The Effects of Sleep on Emotional Target Detection Performance: A Novel iPad-Based Pediatric Game

Annalisa Colonna¹, Anna B. Smith¹*, Stuart Smith², Kirandeep VanDenEshof³, Jane Orgill², Paul Gringras² and Deb K. Pal¹,²

¹ Department of Basic and Clinical Neuroscience, Institute of Psychiatry, Psychology and Neuroscience, King’s College London, London, United Kingdom, ² Evelina London Children’s Hospital, Children’s Sleep Medicine, St. Thomas Hospital, London, United Kingdom

Background: Consolidation of learning occurs during sleep but when it is disturbed there may be an adverse impact upon these functions. While research has focused upon how sleep affects cognition in adulthood, the effects of disrupted sleep are likely to impact more heavily on learning among children and adolescents. We aimed to investigate whether a night’s sleep impacts upon executive function compared with an equivalent wakefulness period. We also wanted to know whether restricting sleep would reduce these effects on performance. To investigate this issue in children, we adapted existing research methods to make them more suitable for this population.

Methods: Using a cross-over trial design, 22 children aged 7–14 completed an updated but previously validated, continuous performance task (CPT) designed to be appealing to children, containing emotional and neutral targets and presented on an iPad. We measured omission and commission errors, mean and variability of reaction times (RTs) immediately and after a delay spent in the following three ways: 11-h intervals of unrestricted and restricted sleep in the style of a ‘sleepover’ and daytime wakefulness. We examined differences in immediate and delayed testing for each dependent variable. Both sleep nights were spent in a specialist sleep lab where polysomnography data were recorded.

Results: While there were no significant main effects of sleep condition, as expected we observed significantly faster and more accurate performance in delayed compared with immediate testing across all conditions for omission errors, RT and variability of RT. Importantly, we saw a significant interaction for commission errors to emotional targets ($p = 0.034$): while they were comparable across all conditions during immediate testing, for delayed testing there were significantly more errors after wakefulness compared with unrestricted sleep ($p = 0.019$) and at a trend level for restricted sleep ($p = 0.063$). Performance improvement after restricted sleep was inversely correlated with sleep opportunity time ($p = 0.03$), total sleep time ($p = 0.01$) and total non-REM time ($p = 0.005$).

Conclusion: This tool, designed to be simple to use and appealing to children, revealed a preserving effect of typical and disrupted sleep periods on performance during an emotionally themed target detection task compared with an equivalent wakefulness period.

Keywords: sleep, emotional processing, executive function, polysomnography, children, spindles
INTRODUCTION

Research with healthy children and adults shows specific memory consolidation occurring during sleep (Marshall and Born, 2007; Wilhelm et al., 2008). Poor sleep quality and quantity can adversely affect memory and cognition including spatial learning (Nguyen et al., 2013), language consolidation (Tamminen et al., 2013) as well as executive function (EF). Much of this research has involved adult participants, although the impact of poor sleep is likely to be even more pronounced during childhood and adolescence (Anderson, 2002).

The challenge for pediatric research is that many of the carefully controlled conditions, measures and paradigms used in adult research are not likely to suit or appeal to children. Furthermore there is evidence that information presented for overnight learning paradigms may need to be particularly salient and engaging for memory consolidation in young people (Stickgold and Walker, 2013).

The development of accessible child-focused measures designed to be sensitive to overnight effects of sleep on memory and cognition are crucial to allow larger pediatric studies to quickly quantify the impact of sleep interventions. The development of a set of tasks designed around a ‘gaming’ approach with an animated child narrator to allow salience, engagement, and ease of use has recently been described (Colonna et al., 2015).

Previous work by Soffer-Dudek et al. (2011) showed that children who experience disruptive sleep are more likely to make omission and commission errors on a target detection task. Sadeh’s team employed a reliable and valid task designed to be engaging to children and adolescents (Rosenberg-Kima and Sadeh, 2010). The stimuli consisted of faces embedded within balloons that drifted upward on a computer screen at a range of speeds, some of which were targets and needed to be ‘popped’ using a mouse. Target definition varied across three different conditions determined either by color of the balloon (green), gender of the face (girl), or emotional expression of the face (happy). Intriguingly, Sadeh’s team found sleep disturbances impacted on performance on the emotional processing condition only.

