Comparing different sleep diaries with activity tracker data

Master thesis

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Abstract

Insomnia is one of the most prevalent sleep disorders, and can have serious mental and physical consequences. Through recent technological and societal developments, new sleep monitoring and treatment methods such as the use of mobile applications are on the rise. As this field is relatively new, this present study aims to compare and evaluate 1) a standardized sleep diary (CSD), 2) a mobile application diary with 3) activity tracker data to assess the which one is best suited for use in a mobile setting. Fifteen participants completed each diary for four nights while simultaneously wearing an activity tracker. The findings suggest that both diaries are good at assessing total sleep time, but are inconsistent on other parameters. Nevertheless, we conclude that the CSD performed the best in this scenario. A user experience questionnaire showed that the mobile application diary was rated considerably better and than the CSD however, and so it seems to be well suited for its intended purpose.

Introduction

Although sleep and sleep behavior have been studied since as early as 1818 (Steinberg & Hergerl, 2014), there has been an increase in sleep research in recent years. While this could be attributed to advancements in research methods, a more pressing issue is that more and more people report trouble sleeping. While sleep studies have long relied on self-report scales to asses sleep quality, the rise of mobile technology has opened up new possibilities to measure sleep. Here we introduce an experiment comparing different instruments to asses sleep behavior.

Sleep is characterized by a lowered state of consciousness, inhibition of voluntary muscle activity and irresponsiveness to outside stimuli (Kalat, 2009). While sleeping, sleep progresses through three increasingly deeper stages before reversing and ultimately entering a special (REM, Rapid Eye Movement) sleep stage. It is during this phase that dreaming occurs most frequently, but dreaming is not exclusive to REM sleep (Dement & Kleinmann, 1957; Solms, 2000). Together the subsequent phases form a sleep cycle. This pattern is then repeated, whereby each cycle decreases in duration, until waking up. During non-REM sleep (NREM, stages 1-3), heart rate slows, body temperature drops and the body regenerates. During stage 3 sleep is very deep; the brain produces delta waves and it is often hard to wake someone in these stages (Carskadon & Dement, 2000).

Although some aspects of sleep are still unclear, it is certain that it is an essential process for mental and physical health. Thus, it seems logical that a lack of sleep result in a reduction on said factors. This is indeed the case, as sleep deprivation (whatever the cause) can cause serious impairments in cognitive and physical functioning. Depending on the degree, sleep deprivation can result in a less effective immune system, slower wound healing and an overall reduction in physical regeneration (Guo & DiPetro, 2010). These symptoms support the hypothesis that sleep is important in restoration. Mentally, a lack of sleep can result in directly impairing high level cognitive processes (Léger et al., 2010; Roth, 2007) or indirectly, by impairing the important low level processes on which higher ones rely (Trujilo, Kornguth & Schnyer, 2009). Roth (2007) shows that this can lead to even more serious consequences as they increase the risk of having an accident. Sleep deprivation also seems to have an effect on memory preservation, although this is still up for debate (Vertes & Siegel, 2005; Walker, 2008).

Lastly, recently there has been some discussion on whether sleeping problems are related to problems with emotional processing. In a study conducted by Wassing et al. (2016), researchers investigated the effects of restless-REM sleep on REM sleep quality, as it is known that REM sleep is important in emotional processing (van der Helm et al., 2011; Wagner, Gais & Born, 2001). They found that restless-REM sleep (which frequently occurs in insomnia) interfered with the overnight processing of emotional distress, which could result in the accumulation of stress and in turn hyper arousal, a very prevalent symptom of insomnia.

Things get more serious when sleep debt increases or when problems with sleeping become chronic. By far the most common sleeping disorder is insomnia, which is characterized by chronic problems with falling asleep and/or periods of wakefulness (Kyle, Morgan & Espie, 2010; Roth, 2007). Alarmingly, an increasing amount of people report problems with sleeping (Beun, 2013). As many as 10-15% of adults suffer from insomnia. Reasons for the increasing number of cases are unclear, although it is speculated that changes in our society could be possibly be responsible for some of the problems (Demirci, Akgönül, Akpinar, 2015; Thomée, Härenstam & Hagberg, 2011). Electrical lights, a rapid increase in (handheld) electronical devices and changing social / practical demands make it possible to work in environments which were previously unsuitable. Staring at screens, which emit light, is major factor in said argument as light stimulates the brain and reduces the secretion of the sleep hormone melatonin (Thomée, Härenstam & Hagberg, 2011).

Measuring sleep

Sleep disorders, when left untreated, can have serious consequences to the mental and physical wellbeing of an individual. Thus, the primary objective in the treatment of sleeping disorders is to reduce or possibly remove the problem entirely. To provide the best possible treatment to a sleeping disorder, a patients sleep behavior must first be assessed. Sleep quality is a common term in diagnosing sleeping problems, but its definition is sometimes unclear (Krystal & Edinger, 2008). While it seems to imply a subjective level of overall sleep satisfaction, the term is also used as an umbrella term for other factors such as: Sleep Onset Latency (SOL), Total Sleep Time (TST) and sleep efficiency (SE; time spent in bed actually sleeping). This may be undesirable however, as several studies have shown that the amount and timing op sleep does not fully explain the problems that people often report in clinical treatment (Carskadon et al., 1976; Krystal, Edinger, Wohlgemuth & Marsh, 2002). It is therefore important to determine all the factors, which contribute to subpar sleeping experiences.

