SLEEPJ, 2019, 1–7

doi: 10.1093/sleep/zsz003
Advance Access Publication Date: 11 January 2019
Original Article

ORIGINAL ARTICLE

Slow wave sleep facilitates spontaneous retrieval in prospective memory

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Abstract

Study Objectives: Previous studies have shown that sleep benefits prospective memory by facilitating spontaneous retrieval processes. Here, we investigated the sleep features supporting such a benefit.

Methods: Forty-nine young adults (mean age ± *SD*: 22.06 ± 1.71 years; 18 males) encoded intentions comprising four related (phone-unplug earphones) and four unrelated (mirror-close the book) cue–action pairs. They were instructed to remember to perform these actions in response to cue words presented during a semantic categorization task 12 h later. The retention interval involved either a period of wakefulness (09:30–21:30; $n = 24$) or overnight sleep with polysomnographic monitoring (21:30–09:30; $n = 25$).

Results: We found a significant Group × Relatedness interaction for prospective memory accuracy ($F = 8.35$, $p < 0.01$). The sleep group successfully executed a significantly higher percentage of related intentions compared to the wake group (mean ± standard error of the mean (SEM): 94.00 ± 2.61% vs 66.67 ± 6.84%, $p < 0.001$). This benefit for related intentions was associated with longer post-learning slow wave sleep ($r = 0.46$, $p < 0.05$). In contrast, the percentage of unrelated intentions successfully executed did not differ between groups (82.00 ± 5.10% vs 72.92 ± 6.88%, $p = 0.29$).

Conclusion: Slow wave sleep after memory encoding may strengthen the preexisting associations between semantically related cues and actions, thereby facilitating subsequent spontaneous retrieval processes.

Statement of Significance

Previous studies have shown that a period of post-encoding sleep benefits prospective memory by strengthening spontaneous retrieval processes. However, the sleep features supporting such a benefit remain unknown. Here, we show that in young adults, sleeping vs staying awake after intention encoding benefits spontaneous retrieval of intentions consisting of semantically related cue–action pairs. Critically, this sleep-related benefit on preexisting associations is linked with more time spent in slow wave sleep (SWS) during the post-learning sleep episode. These findings that reveal preferential processing of preexisting associations during SWS may explain why prospective memory is impaired in individuals with little SWS; e.g. older adults, and suggest that interventions effectively boosting SWS may be beneficial for these individuals.

Key words: memory consolidation; prospective memory; slow wave sleep; spontaneous retrieval; strategic monitoring

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Submitted: 26 July, 2018; **Revised:** 11 December, 2018

Introduction

Prospective memory (PM) is the ability to remember to do something at a particular moment in the future [1]. PM tasks are ubiquitous in everyday situations, such as remembering to pay your bills or remembering to take medications at the right time, failures of which may be catastrophic. Identifying conditions in which the likelihood of failure is minimized and PM retrieval is more effective is important as these highlight adaptions that may be used in everyday contexts.

Recent studies have found that sleep is important for prospective remembering [2–6], and that a period of nocturnal sleep compared to an equivalent period of daytime wakefulness facilitates the consolidation of PM intentions [2–4, 6]. In particular, sleep appears to promote prospective remembering by improving the "spontaneous retrieval" of intentions [6]. The latter occurs when a target stimulus (e.g. a medication bottle) brings the requisite intention to mind (e.g. taking the pill) without drawing attention from an ongoing task. Retrieving a prospective intention thus frees a person from the need to perform "strategic monitoring" [7], i.e. having to hold the intention in mind and monitoring for the appearance of the target stimulus. Sleep may benefit intention execution even under conditions of divided attention [2, 3], making it useful to facilitate PM retrieval in persons who may be busily engaged in multiple tasks throughout the day.

Thus far, it remains uncertain how sleep accomplishes this because little is known about the sleep features critical for PM and the spontaneous retrieval process sleep appears to subserve. In contrast to the wealth of literature documenting the contribution of slow wave sleep (SWS) to declarative memory consolidation [8], only one recent study has hinted at the importance of this sleep stage in PM [4]. Hence, the aim of the present study was to determine if SWS or other sleep stages could account for the sleep benefits on spontaneous retrieval reported in the literature [2, 3, 6].

