.29, 0.96)	0.035	1.09 (0.63, 1.87)	0.765
Sleep Efficiency	0.40 (0.22, 0.71)	0.002	0.95 (0.55, 1.64)	0.847
Sleep Disturbance	0.93 (0.46, 1.87)	0.829	0.65 (0.34, 1.27)	0.207
Sleep Medications	0.66 (0.31, 1.40)	0.274	2.50 (1.07, 5.85)	0.035
Daytime Dysfunction	0.33 (0.18, 0.61)	<0.001	0.87 (0.50, 1.52)	0.636

	6 Months			
	Pooled IG (n=220) vs CON (n=55) (Reference category)		PAS (n=110) vs SO Group (n=110) (Reference category)	
	OR (95% CI)	p	OR (95% CI)	p
Resistance training ≥ 10 min/week (Reference category: < 10 min/week)	2.84 (0.83, 9.66)	0.095	5.54 (1.56, 19.65)	0.008
Resistance Training 2-7 days/week (Reference category: 0-1 days/week)	1.57 (0.47, 5.27)	0.465	3.87 (1.18, 12.65)	0.025
Meeting Activity Guidelines[a] (Reference category: Not Meeting Activity Guidelines)	1.55 (0.45, 5.38)	0.487	3.37 (1.04, 10.92)	0.043
Subjective Sleep Quality[b]	0.24 (0.11, 056)	0.001	1.30 (0.62, 2.73)	0.485
Sleep Onset Latency[b]	0.26 (0.12, 0.66)	0.004	1.13 (0.49, 2.59)	0.777
Sleep Duration[b]	0.46 (0.18, 1.17)	0.102	2.09 (0.89, 4.89)	0.089
Sleep Efficiency[b]	0.44 (0.19, 0.97)	0.041	0.92 (0.41, 2.04)	0.830
Sleep Disturbance[b]	0.44 (0.17, 1.17)	0.101	1.48 (0.59, 3.75)	0.407
Sleep Medications[b]	0.61 (0.18, 2.04)	0.419	0.99 (0.32, 3.10)	0.992
Daytime Dysfunction[b]	0.18 (0.08, 0.40)	<0.001	0.96 (0.45, 2.02)	0.907

Note: a. meeting activity guidelines: ≥150 minutes/week MVPA and 2-7 days/week of RT; b. For all PSQI subcomponent scores, lower scores indicate a better outcome and, as such, an OR <1 indicates that a group is less likely to have a higher (worse) score relative to the reference group.

Supplementary Table 5. *Summary of proportions of responses to System Usability Scale items; Usefulness of the Refresh Study for engaging in physical activity and/or healthy sleep habits*

Over the past 3 months, how useful was the Refresh Study in helping you to…..?		Not-at-all useful		Slightly/ moderately useful		Very/ Extremely useful	
		PAS[a]	SO[b]	PAS[a]	SO[b]	PAS[a]	SO[b]
Increase confidence	To participate in physical activity	21%	N/A[c]	45%	N/A[c]	34%	N/A[c]
Overcome barriers		28%	N/A[c]	47%	N/A[c]	25%	N/A[c]
Increase support		27%	N/A[c]	57%	N/A[c]	16%	N/A[c]
To plan		23%	N/A[c]	55%	N/A[c]	22%	N/A[c]
Stay motivated		22%	N/A[c]	53%	N/A[c]	25%	N/A[c]
Increase confidence	To engage in healthy sleep habits	14%	17%	55%	62%	31%	21%
Overcome barriers		16%	20%	58%	62%	26%	18%
Increase support		20%	36%	59%	49%	21%	15%
To plan		16%	19%	59%	56%	25%	28%
Stay motivated		15%	21%	52%	52%	33%	27%

Over the past *6 months*, how useful was the Refresh Study in helping you to…..?		Not-at-all useful		Slightly/ moderately useful		Very/ Extremely useful	
		PAS[a]	SO[b]	PAS[a]	SO[b]	PAS[a]	SO[b]
Increase confidence	To participate in physical activity	24%	N/A[c]	48%	N/A[c]	28%	N/A[c]
Overcome barriers		28%	N/A[c]	53%	N/A[c]	19%	N/A[c]
Increase support		36%	N/A[c]	50%	N/A[c]	14%	N/A[c]
To plan		31%	N/A[c]	51%	N/A[c]	18%	N/A[c]
Stay motivated		33%	N/A[c]	44%	N/A[c]	23%	N/A[c]
Increase confidence	To engage in healthy sleep habits	23%	22%	49%	66%	28%	22%
Overcome barriers		25%	26%	52%	51%	23%	23%
Increase support		36%	35%	47%	49%	17%	16%
To plan		25%	24%	52%	72%	23%	24%
Stay motivated		23%	22%	57%	58%	20%	20%

Notes: a. PAS = Physical Activity and Sleep Health group; b. SO = Sleep-Health Only group; c. Physical activity data not collected for the SO group.