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THE IMPACT OF SLEEP DEPRIVATION ON VISUAL PERSPECTIVE-TAKING

Sleep deprivation and visual perspective-taking

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Conflict of interest

None

Author contributions

B, JMP and PJM designed the study. AN and JMP collected and analysed the preliminary study data. MB and JMP collected the main study data. MB, JMP, JP analysed the main study data. MB and JMP wrote the paper.

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Abstract

Total sleep deprivation (TSD) is known to alter cognitive processes. Surprisingly, little attention has been paid to its impact on *social* cognition. Here, we investigated whether TSD alters level-1 and level-2 visual perspective taking abilities, i.e., the capacity to infer (a) what can be seen and (b) how it is seen from another person's visual perspective, respectively. Participants completed level-1 and level-2 visual perspective taking tasks after a night of sleep and after a night of TSD. In these tasks, participants had to take their own (Self trials) or someone else's (Other trials) visual perspective in trials where both perspectives were either the same (Consistent trials) or different (Inconsistent trials). An instruction preceding each trial indicated the perspective to take (i.e. the relevant perspective). Results show that TSD globally deteriorates social performance. In the level-1 task, TSD affected the selection of relevant over irrelevant perspectives. In the level-2 task, the effect of total TSD cannot be unequivocally explained. This implies that visual perspective-taking should be viewed as partially state-dependent, rather than a wholly static trait-like characteristic.

Keywords: mentalizing, spatial perspective-taking, executive functions, cognitive empathy

Introduction

Sleep loss is a recognized societal issue, known to markedly impact on a wide range of cognitive functions (Basner et al., 2013). Surprisingly however, perspective taking has received scant attention, despite the fact that we regularly need to place ourselves in another person's shoes to achieve successful social interactions. The negative effect of sleep debt on emotional empathy (i.e., emotional perspective taking) has been evidenced in some studies (e.g. Guadagni et al., 2014; Bellini et al., 2002) but the interplay between sleep and the cognitive side of perspective taking remains unexplored. The only study that investigated the impact of sleep loss on cognitive perspective taking reported slower reaction time on a sarcasm detection task after a night of total sleep deprivation (TSD) than after a whole night of sleep (Deliens et al., 2015a). This effect was not fully explainable by generalized cognitive slowing after TSD. However, proper completion of a sarcasm detection task depends on working memory integrity, to keep in mind the context in which sarcasm may be detected and a series of paralinguistic cues such as the speaker's facial expression and prosody. Since TSD can negatively affect working memory (for a meta-analysis see Lim & Dinges, 2008), this adverse effect may have partially driven the observed effects on sarcasm detection.

In the present study, we assessed the impact of TSD on visual perspective taking (VPT). VPT allows inferring what can or cannot be seen by another person (i.e., a level-1 perspective), and how it is seen by that person (i.e., a level-2 perspective) (Flavell et al., 1981). The ability to infer another person's visual experience is a pivotal source of information for managing social interactions. For instances, it allows inferring: (i) knowledge and beliefs of others about the nearby environment, (ii) which objects they prefer, or (iii) whether they see us or pay attention to us. Congruently, VPT performance correlates with self-reported perspective taking habits (Mattan, Rotshtein & Quinn, 2016; Bukowski & Samson, 2017). Crucially, compared to sarcasm, VPT does not require integrating linguistic and paralinguistic cues, thus leading to lower working memory cost than in a sarcasm detection task.

VPT requires processes to compute another person's visual experience (drawing a line of sight for both level-1 and 2 VPT and, specifically for level-2 VPT, mental body rotation, Surtees et al., 2013) and executive function processes to select the goal-relevant perspective when the self-and the other-perspective are in conflict (Qureshi et al., 2010). Since TSD has been proposed to impact executive functioning (e.g., Muto et al., 2012), we expected that it would affect perspective selection performance when self and other perspectives are conflicting. The influence of TSD on executive functioning could occur in two ways. According to the “state instability” theory (Doran et al., 2001), the reduction of vigilance consecutive to TSD leads to an overall slowdown in performance with indirect effects on executive functions (Lim & Dinges, 2008). A second approach states that sleep loss directly hampers executive functioning by altering the functional integrity of the prefrontal cortex (Durmer & Dinges, 2005). Given that the prefrontal cortex is part of the regions involved in visual perspective taking with the right temporo-parietal junction and the ventral precuneus (Schurz et al., 2015), we should observe a negative effect of sleep loss on VPT performances.