The emotional value of information being processed has been shown to have both a positive and a negative effect upon performance, largely based upon the perceived threat of the emotional stimuli: if the emotional content of the stimulus is non-threatening or ambiguous this may enhance responding to that stimulus to facilitate further investigation but this may well be quite a subtle change and will be less detectable (Pessoa, 2009). However, where stimuli are perceived as threatening, it is thought that the response strategy appears to become more global, possibly drawing on other resources and in this way increasing responses even to non-targets (Verbruggen and De Houwer, 2007). Previous work with adults has shown that disrupted sleep is negatively associated with emotional EF (Sagaspe et al., 2006; Yoo et al., 2007; Killgore et al., 2008; Franzen et al., 2009; van Der Helm et al., 2010). In children, recognition of emotional stimuli increases with sleep (Prehn-Kristensen et al., 2013) while nap withdrawal in toddlers increases the likelihood of negative responses regardless of whether an image is positive or negative and nap withdrawal also leads to negative rather than confused responses to unsolvable puzzles (Berger et al., 2012).

Given that Sadeh’s task had already been shown to be sensitive to sleep disruption in adolescents, it seemed a suitable paradigm to develop further using the programming potential and end-user appeal possible in a contemporary tablet platform. This study set out to repeat and expand the findings of Sadeh’s original study with an updated tool by comparing changes in EF in a wide age range of typically developing children after a period of either unrestricted or restricted sleep with an equivalent daytime period. We tested the hypotheses that (a) performance on the target detection task would improve following unrestricted sleep relative to an equivalent daytime period and (b) restricted sleep would lead to compromised performance change relative to unrestricted sleep.

Previous study designs measuring sleep and cognitive performance in children and adolescents have often been observational, exploring correlations between amount of sleep and performance change, rather than experimental, using control or comparison groups (Astill et al., 2012). Importantly, uncontrolled studies cannot differentiate circadian effects from sleep effects and cannot compare sleep with wakefulness. We chose a balanced crossover trial design to address these issues and allow us to take advantage of also measuring objective standardized sleep parameters.

MATERIALS AND METHODS

Design

This was a balanced crossover trial comparing performance across three types of testing session separated by an interval of at least 1 week: daytime period (D), overnight unrestricted sleep period (S), and an overnight partial restricted sleep period (R). Based on our intended comparison of D with first S and then R, we created five different order groups (SDR; SRD; DSR; RSD; RSD) so there were equal numbers of children with the order DS (n = 13) and SD (n = 14), and also DR (n = 11) and RD (n = 12).

Participants

We recruited a convenience sample of 30 typically developing children (10 female, 20 males) aged 7–14 years old (mean: 11.05 ± 3.45). All children spoke English as their first language, had normal hearing and vision, no medical or psychiatric disorders likely to affect sleep and none took hypnotic medication.

Measures

Executive Functioning

Working with Sadeh, we adapted the previously described Balloons Task (Rosenberg-Kima and Sadeh, 2010) into “Pond Poppers,” an animated target detection game, with two conditions requiring either emotional or gender processing. Like the original game, the goal was to burst predefined target bubbles (rather than balloons) amongst non-target bubbles drifting upward on the screen using a fingertip rather than a mouse as in the original
In the emotionally neutral condition, targets were defined by gender (target faces: girls; non-target faces: boys). In the emotional condition, targets were defined by emotion (target faces: happy; non-targets: sad or neutral). For each condition, there were 70 targets and 130 non-targets, the ratio used in the original task (Rosenberg-Kima and Sadeh, 2010). While the original task used three discrete speeds at which the balloon went from the bottom to the top of the screen, Pond Poppers used a smooth gradient instead, beginning with 2.5 s and ending with 1.1 s for the bubble to travel from bottom to top of screen. Mean reaction time (RT), intraindividual coefficient of variation of reaction time (ICV) (intraindividual standard deviation divided by individual mean), omission (missed targets) and commission errors (non-target hits) were automatically computed and stored wirelessly to a database server. This game was optimized for and presented to the participants on an Apple iPad™ tablet (iPad Air 16GB with 9.7” Retina display, 64-bit A7 chip, running iOS version 8.1) with Sony MDR over-ear headphones.

Sleep
The NPSG montage consisted of an electroencephalogram (EEG) comprised of frontal (F3 and F4), central (C3 and C4) and occipital (O1 and O2) leads with auricular reference electrodes, left and right electro-oculographic (EOG) channels, 3 submental electromyographic channels, 2 lead electrocardiography and pulse oximetry (SpO2). Placement of the EEG electrodes was in accordance with the International 10-20 system (Jasper, 1958). All NPSGs were recorded and analyzed using RemLogic software (versions 2.0.2, 3.2 and 3.4), the Embla N7000 recording system and Embla MDrive/Embla communication unit. Nonin xpod cables and disposable oximeter probes were integrated (via the Embla Patient Unit) to measure SpO2 and pulse rate.