The most common way of assessing sleep behavior is through the use of self report questionnaires (Spruyt & Gozal, 2011). While these can (and often do) include items on sleep/wake duration, the main benefit is the addition of subjective insight. Patients are asked to rate their sleep and provide details on the experience of the previous night. A downside to the use of these questionnaires is that, sleep questionnaires are far les numerous than questionnaires on day-time processes (Spruyt & Gozal, 2011), and are also less standardized (Buysse, Ancoli-Israel, Edinger, Lichtstein & Morin, 2006). As a response, the Pittsburg Sleep Quality Index (PSQI) was developed in 1988 as a faster, more consistent way to examine sleep behavior, and has proven to be a valid and reliable instrument (Buysse et al., 1989; Mollayeva et al., 2015). However, it is an assessment questionnaire - designed to determine sleep quality over a period of 1 month. Sleep diaries, which can give valuable day-to-day insights in patients sleeping patterns, still lacked a standardized variant. (Buysse et al., 2006). The need for a standardized variant rose from the inability to compare and integrate results from previous studies due to differences in diaries (Buysse et al., 2006; Morin, 2003). That changed in 2012, when researchers compiled the Consensus Sleep Diary (CSD), which has become the de-facto sleep diary in sleep research (Carney et al., 2012).

While these developments were a big improvement over the previous situation, it is important to realize that neither instrument can be used on its own. The authors of the CSD also recognize this, and advice the use of a diary in conjunction with other instruments (Carney et al., 2012). Because diaries and other self-report scales are by definition subjective, a more objective instrument is preferred. In the field of objective instruments, polysomnography (PSG) is still viewed as the golden standard (Lockley, Skene & Arendt, 1999; Martoni, Bayon, Elbaz & Léger, 2011). By directly recording brain activity it is possible to get a detailed insight in a patients sleep behavior. The downsides are also clear; it is expensive, cumbersome and the ecological validity is debatable (Martoni et al., 2011). While it remains a highly valuable tool, especially in more severe cases, other instruments are on the rise.

One such instrument is the actigraph (or activity tracker); a method of measuring human activity and it is used more and more in sleep research (Sadeh, 2011). Users wear a wrist-watch like device on their non-dominant arm for a prolonged period (ideally 1-2 weeks). Typically, such a device records movement using an accelerometer, like most phones have, to determine their rotation. This data can then be processed using algorithms to estimate activity. A big advantage in using this method is that patients can be monitored around the clock, while other sleep measuring instruments usually only record night time activity. Studies have shown that activities and day-time behavior affect sleep behavior (Wolfson & Carskadon, 1998), and while actigraphs are not fully featured health trackers, they provide at least some insight. Another obvious benefit is comfort: especially compared to a PSG, where electrodes are attached to the patient's head resulting in an uncomfortable sleeping position, an actigraph is an unobtrusive measuring instrument (Haakma & Beun, 2012). Furthermore, the technology and manufacturing processes have 'matured', thereby increasing the availability and the cost effectiveness of the device (Ancoli-Israel et al., 2003; Sadeh, Hauri, Kripke & Lavie, 1995).

Today, actigraphy is mostly used in diagnosing and treating patients with sleep disorders such as insomnia (Sadeh, 2011). When using the instrument in a clinical setting however, it is important to realize the strengths and weaknesses of the device. While the practical advantages described above are clear, the measuring advantages are sometimes less so. For instance, a big advantage of actigraphy is that is usually very precise in determining sleep duration (TST), periods of wakefulness and differences in sleep behavior from night to night (Ancoli-Israel et al., 2003; Martoni et al., 2012; Sadeh, 2011). However, it also highlights an inherent problem with actigraphy: sleep is not measured directly, but via accelerometers that activate with limb movement. And when you consider that most people who suffer from insomnia do not move when they are awake at night, the possibility of incorrect measurements increases (Haakma & Beun, 2012; Martoni et al., 2012; Sadeh, 2011). While this notion must certainly be taken into account, modern actigraphs and scoring algorithms are more advanced than earlier models and are more resilient to such errors (Sadeh et al., 1995; Martoni et al. 2012). Another problem to the indirect nature of actigraphy is hard to spot nuances in movement using actigraphy; carrying a heavy box will probably fail to show up on the results (Welk, 2002). Other scientists argue that the raw results (counts) often reported in studies are hard to interpret (Murphy, 2008). Nevertheless, studies have shown that the use of actigraphy can facilitate the diagnosing and treatment of people who suffer from the effects of insomnia (e.g. Lichtstein et al., 2006; Martoni et al., 2012). This is especially true due to the fact that self-report questionnaires used to assess sleep behavior are not very accurate in determining certain important characteristics. For example, Van der Berg et al. (2010) showed that estimated patient TST differed from actigraph measured TST by approximately one hour. In another study TST estimated in sleep diaries were compared to PSG TST, and the results showed that diaries underestimated TST (Vaillières & Morin, 2003). Furthermore, while actigraphy is quite effective in assessing sleep behavior in people who suffer from sleep disorders, it works better still in 'healthy' subjects (Morgenthaler et al., 2007; Sadeh & Acebo, 2002).