We sought to first establish the role of sleep in PM by contrasting PM performance across a 12 h retention interval involving daytime wakefulness or overnight sleep monitored with polysomnography (PSG). In our task, we systematically manipulated the level of spontaneous retrieval enabled by using cue–action pairs that differed in semantic relatedness (e.g. switching on an alarm in response to the cue word "clock" vs closing a book in response to "mirror"). On the basis of the multiprocess theory, compared with the unrelated pairs, the stronger cue–action associations of the related pairs would support a more rapid and reflexive delivery of the action to awareness once the cue is encountered [7].

Given sleep's beneficial effects on spontaneous retrieval, we predicted that the execution of actions that were semantically related to the cues would be better after a period of sleep than wakefulness, whereas no such benefit would be observed for unrelated cue–action pairs. We hypothesized that SWS would facilitate this spontaneous retrieval process.

Methods

Participants

Sixty young adults (mean age ± *SD*: 21.79 ± 1.84; 24 males) took part in this study. They reported no history of chronic medical conditions, psychiatric illnesses, or sleep disorders, consumed <5 caffeinated beverages per day, and did not travel across more than two time zones a month prior to the study. All participants provided informed consent, in compliance with a protocol approved by the National University of Singapore Institutional Review Board.

Participants were randomized into the sleep and the wake groups. An interview was conducted at the end of the experiment to check if any failures to perform the task was due to any misunderstanding of the task instructions. It was discovered that 11 participants had misunderstood the task and were thus excluded from all analyses.

The resulting sample consisted of 49 young adults (mean age ± *SD*: 22.06 ± 1.71 years; 18 males). The sleep (n = 25) and the wake groups (n = 24) did not differ in age, gender distribution, consumption of caffeinated beverages per day, body mass index, level of excessive daytime sleepiness (Epworth Sleepiness Scale [9]), self-reported sleep habits, or subjective sleep quality (global score of the Pittsburg Sleep Quality Index [10]) ($p > 0.10$; Table 1).

Study protocol

In the 3 days preceding the study, participants adhered to their habitual sleep schedule at home. This was verified with wrist actigraphy (Actiwatch 2; Philips Respironics, Murrysville, PA). The two groups did not differ in the duration of time in bed (sleep: 7.91 ± 0.70 h vs wake: 7.50 ± 0.79 h, $t = 1.92$, $p = 0.06$) or total sleep time (TST; sleep: 6.61 ± 0.15 h vs wake: 6.23 ± 0.17 h, $t = 1.66$, $p = 0.11$).

Participants in the sleep group arrived at the laboratory in the evening. The encoding session began at 21:30 and lasted for 20 min, after which participants were given a 9 h sleep opportunity. The next morning, participants who were not already awake were awoken by the experimenter at 08:00. The intention retrieval session started at 09:30, i.e. at least 90 min after waking, to minimize any effect of sleep inertia on memory retrieval.

The wake group came to the laboratory in the morning for the encoding session that began at 09:30. Afterward, they were discharged and allowed to engage in their daily routine, with instructions that consumption of caffeinated food or drink and napping was not permitted (verified with actigraphy). Participants returned for the intention retrieval session that began at 21:30.

At the beginning of the encoding and the retrieval sessions, level of subjective sleepiness was measured. This allowed us to determine whether any difference in PM performance between the sleep and the wake groups could be attributed to different levels of alertness.

Prospective memory task

To approximate an everyday situation of prospective remembering, as in previous studies [6, 11], the PM task was embedded in an ongoing activity. Here, we used a semantic categorization task [6] that consisted of 144 trials. In each trial, a word was presented in lower case to the left on a computer screen, and participants had to determine if it was a member of the category word presented in capital letters to the right (hockey SPORT). For "yes" and "no" answers, participants pressed "1" and