Four senior physiologists from the Evelina London Children’s Hospital Children’s Sleep Centre scored the data with repeat scoring by the Chief Physiologist (KvE). The analysis of sleep stages and arousals was performed using 30-s epochs, in accordance with the latest American Association of Sleep Medicine guidelines (Berry et al., 2012). Sleep measures (measured in minutes) included:

- Sleep Opportunity Time
- Total Sleep Time (TST) (the total amount of time the patient is actually asleep (so in stage one, two, three, and REM sleep) thus not including wake periods)
- Amount of REM (Rapid eye movement) as percentage of TST
- Amount of non-REM sleep as percentage of TST
- Amount of REM as percentage of sleep period (the time elapsed from the first epoch of sleep to the final epoch of sleep thus including awake periods)
testing only for all three conditions.

A one-way ANOVA was carried out with sleep condition (daytime, unrestricted, and restricted sleep) and testing time (immediate and delayed) as within-subject variables for each dependent variable.

We used Pearson's correlations to explore associations between significant performance changes during both sleep nights and neuropsychological and PSG measures.

RESULTS

Missing Data Analysis

Thirty children were recruited for the study but there were some drop-outs (see Figure 2): one child did not attend the restricted night; four children did not conform to daytime protocol and three children completed the task incorrectly. Since these children were excluded from the analysis we compared them with those remaining in the study in terms of age, gender and ability and found no significant differences.

Time of Day

We compared immediate testing performance only across all three sleep conditions to examine whether performance differed depending on the time of day. There was no significant effect of time of day for any of the dependent variables.

Order Effects

There were no order effects for commission errors to emotional (F(5,105) = 1.2; p = 0.31) or gender targets (F(5,105) = 0.88; p = 0.42).

Significant main effects of order were observed for mean RT to gender targets (F(5,105) = 35; p < 0.0001) and emotional targets (F(5,105) = 23; p < 0.0001), ICV for gender targets (F(5,105) = 4.9; p = 0.002) and emotional targets (F(5,105) = 2.4; p = 0.041); omission errors to gender targets (F(5,105) = 26; p < 0.0001) and...
emotional targets ($F_{5.105} = 38; p < 0.0001$). Details of post hoc tests are given in Table 1 and described below.

**Reaction Time Speed**

Post hoc tests for the gender condition showed that children were faster the second time compared to the first, ($F_{1.21} = 44; p < 0.0001$) and again from second to third time ($F_{1.21} = 4.8; p < 0.04$). During the emotional condition children became faster across the six sessions: they were significantly faster the second time compared to the first ($F_{1.21} = 21; p < 0.0001$) and from second to third time, third to fourth and fifth to sixth time ($F_{1.21} = 4.0; p = 0.058; F_{1.21} = 3.7; p = 0.068; F_{1.21} = 4.5; p = 0.045$) but with no change from fourth to fifth time.

**Reaction Time Variability**

Reaction time were significantly less variable to gender targets the second time the participants did the task compared with the first ($F_{1.21} = 7.3; p = 0.013$), but variability did not decrease any further. Post hoc tests for variability of RTs to emotional targets did not demonstrate any significant differences.

**Omissions**

Mean omission errors to gender targets decreased significantly the second time the participants did the task compared with the first ($F_{1.21} = 22; p < 0.0001$) and then from second to third time ($F_{1.21} = 4.8; p = 0.04$). After this omission errors plateaued. Mean omission errors to emotional targets decreased significantly from first to second time ($F_{1.21} = 46; p < 0.0001$) and then from third to fourth time they did the task ($F_{1.21} = 29; p < 0.0001$).

**Sleep Effects**

**Main Effect of Condition**

There were no significant main effects of sleep condition for either the gender or emotion condition for any of the dependent variables (see Table 2).