All in all, it can be concluded that actigraphy is an effective method to assess sleep behavior. While there are obvious benefits, there are also inherent disadvantages. However, when used properly and with awareness of its limitation, problems should be avoidable.

Present Study

In the previous sections, we explored and reviewed the state of two key forms of measuring sleep. As we saw, measurement instruments improved over the years, and will continue to do so in the future. But just as measurement instruments evolve through the use of modern technologies, so do treatment therapies. Insomnia is still often treated with medication, and are usually very effective even though the downsides are apparent and well documented (e.g. Holbrook, Crowther, Lotter, Cheng & King, 2000). Cognitive Behavioral Therapies (CBT/CBT-Insomnia) were developed to provide alternative methods of treating insomnia, and studies suggest it is just as effective as medication with the added benefit that the effects seem to last well beyond the treatment period (Edinger et al., 2001; Sivertsen et al., 2011). While CBT-I treatments were sometimes self-administered through the use of books or videos, their effect is sometimes limited by a lack of personalization (Beun, 2013). Today, everybody has a smartphone, potentially opening up a new platform for treatment. Virtual sleep coaches are being developed, which feature a more personal approach and can immediately integrate results acquired through sleep diaries. And while there has been a lot of research on the quality of sleep diaries, the upcoming prospect of the mobile market opens up room for further study. Thus, this experiment aims to compare a sleep diary which can be used in a mobile setting with different, established instruments. We are especially interested in which instrument(s), or combination of, could potentially be used in new forms of treatment like virtual coaches. Three instruments will be compared: 1) the consensus sleep diary - core, 2) a custom, mobile application diary and 3) an actigraph/activity tracker. An actigraph will be used as the objective measurement instrument, as it follows the shift to a more personal, mobile form of insomnia treatment.

The primary objective is not to asses the diagnostic-capabilities of the instruments per se, but to examine how they compare to one another. As such, we can establish several parameters measured by all instruments on which they will be compared: total sleep time, sleep efficiency, wake after sleep onset and sleep onset latency. These sleep parameters can be calculated from each instrument and will be compared with one another. Sleep quality (scored with a grade, 1-10) will also be examined, and while an actigraph is unable to record subjective data, it is possible to determine if the activity data supports the subjective value reported in the diary. As there has been plenty of research on two out of three instruments, it is expected that results will be similar to earlier studies (e.g. Martoni et al., 2012; Van den Berg et al., 2010): participants will underestimate their sleep efficiency and total sleep time on the diaries compared to the actigraph data. However, it is likely that this effect will be smaller than in the mentioned studies, as they were largely conducted on participants that suffered from sleep disorders. Thus, we hypothesize that in line with previous studies, the 'positive' sleep parameters (TST & SE) correlate positively with sleep quality. Second, a negative correlation is expected between the 'negative' sleep parameters (SOL & WASO) and sleep quality. Third, it is expected that the sleep parameters of both diaries will match the same parameters of the actigraph data. This seems logical as essentially they should be measuring the same thing at the same time. As there is a focus on the viability of using one of the instruments in a new treatment method, a more specific question rises as to which one has the least amount of variation. Thus, fourth, we expect that the actigraph will be the most consistent instrument, while the CSD and the mobile application diary will be relatively equal in this part. Fifth and lastly, the usability of the two diaries will be assessed via a small questionnaire, where it is expected that the mobile application will have an edge on the more traditional CSD.

Methods

Participants

In total, fifteen people (nine men and six women) between the ages of 20 and 63 (M = 26.6; SD = 10.4) voluntarily participated in the experiment. One participant was the author (JdK). The remaining participants were recruited via social media and via the Utrecht University SONA study recruitment website. Eligible participants (bachelor students) received compensation in the form of 2 study participation credits. No corresponding financial compensation was available for others, but a gift voucher worth €20, - was randomly allotted to one of the participants. There were no selection criteria other than the minimum age of 18 years and the required possession of a smartphone running Google's Android operating system. Furthermore, the nature of the experiment did not require special sleep behavior.

Measurement instruments

Two different sleep diaries were used for the experiment. The first one was the core version of the dNCS (Dutch digital consensus sleep diary) which is derived and translated, by panel of Dutch sleep experts working with various forms of digital technology, from the original consensus sleep diary (CSD) developed by experts at the Pittsburgh conference (Carney et al., 2012). The diary was replicated using Google Forms, taking care to represent the original version as close as possible. An example the version used in the experiment can be found in appendix A.

The second diary was a mobile application derived from an upcoming virtual sleep coach currently in development at Utrecht University. As it was developed for Google's Android operating system (OS), participants were required to have a smartphone running said OS. Essentially, it is a more modern representation of the CSD resulting in roughly the same information while using alternate ways to input data. An example of this can be seen in figure 1, where the CSD is compared to the mobile application.