VPT has also been shown to be impacted by the perspective-taker’s emotional state. Since TSD is known to affect mood as well (Dinges, Pack, & Williams, 1997), this may be yet a different pathway by which sleep deprivation affects perspective-taking. Hence, TSD-related decrease in VPT performance might be a consequence of mood, reduced vigilance, or altered executive functioning. To determine the responsible mechanism, we additionally surveyed the participants' mood state and administered vigilance and executive function tasks (i.e., inhibition, working memory and flexibility).

Method

Participants

Twenty-four participants gave written informed consent to participate in this study approved by the local ethics committee. Subjects were instructed to keep a regular sleep pattern the three days preceding each testing session (sleep duration >6 hours/night, no nap, bedtime before 1am and wake up before 10am) and to refrain from alcohol and stimulant drinks before and during testing sessions. Sleep-wake regularity was monitored using actigraphic recording (wGT3X-BT, ActiGraph, Pensacola, Florida, USA) and daily completion of the St Mary’s Hospital sleep questionnaire (Ellis et al., 1981). Four participants were excluded from statistical analyses due to irregular sleep pattern (sleep duration< 6 hours). The 20 remaining participants (5 males, 24.2 ± 2.7 years) were French-speaking with intermediate or neutral chronotype (Morningness-Eveningness Questionnaire: range 39-66; Horne & Ostberg, 1976) and no sleep disturbances (Pittsburgh Sleep Quality Index ≤ 5; 3.7 ± 1.3; Buysse et al., 1989). Participants received monetary compensation upon completion of the study.

Measures

Vigilance and sleepiness measures

Vigilance was measured using the 5-minute version of the Psychomotor Vigilance Task (PVT; Dinges & Powell, 1985). Participants had to press a key as quickly as possible to stop a counter that started at randomly selected intervals (from 2 to 10 seconds). Subjective sleepiness was self-rated on the Karolinska Sleepiness Scale (KSS; Akerstedt & Gillberg, 1990).

Mood state

Since happiness, anxiety, shame and guilt can modulate perspective-taking abilities (Bukowski & Samson, 2015; Converse et al., 2008; Todd et al., 2015), they were self-rated at the start of each testing session on a 7-point Likert scale as in Converse and Todd studies. Personality questionnaires were also administered (see Supporting information section 1 for detailed material).

Flexibility task

The Flexibility subtest of the Test for Attentional Performance (Zimmermann & Fimm, 2002) assesses the ability to shift the focus of attention by alternating between two sets of targets. A digit and a letter are simultaneously presented, one on the left and one on the right side of the screen. Subjects must indicate the position in which the target stimulus appears by pressing the corresponding left-hand or right-hand key. Target stimuli were digits in the first block and letters in the second block (no-switch trials = constant target stimuli within a block). In the last block, subjects had to alternately press the keys corresponding to the position of either the number or letter (switch trials = alternating target stimuli). Switch-cost was computed as the difference between performance in switch and in no-switch trials. Each block consists of 50 trials. This computerized task provides a precise measure of RTs (in the millisecond range) without requiring the retrieval of an arbitrary stimulus-response mapping (e.g., left button for red colour or circle shape) which can be affected after TSD.

Working memory task

To assess working memory, we used the N-back task (Owen et al., 2005), a classic updating task. A series of numbers are sequentially displayed on a screen. In the control condition, participants are instructed to press a button whenever the number ‘‘2’’ is displayed (0-back). In the working memory updating condition, they are required to press the button when the displayed number is the same as that presented 2 trials previously (2-back). To achieve the 2-back condition, participants had to maintain and update the series of numbers in working memory. Each of the four blocks (two 0-back and two 2-back blocks) consists of 30 stimuli displayed at a rate of 1/s, with 10 target trials.

Inhibition task

In the bimodal Stroop task (Henry et al., 2012), participants have to decide if the color word heard in the headphones is identical or not to the color of the ink of a written word displayed on the screen. The congruent condition consists of a color word inked in its own color (e.g. color word RED displayed in red), the incongruent condition consists of a color word inked in any of the four colors, other than the one to which it refers (e.g. color word RED inked in green) and the neutral condition consists of a neutral word. Stimuli were displayed until response (see Deliens et al., 2015a for further details). This task provides a precise measure of RTs without requiring arbitrary stimulus-response mapping and allows to distinguish both the Inhibition effect, computed as the difference between performance in the incongruent and neutral conditions, and the congruency effect, computed as the difference between performance in the incongruent and congruent conditions.