### Table 1

| Variable          | First session | Second session | Third session |
|-------------------|---------------|----------------|--------------|
|                   | Test 1 Immediate | Test 2 Delayed | Test 3 Immediate | Test 4 Delayed | Test 5 Immediate | Test 6 Delayed |
| **RT (secs)**     | Mean (SD)     | Mean (SD)      | Mean (SD)     | Mean (SD)     | Mean (SD)      | Mean (SD)      |
| Gender            | 1.51 (0.19)   | 1.34 (0.16)    | 1.28 (0.17)   | 1.27 (0.12)   | 1.24 (0.12)    | 1.21 (0.13)    |
| Emotion           | 1.67 (0.14)   | 1.54 (0.15)    | 1.48 (0.17)   | 1.43 (0.13)   | 1.44 (0.16)    | 1.38 (0.15)    |
| **ICV (secs)**    | Mean (SD)     | Mean (SD)      | Mean (SD)     | Mean (SD)     | Mean (SD)      | Mean (SD)      |
| Gender            | 0.36 (0.07)   | 0.31 (0.07)    | 0.30 (0.07)   | 0.31 (0.04)   | 0.29 (0.04)    | 0.29 (0.07)    |
| Emotion           | 0.41 (0.07)   | 0.38 (0.07)    | 0.36 (0.06)   | 0.36 (0.06)   | 0.38 (0.06)    | 0.37 (0.07)    |
| **Omission errors (number)** | Mean (SD)     | Mean (SD)      | Mean (SD)     | Mean (SD)     | Mean (SD)      | Mean (SD)      |
| Gender            | 20.14 (8.0)   | 15.18 (6.7)    | 12.36 (6.9)   | 11.18 (7.0)   | 9.27 (5.4)     | 8.73 (4.9)     |
| Emotion           | 34.36 (7.6)   | 25.77 (8.5)    | 25.50 (8.5)   | 20.50 (7.4)   | 20.05 (7.3)    | 18.82 (8.1)    |
| **Commission errors (number)** | Mean (SD)     | Mean (SD)      | Mean (SD)     | Mean (SD)     | Mean (SD)      | Mean (SD)      |
| Gender            | 6.73 (6.0)    | 5.86 (7.7)     | 4.32 (4.0)    | 9.32 (16.9)   | 6.41 (5.4)     | 6.14 (5.6)     |
| Emotion           | 12.27 (9.8)   | 13.36 (11.1)   | 11.64 (7.4)   | 16.64 (14.5)  | 16.68 (12.6)   | 13.91 (8.9)    |

For all dependent variables Session 1 < Session 2; Session 2 < Session 3 ($p < 0.01$) except ICV errors Session 2 vs. Session 3 and commission errors for all sessions.

### Table 2

| Variable          | Daytime | Unrestricted sleep | Restricted sleep |
|-------------------|---------|-------------------|-----------------|
|                   | Immediate | Delayed | Immediate | Delayed | Immediate | Delayed |
| **RT (secs)**     | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) |
| Gender a***       | 1.35 (0.2) | 1.26 (0.16) | 1.33 (0.2) | 1.29 (0.14) | 1.35 (0.16) | 1.26 (0.1) |
| Emotion a***      | 1.5 (0.2)  | 1.46 (0.2)  | 1.5 (0.17)  | 1.46 (0.12) | 1.52 (0.18) | 1.41 (0.15) |
| **ICV (secs)**    | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) |
| Gender            | 0.33 (0.07) | 0.31 (0.06) | 0.29 (0.07) | 0.29 (0.06) | 0.31 (0.063) | 0.30 (0.059) |
| Emotion a** b*    | 0.39 (0.06) | 0.37 (0.06) | 0.36 (0.069) | 0.37 (0.071) | 0.39 (0.05) | 0.35 (0.06) |
| **Omission errors (number)** | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) |
| Gender            | 14.09 (8.9) | 13.6 (8.7) | 13.88 (8.8) | 10.31 (6.1) | 14.00 (6.9) | 11.2 (4.6) |
| Emotion a***      | 28.05 (10.4) | 22.72 (9.0) | 26.04 (9.5) | 20.36 (8.3) | 25.81 (9.6) | 22.00 (8.1) |
| **Commission errors (number)** | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) | Mean (SD) |
| Gender            | 5.36 (4.9)  | 10.45 (17.8) | 5.68 (6.3)  | 4.86 (3.8)  | 6.41 (4.6)  | 6.00 (6.6)  |
| Emotion b**       | 11.95 (6.4) | 19.27 (16.1) | 12.59 (9.7) | 11.14 (6.9) | 15.95 (13.5) | 13.50 (8.7) |

$a =$ significant main effect of testing time; $b =$ significant interaction effect of condition and testing time (no main effect of sleep) $^*$ $p < 0.10$ (trend), $^{**}p < 0.05$, $^{***}p < 0.01$.  