Actigraphy was the third measurement method in the experiment, and the model used was the 'GENEActiv Original' (ActivInsights Ltd., Kimbolton, UK) activity tracker. They were chosen because of their availability, ease of use and relatively moderate financial cost. Aside from recording motion it also stores ambient light and temperature values. However, these measurements were of no use to the experiment and were discarded for the current analysis. The Geneactiv recorder was set to record at a frequency of 30Hz for a total of 21 days – more than enough for the duration of this study.

Usability, or user experience, was assessed with a small 10 item questionnaire, which was scored on a 5-point likert scale. It can be found (in Dutch) in appendix B. For the purpose of not giving one diary an advantage by always being the first one in a measuring period, all participants were randomly assigned to a 'condition'. One half completed the CSD diary in the first period and the app diary in the second; the order was turned around for the other half of the participants.

Procedure

To avoid confusion and interference when using two diaries simultaneously, the experiment was divided into two separate phases. During each phase, participants wore an actigraph day and night for four days, while also completing a sleep diary every morning. The two phases were separated by an 'off day'. Thus, the experiment totaled 2 phases x 4 days + 1 'off day' = 9 days of testing. Participants were instructed to wear the actigraph as often as possible, except when showering/bathing, during high intensity sports (boxing etc.), and during the 'off day'.

Participants made a separate appointment with the author for a first meeting, where they were briefed on the purpose of the experiment and received an actigraph. They also received instructions on how to properly wear and maintain the device, install the application, and how to complete both diaries. All the necessary instructions were also made available as a handout (see appendix C). The participants were free to start at any moment after the first meeting. After about two weeks, most participants were finished with the measuring period and were ready for the final meeting where they were debriefed and completed a small usability questionnaire.

Data conversion

Data processing was a necessary step before the actual analysis could begin. Raw mobile application diary data was extracted using Matlab r2015b and r2016a in conjunction with the JSONlab extension. Next, sleep parameters for both the CSD and the app were calculated. For on overview of the sleep parameters used, refer to table 1.

Table 1
All sleep parameters used in the experiment and how they are calculated.

TST (total sleep time)	Total time (minutes) between sleep onset time and final wake time – time spent not asleep
SE (sleep efficiency)	TST divided by analysis period (period between trying to fall asleep and final wake time) * 100%
SOL (sleep onset latency)	Time (in minutes) from trying to fall asleep to sleep onset time
WASO (wake after sleep onset	Total time (in minutes) spent not asleep between sleep onset time and final wake time

The actigraph data was processed using Matlab r2015b and the Actant sleep analysis toolbox (te Lindert & van Someren, 2013). As the sleep diaries were not used concurrently, they could not be directly compared to one another. Thus, they were compared with their respective activity tracker data. After data extraction and initial processing, it became clear that the actigraph data did not reliably produce the expected results: if a participant recorded 4 days, only 3 would show up. This is probably the result of participant not wearing the device all day, or other misuse of the device. Thus, it was decided that diary data, which could not be matched with activity tracker data was excluded from further analysis. Ultimately, this meant that around 30% of the data gathered by actigraphy was unusable. To prevent unnecessary reduction in statistical power, all data from one instrument (diary + actigraph data) was pooled over participants into one dataset. This was done for both instruments, which led to two definitive datasets ready for final analysis (the consensus sleep diary, 39 nights and mobile application diary, 43 nights).

Results

The consensus sleep diary and the mobile application diary were compared on four sleep parameters with simultaneously recorded activity tracker data. An overview of the parameters can be seen in table 2. One of the objectives was to determine if one instrument was more consistent. It seems that the actigraph and the mobile application are the most consistent instruments, with similar variation across the measuring periods. This is especially true for the actigraph, as the standard error and standard variations are closely matched across the two phases - suggesting it is both accurate and consistent.

Table 2

An overview of the sleep parameters derived from both the consensus sleep diary (top half, N= 39) and the mobile application (bottom half, N = 43) with mean, standard error and standard deviation. Acronyms: SCD = consensus sleep diary. App = mobile application. TST = total sleep time in minutes; actual time slept. SE = Sleep efficiency (%); calculated as TST / analysis period (period between lights out time and final wake time). WASO = Wake After Sleep Onset; total time not asleep after sleep onset in minutes. SOL = Sleep Onset Latency; time in minutes. Sleep quality = score 1-10.

	Mean		Std. Deviation
Consensus sleep diary	Statistic	Std. Error	Statistic
TST csd (min.)	428.59	15.91	99.36
TST acti (min.)	402.86	11.61	72.51
SE csd (%)	90.95	1.73	10.81
SE acti (%)	86.92	0.84	5.27
WASO csd (min.)	13.46	3.75	23.43
WASO acti (min.)	32.74	2.22	13.89
SOL csd (min.)	23.85	5.28	33.00
SOL acti (min.)	18.05	2.69	16.77
SCD sleep quality	7.13	0.31	1.94
Mobile application diary			
TST app (min.)	455.56	11.35	74.42
TST acti (min.)	421.44	11.42	74.90
SE app (%)	94.60	0.69	4.50
SE acti (%)	87.74	0.78	5.08
WASO app (min.)	18.14	3.10	20.33
WASO acti (min.)	31.97	1.94	12.70
SOL app (min.)	7.67	2.25	14.77
SOL acti (min.)	11.69	2.50	16.38
App sleep quality	6.77	0.17	1.13