Level-1 Visual perspective-taking task

In the level-1 VPT task (adapted from Surtees et al., 2016; Figure 1), participants have to decide whether a number of red dots is visible from their own or from an avatar's perspective (i.e. "Self" vs. "Other" trials). Participants are first presented with a written perspective prompt (“HE/SHE” or “YOU”) indicating the perspective to take in the decision ("Does he see…?" or "Do you see…?") followed by a written number (from 0 to 3) prompt indicating the number of red dots to verify ("Does he see 2 red dots?"). Following the presentation of the perspective and number prompts on the screen, a cartoon picture is presented depicting an avatar standing next to a table. Participants are asked to decide as fast and as accurately as possible whether the written prompts correctly depicts the picture by pressing the corresponding key ("Yes" or "No" buttons). In this task, the dots are either all visible by both the avatar and the participant (Consistent trials) or some are unseen by the avatar (Inconsistent trials).

Level-2 Visual perspective-taking task

The level-2 VPT task (adapted from Surtees et al., 2016; Figure 1) is similar to the level-1 VPT except that participants are asked to decide which number they see from their own or from the avatar's perspective (i.e. "Self" vs. "Other" trials). The number prompts are 6 or 9 and refer to the number itself, visible from either the self-perspective or the other person's perspective ("Does he see a 6?"). Participants are asked to decide as fast and as accurately as possible whether the written prompt correctly depicts the picture by pressing the corresponding key. In the level-2 task, the number 6 or 9 is always visible to the participant and the avatar, but the number is either presented vertically so that the number looks like the same number from both perspectives (Consistent trials) or horizontally on the table so that 6 or 9 look different – like a 9 or 6, respectively – to the participant and the avatar (Inconsistent trials).

For both level-1 and -2 VPT, reaction times (RTs) and accuracy were collected across conditions [2 (Perspective: Self vs. Other) x 2 (Consistency: Consistent vs. Inconsistent)]. As in the original paradigm (Samson et al., 2010), only matching trials ("yes" response) were analyzed because mismatching trials ("no" response) are artificially unbalanced (number prompts in Consistent mismatching trials can never match the Self or Other perspective and are thus particularly easy to respond to). Overall, for each VPT task (level-1 and level-2), there were 24 trials in each condition (Matching x Perspective x Consistency) plus an 8-trial practice session. In both tasks, participants were told they had less than 2 sec to provide a response; which would otherwise be considered as an error.