---

Frontiers in Psychology | www.frontiersin.org 5  March 2018 | Volume 9 | Article 241
Main Effect of Testing Time

There was a significant effect of testing time for RT to gender targets ($F_{2,42} = 26; p < 0.0001$) and emotion targets ($F_{2,42} = 31; p < 0.0001$), variability of response to emotional targets only ($F_{2,42} = 5; p = 0.032$) and for omission errors to gender targets ($F_{2,42} = 13; p = 0.002$) and emotion targets ($F_{2,42} = 88; p < 0.0001$). There was no significant main effect of testing time during either gender or emotion condition for commission errors.

Interaction Between Condition and Testing Time

During the emotional condition, there was a significant interaction for a variable defining the first session (daytime, sleep or restricted) primarily from first to second time of playing the game we added errors. The interaction between condition and testing time for commission errors remained significant ($F = 3.7; p = 0.034$) and differences were analyzed with *post hoc* tests to interpret this outcome and to acquire effect sizes: there were no significant differences in number of errors during immediate testing for either condition, but during delayed testing there were significantly more errors during the daytime condition compared with unrestricted sleep ($p = 0.019; \eta^2 = 0.26$) and at a trend level for the restricted sleep condition ($p = 0.063; \eta^2 = 0.17$) (see Figure 3).

**Correlational Analysis**

**Correlations With Change in Commission Errors**

Performance change was defined as the difference between immediate to delayed testing expressed as a percentage of number of commission errors at immediate testing (positive value indicates improvement in performance).

During the unrestricted night, we found a positive correlation approaching significance between age and performance change ($r = 0.42; n = 22; p = 0.06$) so that with increasing age, performance improved from immediate to delayed testing. There was no significant association with sleep quality as measured by the total sleep disturbance as measured by (SHQ).

During the restricted night we observed significant negative correlations with performance change and total sleep opportunity time ($r = -0.47; n = 22; p = 0.03$), total sleep time ($r = -0.54; n = 22; p = 0.01$) and total non-REM ($-0.58; n = 22; p = 0.005$) so that performance improved with decreased sleep duration (see Table 3).

No other significant associations were observed.

**DISCUSSION**

In this current study, we have shown that it is possible to preserve the validity of a previously established paradigm (Soffer-Dudek et al., 2011) whilst presenting this to children on a contemporary tablet device and using updated graphics. Importantly, our findings reflect those of the original observational study upon which ours is based. This original study showed that the number of commission errors was positively correlated with

---

**TABLE 3** Means standard deviations (SD) for each polysomnography (PSG) measure for each sleep condition and correlations (r) between each PSG measure and difference in immediate and delayed commission errors for each condition.

| Sleep features          | Unrestricted sleep | Restricted sleep | Emotion commission errors performance change |
|-------------------------|--------------------|------------------|---------------------------------------------|
|                         | n  | Mean (SD) | r  | p  | n  | Mean (SD) | R  | p  |
| Sleep opportunity (TRT) (mins) | 22 | 519.3 (53.3) | -0.07 | 0.77 | 22 | 317.4 (63.0) | -0.47 | 0.03 |
| Total sleep time (TST) (mins) | 18 | 446.0 (53.5) | 0.04 | 0.87 | 22 | 288.4 (62.3) | -0.54 | 0.01 |
| % NREM of TST | 16 | 85.1 (3.2) | 0.25 | 0.36 | 22 | 88.9 (4.6) | 0.14 | 0.53 |
| % NREM of sleep period | 16 | 75.4 (6.3) | 0.13 | 0.62 | 22 | 82.3 (8.6) | -0.23 | 0.31 |
| % REM of TST | 16 | 14.9 (3.3) | -0.24 | 0.37 | 22 | 10.8 (4.1) | -0.16 | 0.47 |
| % REM of sleep period | 16 | 13.6 (2.9) | -0.20 | 0.45 | 22 | 10.4 (4.4) | -0.19 | 0.39 |
| Total NREM (mins) | 16 | 380.8 (49.2) | 0.09 | 0.73 | 22 | 244.6 (69.1) | -0.58 | 0.006 |
| Total REM (mins) | 16 | 66.5 (16.7) | -0.17 | 0.51 | 22 | 33.1 (18.6) | -0.33 | 0.14 |
overnight disruptions to sleep (Soffer-Dudek et al., 2011), thus demonstrating an association between sleep and commission errors in a very similar task.

We found both restricted and unrestricted sleep appeared to preserve performance, in contrast to an equivalent daytime period after which performance declined. Other studies have shown that sleep can affect other cognitive functions in this way. For example, the performance of adults using motor memory tasks has worsened over a daytime period compared to a night time period (Rickard et al., 2008; Ribeiro Pereira et al., 2015; Nettersheim et al., 2015). Our findings suggest that we can extend this finding to target detection processes in children.