To assess the size and the direction of the relationship between the sleep parameters and the measuring instruments, a bivariate Pearson's correlation coefficient was calculated. The coefficients for the consensus sleep diary are shown in table 3. In concurrence with what was hypothesized, the sleep parameters from the CSD all correlate moderately to strongly with their respective actigraph counterparts: TST ($r_{(39)}$ = .706, p <.001); SE ($r_{(39)}$ = -.360, p = .024); WASO ($r_{(39)}$ = -.327, p = .042) and SOL ($r_{(39)}$ = -.333, p = .038). The expected negative relation between sleep quality and the 'negative' sleep parameters (WASO & SOL) was found partially, with $WASO_{acti}$ - $r_{(39)}$ = -.326, p = .043 and SOL_{csd} - $r_{(39)}$ = -.375, p = .019 showing a moderate coefficient in the expected direction. Sleep quality with SOL_{acti} - $r_{(39)}$ = .325, p = .044 is an effect in an unexpected direction, and the expected sleep quality/$WASO_{csd}$ coefficient was not found at all. The same is true for the 'positive' sleep parameters, all of which showed no correlation with sleep quality.

Table 3

Pearson r correlation coefficients for the sleep parameters derived from the consensus sleep diary crossed with those derived from activity tracker data (N=39). ***Bold*** *coefficients highlight statistically significant results. Acronyms: csd = consensus sleep diary. Acti = activity tracker parameter. TST = Total Sleep Time. SE = Sleep efficiency; calculated as TST / analysis period (period between lights out time and final wake time). WASO = Wake After Sleep Onset, SOL = Sleep Onset Latency.*

Pearson *r* correlation matrix consensus sleep diary

		1	2	3	4	5	6	7	8	9
1	*TST csd*	-								
2	*TST acti*	**.706****	-							
3	*SE csd*	**.812****	**.392***	-						
4	*SE acti*	-0.225	**.339***	**-.360***	-					
5	*WASO csd*	**-.508****	-0.276	**-.613****	0.215	-				
6	*WASO acti*	**.347***	0.121	**.409****	**-.597****	**-.327***	-			
7	*SOL csd*	**-.501****	-0.129	**-.685****	0.283	-0.117	-0.217	-		
8	*SOL acti*	0.186	-0.122	0.279	**-.535****	0.020	-0.068	**-.333***	-	
9	*SCD sleepquality*	0.303	0.185	0.198	0.059	0.150	**-.326***	**-.375***	**.325***	-

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Correlation coefficients for the mobile application diary are shown in table 4. Of the expected relation between the sleep parameters of the mobile application and their corresponding actigraph counterparts, only TST was found to correlate $r_{(43)}$ = .912, p = <.001; the rest (SE, WASO and SOL) did not. The expected positive relation between the 'positive' parameters and sleep quality was found partially, with TST_{acti} - $r_{(43)}$ = .316, p = .039 and SE_{acti} - $r_{(39)}$ = .383, p = .011 correlating moderately. Again, no relationship was found between the ‘negative’ sleep parameters and sleep quality. Note that in tables 2 and 3, there are correlation coefficients, which were not mentioned as they were of no interest to the purpose of the experiment; it makes sense that an increase in sleep onset latency results in a decrease in total sleep time.

Table 4

Pearson r correlation coefficients for the sleep parameters derived from the mobile application crossed with those derived from activity tracker data (N=43). ***Bold*** *coefficients highlight statistically significant results. Acronyms: app = mobile application parameter, Acti = activity tracker parameter, TST = Total Sleep Time, SE = Sleep efficiency (calculated as TST/analysis period*100%), WASO = Wake After Sleep Onset, SOL = Sleep Onset Latency.*

Pearson *r* correlation matrix mobile application

		1	2	3	4	5	6	7	8	9
1	*TST app*	-								
2	*TST acti*	**.912****	-							
3	*SE app*	**.335***	0.069	-						
4	*SE acti*	0.098	**.369***	0.107	-					
5	*WASO app*	0.160	**.388***	**-.666****	0.124	-				
6	*WASO acti*	**.444****	**.360***	-0.054	-0.295	0.128	-			
7	*SOL app*	**-.350***	-0.281	**-.497****	-0.281	-0.261	0.059	-		
8	*SOL acti*	0.061	-0.124	-0.081	**-.604****	0.199	-0.069	-0.137	-	
9	*App sleepquality*	0.206	**.316***	0.070	**.383***	0.141	-0.164	-0.233	-0.095	-

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

Lastly, the usability of both diaries was assessed with a small questionnaire. Ease of use, time taken, convenience, completeness and overall satisfaction were scored for each diary with a five point likert scale. Category four, which assessed the completeness of each diary by questioning if the participant would have liked to enter more information, was reverse scored so as that in all categories a higher score means a better performance. As seen in table 5, the mobile application diary had a slight edge over the sleep consensus diary, as it scored higher in all categories bar one, ‘completeness’.

Table 5

Results from the usability questionnaire (N=15). Participants scored 5 categories on a 5-point likert scale. A higher score corresponds with a better result. The full questionnaire (in Dutch) can be found in appendix B. Note that category 4 "completeness" was reversed scored to properly represent the correct answer.