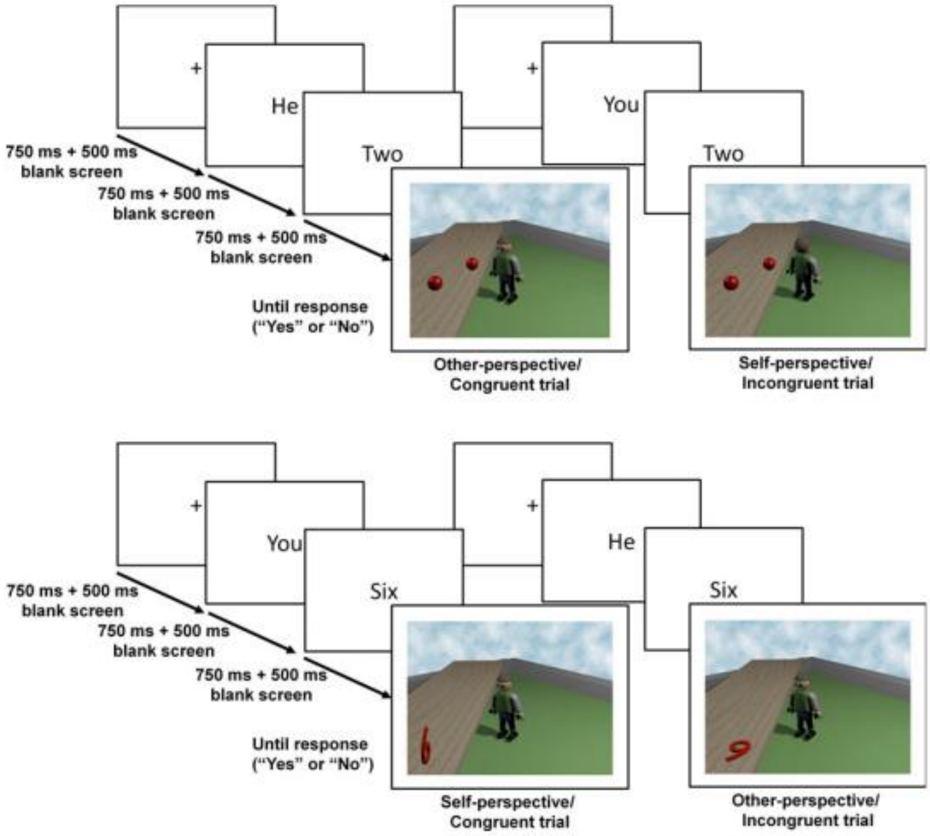

Figure 1. Time–course of a trial in the levels-1 and -2 visual perspective-taking tasks.

Procedure

The experiment had a randomized cross over design with two conditions, a total sleep deprivation (TSD) and a regular sleep (RS) condition, held one week apart (Figure 2).

Before the experimental night, participants followed a 3-day regular sleep schedule as verified by sleep diaries confirmed by wrist actigraphy. In the TSD condition, participants stayed in the laboratory from 19:00 to 10:00 and were constantly monitored by two experimenters. Throughout the course of the TSD night, participants were instructed to remain seated and to engage in non-strenuous activities (e.g. reading, surfing the Internet or watching movies). Free water and hourly isocaloric meals were available. Every hour throughout the TSD night, subjects performed the PVT and completed the KSS to estimate the evolution of objective and subjective vigilance levels, respectively. In the RS condition, participants arrived at the laboratory in the morning for the testing session after a night of sleep at home. At 9:00, all participants performed a battery of tasks (± 45 min) always carried out in the following order: KSS, PVT, mood scales, Flexibility, VPT level-1, VPT level-2, visual-rotation (not analyzed here), N-back and Stroop.

Statistical analyses

Statistical analyses were performed using IBM SPSS Statistics 21.0 (IMB corp., Armonk, NY). Data expressed as mean ± standard deviation are reported Table 1. Significance level was set at p<0.05 (two-tailed). Post-hoc tests in ANOVAs were performed using paired Student t-tests; Bonferroni-corrected significance levels are added when relevant, but did not modified statistical interpretations.

In the PVT, vigilance was computed using the Reciprocal Response Time (RRT = mean 1/RTs; Basner & Dinges, 2011). Lower RRT reflects poorer performance.

In the other tasks, RTs for correct responses and error rates (ER) were merged to compute inverse efficiency scores (IES= RT/(1-ER)). The IES allows comparing different groups with a single measure. IES results were in line with RT and ER results (see Supporting information section 2). Outliers (> 2SD outside the mean of the group in the TSD or RS condition) were computed for each task separately. Participants excluded in the different analyses are thus different individuals.

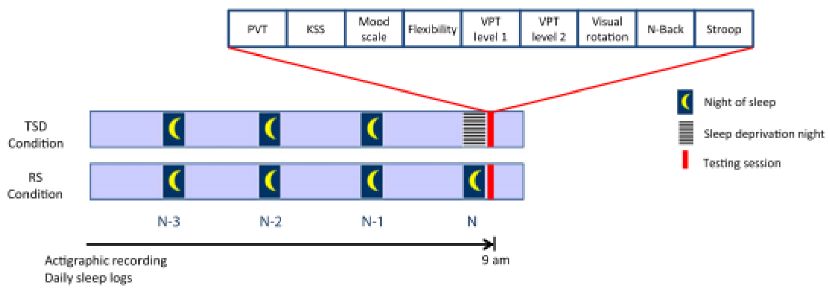

Figure 2. Experimental design. Regular sleep condition (RS), total sleep deprivation condition (TSD), Karolinska Sleepiness Scale (KSS), Psychomotor Vigilance Task (PVT) and visual perspective-taking task (VPT).