We based our game on a paradigm that had already been shown to be sensitive to sleep in children and adolescents. Relatively little research has been carried out that examines the impact of sleep on EF in children but a recent meta-analysis demonstrated that EF is influenced by sleep restriction in children and is associated with modest effect sizes (Astill et al., 2012). While EF encompasses a wide band of skills, target detection has produced reasonable effect sizes of $d = 0.5$ where targets are defined by their emotional status. Our results confirm that this particular EF is sleep sensitive and suggest that our game has potential for development as an alternative indicator of sleep deficiency.

Sleep during restricted conditions also preserved performance compared with an equivalent daytime period at a level that approached significance. The conditions we provided during our restricted night aimed to replicate 'sleep-over' conditions, where children watched a movie and went to bed later than normal. We acquired precise measures of sleep quantity to confirm that sleeping hours and corresponding REM and non-REM time were reduced during this night (see Table 3). Thus, our study seems to support other research which shows that children have resilience to acute partial sleep deprivation, compensating EF reasonably well and in fact, we found an inverse correlation between performance and sleep duration and non-REM sleep, which suggests that sleep processes may work in a compensatory way when sleep is undisturbed but restricted. It seems likely that chronic rather than acute sleep deprivation impacts upon performance in children and adolescents as indicated by earlier studies (Anderson et al., 2009; Molfese et al., 2013; Kuula et al., 2015; de Bruin et al., 2016).

The ability to detect emotional information is likely to have particular relevance, since identifying emotional expressions plays a key role in social communication and is related to psychopathology and adjustment in childhood and adolescence when these skills are developing, and in adulthood (Phillips et al., 2003; Leppänen, 2006). Our study supports earlier work showing that emotional intelligence is impacted upon by sleep deprivation (Killgore et al., 2008).

**Limitations**

The main limitation of this study is the relatively small group of participants, and different age groups studied. Whilst the ability to capture full sleep, polysomnographic physiological data is important and sets this study apart from many, it also increases the cost and complexity, and arguably the monitoring itself can alter sleep quality. The iPad autonomous platform lends itself to testing large numbers of children remotely (without full polysomnography) and we are also pursuing this alternative model. The hospital setting for overnight sleep interventions, and home setting for daytime conditions may have influenced the children’s task performances, although previous research in a different population of young people found no effect of setting (Galer et al., 2015).

We recognize that although the discriminative task was one of recognizing images of facial emotions, we cannot be certain that this is a task that really taps the processing of emotional expression, as the faces can also be conceptualized as simply more challenging complex images than the gender images. Our future work will focus on equalizing the cognitive load in order to disentangle this confound.

Despite our decision to test children 1 h after waking, we recognize that sleep inertia is a potential confounder and is likely to impact upon performance and some children can take up to 4 h to return to their normal performance. This may have a greater effect after a night of sleep deprivation than a night of normal sleep which may well act as a confounder (Sadeh et al., 2002). However, in this sample of children we didn’t see a difference in commission errors in the morning following restricted compared with non-restricted sleep so sleep inertia seems not to have had a differential effect on this kind of sleep in this sample of children.

**CONCLUSION**

Using a unique gamified tool specifically developed for children, we have shown that sleep has a preserving effect upon a specific facial emotion image recognition task and this skill is conserved even after a single night of restricted sleep.

The task is engaging, does not require administration by trained psychologists, and can be administered remotely across large populations. Our next goals are to observe the effects of chronic sleep deprivation on the same task and define its properties in children with various neurodisabilities.

**AUTHOR CONTRIBUTIONS**

ABS and AC were involved in development of idea, recruitment, research, and writing of manuscript. SS, KVDE, and JO were involved in research and writing of manuscript. PG and DP were involved in development of idea, planning the research, design and writing of manuscript.

**FUNDING**

This study was funded by The Psychiatry Research Trust (PAL 31).
ACKNOWLEDGMENTS

We would like to thank all the parents and children who took part in our study and also acknowledge the huge contribution made by Louis Serkis and our programmers Despark and also the Sleep Physiologists Sakina Dastagir, Laura Crewe, Amarita Banga, Richard Dorn, and Suhilla Hashimi of the Children’s Sleep Centre for performing and analyzing the sleep study data. We would like to thank Julia Chapman and Sean Higgins of the Sleep Disorders Centre, Guys Hospital, for the kind use of their facilities. We would also like to acknowledge the contribution made by the late Professor Avi Sadeh to this study in terms of the development of the idea and the planning of the research design, and of course to the field in general.