	Consensus sleep diary		Mobile application diary	
	Mean	Std. Deviation	Mean	Std. Deviation
Ease of use	3.50	1.16	4.14	0.66
Time taken	4.21	1.05	4.71	0.47
Convenience	3.21	0.97	4.00	0.88
Completeness	2.50	1.34	2.29	1.33
Overall satisfaction	3.43	1.02	4.21	0.70

Discussion

Sleep research has traditionally been based around the collection of data through the usage of self-report sleep diaries. However, there were also difficulties in integrating the results of different studies as no standardized version was present for quite some time (e.g. Buysse et al., 1989; Buysse et al., 2006; Mollayeva et al., 2015; Morin, 2003; Spruyt & Gozal, 2011). This changed with the development of the consensus sleep diary, which has become the de-facto sleep diary in the scientific community (Carney et al., 2012). Even more recently, advancements in technology have resulted in new ways of measuring sleep such as the use of computers, phones and tablets in a more personal treatment of patients and a variety of health trackers which enable researchers to unobtrusively monitor sleep with increasing accuracy. As the usage of mobile technology in the treatment of insomnia and other sleep disorders will only increase in the coming years, it is desirable to select the instruments which are best suited for this new era of sleep research.

In this present study we compared two sleep diaries with actigraph data. A key point of interest was to see if the sleep parameters derived from the diaries matched those of the actigraph, as it would support their accuracy. The expected effects were found to some extent. Regarding the consensus sleep diary, all parameters (TST, SE WASO & SOL) show moderate to strong correlation with their actigraph counterparts. While TST showed a positive relationship, SE, WASO and SOL all have negative correlation coefficients. This suggests that compared to activity tracker data, participants tend to over- and underestimate these respective parameters. While this could certainly be the case as it is a common trend seen in sleep research (Backhaus, Junghans, Broocks, Briecks & Hohagen, 2002), another explanation would be that actigraphy is not the best instrument in detecting wakefulness (e.g. Haakman & Beun, 2012; Martoni et al., 2012; Kushida et al., 2001; Sadeh, 2011).

The results of the mobile application diary also show unexpected results: SE, WASO and SOL show no correlation whatsoever to their respective actigraph sleep parameters. While this could be due to the same reasons as mentioned above, it is more likely that another factor contributes to these effects. An inspection of the raw dataset reveals that participants often failed to report their WASO and SOL in their sleep diary. While this may occur occasionally, it is highly unlikely that anyone falls asleep instantly. The reason why many participants reported no WASO and SOL times are unclear. A lack of motivation, both intrinsic (the participants were not trying to improve their bad sleep behavior) and extrinsic (no compensation) is quite possible.

However, both diaries correlate highly with actigraph data on TST, supporting the earlier notion that actigraphs are good at detecting states of sleep (Kushida et al., 2011) and suggesting that both the consensus sleep diary and the mobile application diary are well suited for assessing total sleep time. Thus, the first hypothesis can be confirmed, albeit for TST only.

Regarding the expected effects of the ‘positive’ and ‘negative’ sleep parameters, both diaries again show mixed results. Inconsistent correlation coefficients lead to the rejection of the second and third hypotheses. Sleep quality, except for a moderate negative relationship between SOL and CSD sleep quality, shows almost no connection with the sleep parameters in both diaries whereas the actigraph data does show some. CSD sleep quality moderately correlates with actrigraph estimated WASO and SOL, and app sleep quality shows a moderate correlation with actigraph estimated TST and SE, with all relationships following the expected direction. While it is known that time spent sleeping does not always contribute to sleep quality (Carskadon et al., 1976; Krystal et al., 2002) it is likely that these effects (or lack of) are the result of the same problems (participants failing to report WASO and SOL) described above, as they originate from the same raw data. It is also a possibility that sleep diaries, compared to actigraphy, are simply less adequate in assessing subjective sleep quality.

Another point of interest was which one of the instruments was best suited for use in the new mobile market. For example, some developers are interested in whether actigraphy could be used as an additional instrument besides their dedicated application. In this case, a consistent instrument would be best suited as it should deliver the least variation during a measurement period. As expected, the actigraph was the most consistent instrument throughout the measuring period. However, it is debatable if an actigraph would be of added benefit to treatment methods using mobile applications. As seen and discussed above, actigraphy is well suited to assess TST. However, the mobile application diary was about as accurate. When TST is the parameter of primary interest to the application-developer, and taking into account that actigraphy is less accurate in capturing wakefulness together with the fact that in a professional setting, users probably suffer some form of sleep disorder, and with the added financial and logistical costs of supplying patients with an actigraph it is hard to recommend using the device as an additional instrument, especially since it slightly defeats the purpose of having a accesible, easy to use personal treatment method that is achieved with having a mobile application.

The results of the user experience questionnaire suggest that the app was preferred by the majority of the participants, consistently getting higher scores. This follows the trend of the modern society moving to the digital age. A slightly negative side effect of this trend also surfaced, as some of the older participants reported they had slightly more difficulty with the app than the traditional consensus sleep diary. As often more older than young people report problems with sleeping, developers should keep this in mind when designing their applications.