Table 1. Characteristics of the sleep and wake groups

	Sleep		Wake			
	Mean	*SD*	Mean	*SD*	t / χ^2	*p*
n	25	—	24	—	—	—
Age (years)	21.76	1.61	22.38	1.79	1.26	0.21
Gender (number of males)	12	—	6	—	2.79	0.10
Caffeinated drinks per day (cups)	0.96	0.92	0.85	0.68	0.46	0.65
Body mass index (kg/m^2)	21.11	3.17	21.71	3.63	0.62	0.54
Epworth Sleepiness Scale score	5.48	1.92	4.71	2.40	1.25	0.22
Self-reported habitual sleep						
TIB on weekdays (h)	7.76	0.53	7.95	0.74	1.04	0.30
TIB on weekends (h)	8.10	0.74	8.16	0.54	0.30	0.76
TIB on average (h)	7.86	0.46	8.01	0.67	0.94	0.35
TST on weekdays (h)	7.23	0.73	7.26	0.84	0.13	0.90
TST on weekends (h)	7.57	0.65	7.61	0.62	0.22	0.83
TST on average (h)	7.33	0.64	7.36	0.74	0.16	0.87
PSQI global score	2.56	1.56	2.46	1.64	0.22	0.83

TIB = time in bed; TST = total sleep time; PSQI = Pittsburg sleep quality index.

"2" on the keyboard, respectively. Performance was indicated by the proportion of trials correctly responded to. Median reaction time (RT) for these correct trials for each participant was also derived [5].

In the encoding session, after completion of the semantic categorization task, participants were told that researchers had a secondary interest in their ability to remember to perform actions in the future. So far, previous studies have used tasks that have had relatively low demands on associative memory wherein the same action is required for all the cues [5]. However, in everyday life, actions are typically associated with different cues. Thus, the present study sought to increase the ecological validity of the PM task by pairing different cues with different actions that would need to be physically performed. We also manipulated the semantic relatedness of the cue–action pairs by asking participants to remember four semantically related (e.g. switching on an alarm in response to the target word "clock") and four unrelated cue–action pairs (e.g. closing a book in response to "mirror"). Participants were told that the next time they performed the semantic categorization task, on seeing each cue word, they were to press the "Q" key to pause the task and immediately perform the associated action (see Supplementary Material for detailed protocol and lists of pairs). Participants were given 3 min to learn the cue–action pairs. Afterward, they were required to verbally recall the pairs to the experimenter until all were recalled correctly. All participants achieved 100% accuracy on the first recall attempt.

In the retrieval session, instructions for the semantic categorization task were presented again, but no mention of the PM task and cue words was made. Each cue occurred only once and in the same order for all participants. PM performance was quantified by the percentage of cue words correctly responded to within 5 trials of the semantic categorization task. On completion of the task, participants performed a recognition test for the cue words and actions. Accurate recognition performance would preclude the possibility that any failure of PM was driven by the retrospective component of PM, i.e. not executing the action because the content of the intention was forgotten. Lastly, in a final debrief, a short interview was conducted to determine whether participants had fully understood the task's requirements.

Karolinska Sleepiness Scale

Level of subjective sleepiness was evaluated with the Karolinska Sleepiness Scale (KSS [12]). Participants rated their current level of sleepiness on a 9-point Likert scale (1, very alert; 9, very sleepy, great effort to keep awake).

Actigraphy

Sleep patterns were assessed with wrist-worn actigraphy (Actiwatch 2; Philips Respironics Inc., Pittsburgh, PA) for verification of compliance with the self-reported habitual sleep schedule during the 3-day period prior to the study. Temporal resolution was set at 2 min, and data were scored with the Actiware software (version 6.0.2). TST was calculated using a medium sensitivity algorithm, with which an activity count greater than or equal to 40 was defined as waking. Participants also kept a sleep diary during the actigraphically monitored period at home. Bedtimes and wake times were determined by self-reported sleep-wake timing on a sleep diary and the event markers on the actogram.

Polysomnography

Electroencephalographic (EEG) signals during overnight sleep were recorded using a six-channel EEG montage (F3-A2, F4-A1, C3-A2, C4-A1, O1-A2, and O2-A1) according to the 10–20 system. Eye movement and muscle tone were recorded through left and right electrooculographic (EOG) and submental electromyographic (EMG) electrodes that are respectively referenced to A2 and A1. The ground and common reference electrodes were placed at Cz and FPz, respectively.

EEG, EOG, and EMG signals were recorded using a Comet Portable EEG system from Grass Technologies (Astro-Med, Inc., West Warwick, RI). The sampling rate and the storage rate were

800 Hz and 200 Hz, respectively. The low-pass and high-pass filters were set at 35 Hz and 0.3 Hz for the EEG signals and 70 Hz and 10 Hz for the EMG signals. Electrode impedance was kept below 5 kΩ. Sleep staging was performed according to the American Academy of Sleep Medicine criteria [13]. TST and the duration of each sleep stage were derived.