REFERENCES

Anderson, R., Storfer-Isser, A., Taylor, H. G., Rosen, C. L., and Redline, S. (2009). Associations of executive function with sleepiness and sleep duration in adolescents. Pediatrics. 123.e701–7. doi: 10.1542/peds.2008-1182

Anderson, P. (2002). Assessment and development of executive function (EF) during childhood. Child Neuropsychol. 8, 71–82. doi: 10.1076/chns.8.2.71.8724

Astill, R. G., Van der Heijden, K. B., Van IJzendoorn, M. H., and Van Someren, E. J. (2012). Sleep, cognition, and behavioral problems in school-age children: a century of research meta-analyzed. Psychol. Bull. 138, 1199–1138. doi: 10.1037/a0028204

Berger, R., Miller, A., Seifer, R., Cares, S., and Lebourgeois, M. (2012). Acute sleep restriction effects on emotion responses in 30 to 36 month old children. J. Sleep Res. 21, 235–246. doi: 10.1111/j.1365-2869.2011.00962.x

Berry, R. B., Brooks, R., Gamaldo, C. E., Hardling, S., Marcus, C., and Vaughn, B. (2001). Psychometric properties of the strengths and difficulties questionnaire (CSHQ): psychometric properties of a survey instrument for school-aged children. Sleep 23, 1043–1051. doi: 10.1093/sleep/23.8.1043

Benson, C. G., Liu, Y., and Smith, B. K. (2009). Associations of executive function with sleepiness and sleep duration in school-aged children. Sleep 32, 1109–1138. doi: 10.1093 slept/32.8.1109

Colonna, P. L., Buysse, D. J., Dahl, R. E., Thompson, W., and Siegle, G. J. (2009). Sleep deprivation alters pupillary reactivity to emotional stimuli in healthy young adults. Biol. Psychol. 80, 300–305. doi: 10.1016/j.biopsycho.2008.10.010

Galer, S., Urbain, C., De Tiège, X., Emeriau, M., Leproult, R., Deliens, G., et al. (2015). Impaired sleep-related consolidation of declarative memories in idiopathic focal epilepsies of childhood. Epilepsy Behav. 43, 16–23. doi: 10.1016/j.yebeh.2014.11.032

Goodman, R. (2001). Psychometric properties of the strengths and difficulties questionnaire. J. Am. Acad. Child Adolesc. Psychiatry. 40, 1337–1345. doi: 10.1097/00004583-200111000-00015

Jasper, H. H. (1958). The ten twenty electrode system of the international federation. Electroencephalogr. Clin. Neurophysiol. 10, 371–375.

Killgore, W. D., Kahn-Greene, E. T., Lipizzi, E. L., Newman, R. A., Kambimori, G. H., and Balkin, T. J. (2008). Sleep deprivation alters perceived emotional intelligence and constructive thinking skills. Sleep Med. 9, 517–526. doi: 10.1016/j.spmj.2007.07.003

Kuula, L., Pesonen, A.-K., Martikainen, S., Kajantie, E., Lahtti, J., Strandberg, T., et al. (2015). Poor sleep and neurocognitive function in early adolescence. Sleep Med. 16, 1207–1212. doi: 10.1016/j.sleep.2015.06.017

Leppänen, J. M. (2006). Emotional information processing in mood disorders: a review of behavioral and neuroimaging findings. Curr. Opin. Psychiatry 19, 34–39. doi: 10.1097/01.yco.0000191500.46411.00

Marshall, L., and Born, J. (2007). The contribution of sleep to hippocampus-dependent memory consolidation. Trends Cogn. Sci. 11, 442–450. doi: 10.1016/j.tics.2007.09.001

Molfese, D. L., Ivenenko, A., Key, A. F., Roman, A., Molfese, V. J., O'Brien, L. M., et al. (2013). A one-hour sleep restriction impacts brain processing in young children across tasks: evidence from event-related potentials. Dev. Neuropsychol. 38, 317–336. doi: 10.1080/87565641.2013.791697

Nettersheim, A., Hallschmid, M., Born, J., and Diekelmann, S. (2015). The role of sleep in motor sequence consolidation: stabilization rather than enhancement. J. Neurosci. 35, 6696–6702. doi: 10.1523/JNEUROSCI.1236-14.2015