There were a few factors, which probably contributed to the results seen above. Participants did not always adhere to the instructions they were given. For example, while the instructions were clear in the regard that all the nights of one study phase (4 nights) should be completed in succession, inspection of the data revealed that many did in fact miss a day, which they then caught up to later in the week. This can create problems in data processing, as the toolbox used was susceptible to failure when processing single nights. Another related issue was that the activity trackers used in this experiment do not come with a dedicated software package and relatively outdated firmware, which impacts ease of use compared to other models and in this case led to sizeable levels of data exclusion. Although again, participants were not compensated and may have lacked motivation, the instructions perhaps did not stress the importance a continuous measuring period enough. Lastly, a small sample size could also be a contributing factor to the unexpected results. Fifteen participants delivered data, but not all data was usable because of several small problems with data gathering and extracting. It is interesting to see if a larger sample size would have resulted in more consistent, predictable results, as seen in several earlier studies (e.g. Lichtstein et al., 2006; Van den Berg et al., 2010).

However, these mentioned limitations applied to the whole study, and thus they should not affect just one instrument. This was indeed the case, as the pooled datasets were almost of equal size. While improvements to the above mentioned limitations would have probably resulted in more coefficients with lower p values, it also unlikely that they would have changed the results drastically. Therefore, we must assume that in this scenario, the CSD was a better predictor for many of the measured sleep parameters.

In conclusion, the current study showed results that are somewhat comparable with those found in previous studies (Ancoli-Israel et al., 2003; Lichtstein et al., 2006; Lockley, Skene & Arendt, 1999; Natale et al., 2015; Sadeh, 2011; Van den Berg et al., 2010). However, getting consistent, accurate sleep measurements is a difficult process as variations in study results seem to occur frequently in the field. Both the CSD and the app seem to be excellent in assessing total sleep time, while problems with data acquisition undermine potential of the other parameters. Therefore, we suggest that further research should focus on why there seems to be a large difference between patient and actigraph reported wake times, or if this effect occurs in other samples at all. However, while this study has some limitations in regard with data processing, data loss was about equal for each diary and thus we conclude that the CSD is a better predictor for the parameters measured than the mobile application diary. Nevertheless, the mobile application was well received by participants and it seems to be well suited for its intended purpose. The findings of this study together with the fact that the current landscape is rapidly changing, highlights the fact that there is a need for ongoing research into these new research methodologies.

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Appendix A: digitaal Nederlands Consensus Slaapdagboek - Kern (dNCS-K) Ochtend

Een slaapdagboek is ontworpen om informatie te verzamelen over uw dagelijkse slaappatroon. Vul het slaapdagboek alstublieft elke dag in; het liefst tussen een half uur en een uur na opstaan of daar zo dicht mogelijk bij. Als uw slaap of functioneren overdag beïnvloed wordt door een ongewone gebeurtenis (bijvoorbeeld door ziekte of een spoedgeval) maak dan een korte aantekening hierover in uw dagboek.
In het slaapdagboek betekent het woord 'dag' de tijd die u wakker wilt zijn; het woord 'bed' is de plek waar u normaal gesproken slaapt. U hoeft zich geen zorgen te maken over het opgeven van exacte tijdstippen, kijk ook niet de hele tijd op de klok. Als u een tijd niet meer weet, geef dan alstublieft uw beste schatting.
Dit dagboek vult u <dag> ochtend in en gaat over de nacht van <gister> op <vandaag>.

1. Hoe laat bent u naar bed gegaan?
Geef het tijdstip aan waarop u naar bed bent gegaan, bijvoorbeeld 22 uur 30 min. Dit hoeft niet de tijd te zijn waarop u probeerde in slaap te vallen.
2. Hoe laat sloot u uw ogen om te gaan slapen?
Geef de tijd aan waarop u uw ogen sloot om in slaap te vallen, bijvoorbeeld 22 uur 45 min.
2b. Heeft u vannacht geslapen? 3. Hoe lang duurde het voordat u in slaap viel?
Hoe lang duurde het voor u sliep nadat u uw ogen sloot om in slaap te vallen?
4. Hoeveel keer werd u wakker? (het uiteindelijke ontwaken niet meetellen)
Hoe vaak bent u wakker geworden tussen het tijdstip waarop u voor het eerst in slaap viel en het moment dat u uiteindelijk wakker werd?
5. Hoe lang duurden deze momenten van wakker zijn ongeveer bij elkaar?
Hoe lang was u wakker vanaf het moment dat u voor het eerst in slaap bent gevallen tot het uiteindelijke ontwaken? Bijvoorbeeld: als u 3 keer wakker bent geweest gedurende 20, 35 en 15 minuten, telt u deze minuten bij elkaar op (20+35+15=70 minuten, oftewel 1 uur en 10 minuten) en kiest dan de tijdsduur die er het dichtst bij komt (in dit geval 1 uur).
6. Hoe laat werd u uiteindelijk wakker?
Geef de tijd aan van de laatste keer waarop u uiteindelijk wakker werd.

7. Hoe laat bent u uiteindelijk opgestaan?

Hoe laat stond u op omdat u niet meer verder wilde slapen? Dit kan een ander tijdstip zijn dan het uiteindelijke wakker worden (bijvoorbeeld: u bent om 6:35 uur wakker geworden, maar pas om 7:20 uur opgestaan).