Statistical analyses

All analyses were performed with SPSS 24.0 (IBM, Chicago, IL). To determine if sleep would benefit the execution of PM intentions compared to the wake group, and whether this would be moderated by relatedness of the intention, we performed a repeated measures analysis of variance (ANOVA) for the percentage of PM intentions executed with group (sleep, wake) and relatedness (related, unrelated) as predictors. Group contrasts were tested with independent samples t tests. For the significant group contrast on related cue–action pairs (refer to the Results section for details), to examine whether this facilitatory effect of sleep on spontaneous retrieval remained significant after controlling for the extent of monitoring used by the participants, we conducted an analysis of covariance analysis with both the accuracy and the RT measures from the ongoing task in the retrieval session as covariates.

In addition, Pearson correlational analyses were performed to investigate whether the sleep benefit on performance on the PM task was related to TST and the duration of each sleep stage.

To examine whether groups differed in the use of a monitoring strategy in the retrieval session, which is evidenced by costs to performance on the semantic categorization task in the retrieval session relative to the encoding session, we performed a repeated measures ANOVA for ongoing task accuracy and RT with group (sleep, wake) and session (encoding, retrieval) as predictors. Group contrasts were tested with independent samples t tests, and changes in performance across sessions were tested with paired samples t tests for each group. Also, Pearson correlational analyses were performed to determine whether TST and the duration of each sleep stage would be related to semantic categorization performance in the post-sleep retrieval session.

Finally, a repeated measures ANOVA was conducted to determine if levels of subjective sleepiness varied across the encoding and retrieval sessions and between groups. Independent samples and paired samples t tests were respectively conducted for examining group contrasts in each session, and changes in KSS scores from encoding to retrieval for each group. Pearson correlational analyses were performed to check for any associations between subjective sleepiness and PM performance in the retrieval session.

Results

Prospective memory performance

Although we did not find a significant main effect of relatedness ($F = 0.83$, $p = 0.37$), and the significant main effect of group ($F = 6.33$, $p < 0.05$) seemed to suggest that relative to the wake group the sleep group had better overall performance in the PM task, the significant Group × Relatedness interaction ($F = 8.35$, $p < 0.01$) revealed that the sleep effect differed between semantically related and unrelated cue–action pairs. Specifically, although the sleep group successfully executed a higher percentage of related intentions compared to the wake group (mean ± SEM: 94.00 ± 2.61% vs 66.67 ± 6.84%, $t = 3.79$, $p < 0.001$), there was no significant group difference in the percentage of successfully executed unrelated intentions (82.00 ± 5.10% vs 72.92 ± 6.88%, $t = 1.07$, $p = 0.29$; Figure 1). Notably, the beneficial effect of sleep on related cue–action pairs remained statistically significant even after controlling for the accuracy and speed measures from the ongoing task. This finding points to a significant benefit of sleep on related intentions via spontaneous retrieval regardless of the extent of monitoring (related: $F = 12.49$, $p < 0.001$).

In the recognition test for the cue-action pairs upon completion of the prospective memory task, all participants attained perfect accuracy (100%), indicating that PM failures were not because of participants forgetting the content of the intention.

Relationship between sleep architecture and prospective memory performance

As a sleep benefit was found for related pairs, Pearson correlational analyses were performed to determine the relationship between sleep parameters and the percentage of related intentions executed by the sleep group. We found that participants who had greater amounts of post-learning N3 sleep successfully executed more related intentions ($r = 0.46$, $p < 0.05$, Table 2). Although there was a marginally nonsignificant association between post-learning N2 sleep and the percentage of related intentions executed ($r = -0.34$, $p = 0.09$), whether N2 sleep plays a critical role in PM remains to be examined in future studies with a larger sample size. There were no significant associations with any other sleep parameters ($p > 0.09$).