Nguyen, N. D., Tucker, M. A., Stickgold, R., and Wamsley, E. J. (2013). Overnight sleep enhances hippocampus-dependent aspects of spatial memory. Sleep 36, 1051–1057. doi: 10.5665/sleep.2808

Owens, J., Spiritó, A., and McGuinn, M. (2000). The children's sleep habits questionnaire (CSHQ): psychometric properties of a survey instrument for school-aged children. Sleep 23, 1043–1051. doi: 10.1093/sleep/23.8.1043

Pessoa, L. (2009). How do emotion and motivation direct executive control? Trends Cogn Sci. 13, 160–166. doi: 10.1016/j.tics.2009.01.006

Phillips, M. L., Drevets, W. C., Rauch, S. L., and Lane, R. (2003). Neurobiology of emotion perception II: implications for major psychiatric disorders. Biol. Psychiatry. 54, 515–528. doi: 10.1016/S0006-3223(03)0171-9

Prehn-Kristensen, A., Munz, M., Molzow, I., Wilhelm, I., Wiesner, C. D., and Baving, L. (2013). Sleep promotes consolidation of emotional memory in healthy children but not in children with attention-deficit hyperactivity disorder. PLoS One 8:e65098. doi: 10.1371/journal.pone.0065098

Reynolds, C. R., and Vlores, J. (2007). Test of Memory and Learning (TOMAL-2). Austin, TX: PRO-ED.

Ribeiro Pereira, S. I., Beijamini, F., Vincenzi, R. A., and Louzada, F. M. (2015). Re-examining sleep × x effect on motor skills: How to access performance on the finger tapping task? Sleep Sci. 4, 4–8. doi: 10.1016/j.sleepsci.2015.01.001

Rickard, T. C., Cai, D. J., Rieth, C. A., Jones, J., and Ard, M. C. (2008). Sleep does not enhance motor sequence learning. J. Exp. Psychol. 34, 834–842. doi: 10.1037/0278-7393.34.4.834

Rosenberg-Kima, R. B., and Sadeh, A. (2010). Attention, response inhibition, and face-information processing in children: The role of task characteristics, age, and gender. Child Neuropsychol. 16, 388–404. doi: 10.1080/02697041003671192

Sadeh, A., Gruber, R., and Raviv, A. (2002). Sleep, neurobehavioral functioning, and behavior problems in school-age children. Child Dev. 73, 405–417. doi: 10.1111/1467-8624.00414

Sagaspe, P., Sanchez-Ortuno, M., Charles, A., Taillard, J., Valtat, C., Bioulac, B., et al. (2006). Effects of sleep deprivation on color-word, emotional, and specific stroop interference and on self-reported anxiety. Brain Cogn. 60, 76–87. doi: 10.1016/j.bandc.2005.10.001

Soifer-Dudek, N., Sadeh, A., Dahl, R. E., and Rosenblat-Stein, S. (2011). Poor sleep quality predicts deficient emotion information processing over time in early adolescence. Sleep 34, 1499–1508. doi: 10.5665/sleep.1386

Stickgold, R., and Walker, M. P. (2013). Sleep-dependent memory triage: evolving generalization through selective processing. Nat. Neurosci. 16, 139–145. doi: 10.1038/nn.3303

Tamminen, J., Rovio, K., and Wills, A. (2009). Sleep and daytime functioning in young children: a critical review. Curr. Opin. Psychiatry 19, 208–217. doi: 10.1097/01.yco.0000309150.46411.00

Verbruggen, F., and De Houwer, J. (2007). Do emotional stimuli interfere with response inhibition? Evidence from the stop signal paradigm. Cogn. Emot. 21, 391–403. doi: 10.1080/02699930600623081
Wechsler, D. (1999). *Wechsler Abbreviated Scale of Intelligence*. San Antonio, TX: The Psychological Corporation.

Wertz, A. T., Ronda, J. M., Czeisler, C. A., and Wright, K. P. (2006). Effects of sleep inertia on cognition. *J. Am. Med. Assoc.* 295, 159–164. doi: 10.1001/jama.295.2.163

Wilhelm, I., Diekelmann, S., and Born, J. (2008). Sleep in children improves memory performance on declarative but not procedural tasks. *Learn. Memory* 15, 373–377. doi: 10.1101/lm.803708

Yoo, S.-S., Hu, P. T., Gujar, N., Jolesz, F. A., and Walker, M. P. (2007). A deficit in the ability to form new human memories without sleep. *Nat. Neurosci.* 10, 385–392. doi: 10.1038/nn1851

**Conflict of Interest Statement:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.