8. Hoe zou u de kwaliteit van uw slaap beoordelen?

'Kwaliteit van slaap' is uw gevoel of u goed of slecht heeft geslapen.

9. Commentaar (indien van toepassing)

Als u een aanvullende opmerking wilt maken die van belang is voor uw slaap, noteert u deze opmerking dan hier.

Appendix B: Usability questionnaire

	Vragen over de mobiele applicatie	1 Helemaal mee oneens	2	3	4	5 Helemaal mee eens
1	Ik vond de app gemakkelijk in gebruik					
2	Het kostte me niet veel tijd om de app in te vullen					
3	Ik vond de app erg handig					
4	Eigenlijk had ik nog meer dingen in de app willen invullen					
5	In het geheel ben ik tevreden over de app					

	Vragen over het slaapdagboek	1	2	3	4	5
1	Ik vond het slaapdagboek gemakkelijk in gebruik					
2	Het kostte me niet veel tijd om het slaapdagboek in te vullen					
3	Ik vond het slaapdagboek erg handig					
4	Eigenlijk had ik nog meer dingen in het slaapdagboek willen invullen					
5	In het geheel ben ik tevreden over het slaapdagboek					

Appendix C: Participant instruction handout (Dutch)

1. Horloge omdoen

Je hebt een activiteitsmeter gekregen in de vorm van een horloge. Draag deze aan je **niet-dominante hand**. Ben je dus rechtshandig, draag het horloge dan links (en vice-versa). Het is belangrijk dat je het horloge **zo veel mogelijk om hebt**, dus ook overdag. Verder is het horloge waterdicht, maar doe hem tijdens het douchen liever af. Naast beweging meet het horloge ook omgevingslicht en lichaamstemperatuur. Dit is voor het onderzoek niet belangrijk. Het is dan ook geen probleem om het horloge onder je shirt of trui te dragen.

2. De dagboek app op je telefoon installeren en registreren

Tijdens het onderzoek maken we onder andere gebruik van een slaapdagboek in de vorm van een app. Typ onderstaande link in je browser of scan de QR code met je telefoon. Nadat de app geïnstalleerd is kan je deze openen, en je registreren met de registratiecode die je hebt gekregen op een apart blaadje**. Let op: activeer de app pas zodra je met deze fase van het onderzoek begint**. Open hiervoor de app en druk onderaan op ‘Activeren’. Zodra dit gedaan is kan je niet opnieuw activeren. Deze code bestaat altijd uit zes hoofdletters (voorbeeld **XZXZXZ)**. Zorg ervoor dat je de code juist invult, anders komt de data niet goed binnen!

https://play.google.com/apps/testing/nl.uu.science.sleepcare.diary

3. Slapen!

Je bent klaar om met het onderzoek mee te doen! Ga gewoon slapen zoals je dat elke andere nacht ook doet. Je hoeft je slaapgedrag dus niet aan te passen.

4. Dagboek invullen

De volgende morgen vul je het slaapdagboek op de app in. Doe dit bij voorkeur meteen nadat je wakker wordt of opstaat, dan weet je alles nog het beste. Je opent hiervoor de app, drukt onderaan op ‘invullen’ en volgt de stappen. Let er op dat je elk tabje bovenaan meeneemt en invult.

5. Herhalen

Vervolgens herhaal je stap 3 & 4 nog drie keer, zodat je **4 nachten** geslapen hebt en **4x de app hebt ingevuld**. Hierna ben je klaar met deze fase.

1. Horloge omdoen

Je hebt een activiteitsmeter gekregen in de vorm van een horloge. Draag deze aan je **niet-dominante hand**. Ben je dus rechtshandig, draag het horloge dan links (en vice-versa). Het is belangrijk dat je het horloge **zo veel mogelijk om hebt**, dus ook overdag. Verder is het horloge waterdicht, maar doe hem tijdens het douchen liever af. Naast beweging meet het horloge ook omgevingslicht en lichaamstemperatuur. Dit is voor het onderzoek niet belangrijk. Het is dan ook geen probleem om het horloge onder je shirt of trui te dragen.

2. Slapen!

Je bent klaar om met het onderzoek mee te doen! Ga gewoon slapen zoals je dat elke andere nacht ook doet. Je hoeft je slaapgedrag dus niet aan te passen.

3. Slaapdagboek invullen

De volgende morgen vul je het slaapdagboek op de website in. Doe dit bij voorkeur meteen nadat je wakker wordt of opstaat, dan weet je alles nog het beste. Vul de link hieronder in op je mobiele telefoon (of laptop/tablet) of scan de QR code. Belangrijk bij het invullen is om te zorgen dat je je participant nummer (voorbeeld **12)** goed invult zodat de data goed verwerkt wordt. Deze staat op het andere formulier wat je gekregen hebt. Let op: deze code verschilt dus van de andere registratie code die je gekregen hebt.

http://goo.gl/forms/jwFmQh3HAJ

4. Herhalen

Vervolgens herhaal je stap 3 & 4 nog drie keer, zodat je **4 nachten** geslapen hebt en **4x de het dagboek hebt ingevuld**. Hierna ben je klaar met deze fase.