Semantic categorization task performance

A significant main effect of session was found, indicating that accuracy was poorer ($F = 60.37$, $p < 0.001$; Table 3) and RT was longer ($F = 98.21$, $p < 0.001$) in the retrieval session compared to the encoding session. However, decline in the ongoing task performance did not differ between the two groups as the Group

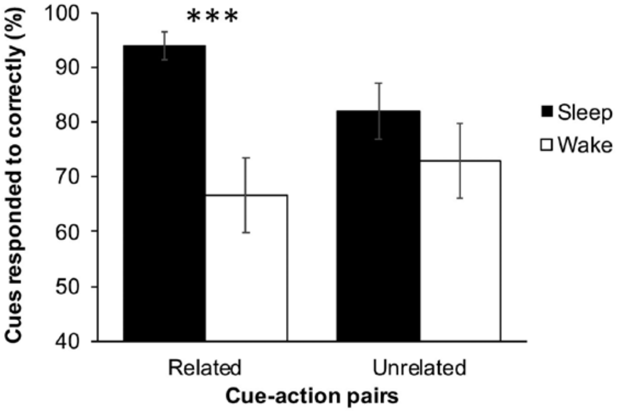

Figure 1. Prospective memory performance after the sleep and the wake retention intervals. Means and standard errors of the mean for the percentages of semantically related and unrelated cue–action pairs successfully executed were plotted for the sleep group (black bars) and the wake group (white bars). ***$p < 0.001$.

× Session interactions were not statistically significant ($F < 1.51$, $p > 0.23$). This suggests that sleep did not modulate the additional resources required to monitor for the cue words in the retrieval relative to the encoding sessions. In addition, no significant associations were found between any sleep parameters and ongoing task measures in the post-sleep retrieval session ($ps > 0.17$; Supplementary Table S1).

Subjective sleepiness

We found no significant main effect of session on KSS scores ($F = 1.66$, $p = 0.20$, Table 3), indicating that levels of sleepiness measured at encoding and retrieval were similar. Further, neither the main effect of group nor the Group × Session interaction was statistically significant ($F = 0.22$, $p = 0.64$; $F = 1.66$, $p = 0.20$): the two groups did not differ in KSS scores assessed at either the encoding ($t = 1.00$, $p = 0.32$) or retrieval session ($t = 0.13$, $p = 0.90$). In addition, there were no significant correlations between subjective sleepiness measured at the retrieval session and the number of related (sleep: $r = -0.18$, $p = 0.38$, wake: $r = -0.01$, $p = 0.96$) and unrelated intentions executed (sleep: $r = -0.13$, $p = 0.54$, wake: $r = 0.13$, $p = 0.54$).

Discussion

In this study, we contrasted PM performance following a period of daytime wakefulness and nocturnal sleep with PSG monitoring. We found that sleep preferentially facilitated the execution of actions that had preexisting associations with the cue words, highlighting the beneficial effects of sleep on spontaneous retrieval processes in PM. Critically, this sleep-related benefit was positively associated with the duration of SWS obtained during the post-learning period. Notably, 21.2% of the variance of this sleep benefit was explained by the duration of post-learning SWS ($r = 0.46$).

The present findings dovetail with an earlier study by Diekelmann *et al.* [4] showing that PM performance was better after sleeping in the first half of the night, when SWS is abundant, as compared to sleeping in the second half of the night which is rich in rapid eye movement (REM) sleep. Together, both findings support a facilitatory role for SWS in PM.

How might sleep have promoted the spontaneous retrieval of related intentions? It is well known that SWS promotes the strengthening of declarative memory through memory replay alongside increased neural network efficiency by synaptic downscaling [14–16]. Also, recently encoded memoranda can be more effectively consolidated during sleep if they are associated with prior knowledge [17, 18]. Here, sleep preferentially enhanced retrieval of cue–action pairs that were already part of existing “action schemas”. Action schemas in PM have been previously alluded to by a number of researchers [19–21]. As with knowledge schemas, action schemas guide expectations surrounding cue objects. Such preexisting associations within related intentions are likely to have been preferentially processed during sleep, increasing their level of resting activation [22]. Hence, on encountering a cue word at test, a lower threshold would be required for detection and subsequent reflexive delivery of the action to awareness.

Notably, the beneficial effect of sleep could not be attributed to greater monitoring effort by the sleep group. In the ongoing task, accuracy reduced and RT increased from encoding to retrieval in both groups, indicating that additional resources were used to monitor for the cue words in both groups. Critically, given that the changes in these ongoing task measures were similar between the sleep and wake groups, there was little evidence that sleep modulated the monitoring strategies involved in PM.

Moreover, the sleep benefit on PM could not be attributed to the reduction of sleepiness as subjective sleepiness did not significantly differ between the groups at encoding or retrieval.

Table 2. Means and *SD*s of sleep architecture and Pearson correlations with performance for related intentions in the prospective memory task

	Mean ± SD	*r*	*p*
Total sleep time (min)	486.9 ± 33.0	0.18	0.39
N1 (min)	35.2 ± 20.8	0.07	0.75
N2 (min)	280.0 ± 39.0	−0.34	0.09
N3 (min)	67.8 ± 26.0	0.46	<0.05
Rapid eye movement sleep (min)	103.9 ± 30.1	−0.09	0.68

Table 3. Performance for the semantic categorization task and levels of subjective sleepiness for the sleep and wake groups

	Encoding		Retrieval			
	Mean	SEM	Mean	SEM	*t*	*p*
Accuracy (%)						
Sleep group	93.22	0.68	90.06	0.70	6.47	<0.001
Wake group	91.81	0.94	87.59	1.16	5.11	<0.001
	$t = 1.23$, $p = 0.23$		$t = 1.85$, $p = 0.07$			
Median reaction time (ms)						
Sleep group	1119	50	1498	68	9.66	<0.001
Wake group	1183	60	1479	81	5.25	<0.001
	$t = 0.83$, $p = 0.41$		$t = 0.18$, $p = 0.86$			
KSS scores						
Sleep group	3.24	0.18	2.92	0.22	1.77	0.09
Wake group	2.96	0.22	2.96	0.19	0.00	>0.99
	$t = 1.00$, $p = 0.32$		$t = 0.13$, $p = 0.90$			

SEM = standard error of the mean; KSS = Karolinska Sleepiness Scale; *t* values were derived from paired or independent samples *t* tests.

In addition, there was no significant correlation between subjective sleepiness and PM performance. Finally, any failure to execute unrelated intentions was unlikely to be due to the inability to retrieve the content of the intention because all participants attained perfect scores on the recognition test at the end of the retrieval session.

Our finding that sleep benefits *related but not unrelated pairs* points to the specific role of sleep in facilitating spontaneous retrieval processes in a PM task. Thus, to maximize the benefit of sleep, one should select cues that build on preexisting cue–action associations to initiate intentions. As sleep facilitates spontaneous retrieval processes that enable the associated action to be delivered to consciousness with little cognitive resources once the cue is encountered, this holds promise for individuals who may be busily engaged with numerous tasks throughout the day.

Limitations and future studies

In this study, the sleep and wake groups were tested at different times of day, and we did not include a circadian control group. However, as previous studies have found no time of day effect on PM [23], and we did not find any significant group difference in the level of subjective sleepiness at either encoding or retrieval, it is unlikely there was significant circadian influence on the observed benefits.

Although we focused our investigation on a young adult sample and conclusions regarding other age groups remain to be studied, given that SWS is reduced with aging [24], it is possible that age-related sleep changes may account for the poorer PM documented in older adults [25]. Moreover, although we did not find any significant associations between REM sleep and intention execution, it is possible that REM sleep may play a more prominent role in PM in older adults who face age-related reductions in SWS and have compensatory increases in REM sleep [26], because REM sleep may be important for memories that have future relevance [27].

In addition, the present correlational design used to examine the association between SWS and related intentions in PM precludes conclusions regarding causality. Future studies should seek to further address the role of SWS on PM through the systematic manipulation of SWS.

Finally, to confirm that spontaneous retrieval processes is the major contributor to sleep-related improvement of PM retrieval, future research might consider using tasks or conditions that discourage monitoring [28], e.g. presenting the target only after many trials of the ongoing task [29], or having focal PM targets [23, 30].

Conclusions

Sleep facilitated spontaneous processes at retrieval and preferentially benefitted the execution of intentions involving a semantically related cue. This effect of sleep was associated with more time spent in SWS during the post-learning sleep episode. These findings are in line with PM impairment observed in individuals with little SWS, e.g. older adults [25, 31], and point to the potential memory benefit of interventions boosting this sleep feature.

Supplementary Material

Supplementary material is available at *SLEEP* online.

Funding

This work was supported by the National Medical Research Council, Singapore (NMRC/STaR/0004/2008 and NMRC/STaR/015/2013) awarded to M.W.L.C. and the National Research Foundation, Singapore (NRF2016_SOL002).

Conflict of interest statement. None declared.

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