Results

Sleepiness and vigilance

Participants showed higher mean sleepiness scores (KSS) for the five first hours of the TSD night (7 pm - 11 pm, 3.410 ± 1.298) than for the five last hours (5 am - 9 am, 7.880 ± 1.100; t_{19} = -13.705; $P < .001$) and higher vigilance level (higher RRT) for the five first hours of the TSD night (7 pm - 11 pm, 3.126 ± 0.328) than for the five last hours (5 am - 9 am, 2.732 ± 0.480; t_{19} = 7.394; $P < .001$). At 9 AM, before the testing session, participants in the TSD condition reported significantly higher sleepiness (t_{19} = 10.971, $P < .001$) and showed less vigilance (t_{19} = 5.658, $P < .001$) than in the RS condition. For more information about sleep variables the days before the testing sessions and during the TSD night, see Supporting information section 3.

Mood state

Paired t-tests on self-reported feelings before the testing session did not reveal any differences between the RS and TSD conditions (all *P*s > .119).

Flexibility task

A repeated ANOVA was computed on the mean IES with Sleep (RS vs TSD) and Switching (Repeat vs Switch trials) as within-subject variables. Results showed a significant effect of Sleep ($F_{1,19}$ = 6.007, P = .024) with better performance in the RS condition, Switching ($F_{1,19}$ = 94.786, P < .001) with better performance in Repeat trials, and a Sleep x Switching interaction ($F_{1,19}$ = 5.228, P = .034). Analysis of the Sleep x Switching interaction disclosed a higher switching cost (Switch *minus* Repeated trials) after TSD than after a whole night sleep (t_{19} = 2.286, P = .034) (Figure 3).

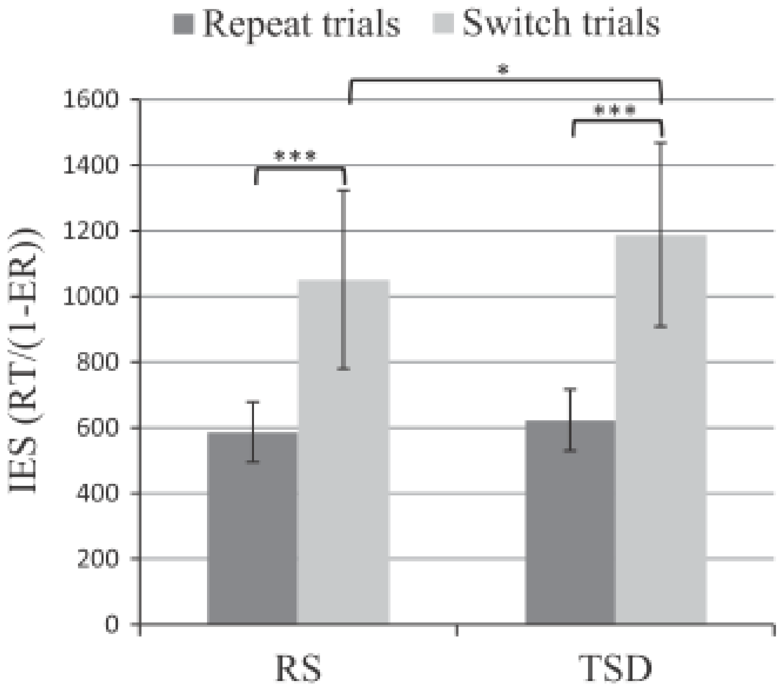

Figure 3. Performance in the flexibility task. Task-switching performance in the flexibility task computed on the inverse efficiency scores (IES) as a function of factors sleep (RS versus TSD) and trials (repeat versus switch trials). RS: regular sleep group; TSD: total sleep deprivation group. ***P < 0.001; *P < 0.05. Error bars indicate standard deviations.

Working memory task

A repeated 2 (Sleep: TSD vs. RS) x 2 (Load: 0- vs 2-back) ANOVA was conducted on the mean IES. Three participants were not included in the analyses, one for technical reasons and two for outlying performance in the TSD condition. The ANOVA revealed a main effect of Sleep ($F_{1,16}$ = 4.990, P = .040) with better performance in the RS condition, and a main effect of Load ($F_{1,16}$ = 43.097, P < .001) with better performance in the 0-back (low working memory load) trials, but no Sleep x Load interaction ($F_{1,19}$ = 1.574, P = .228).

Table 1 Significant effects of sleep through within-subject comparison total sleep deprivation versus rested sleep

Measure	*Effects of sleep*	*Total sleep deprivation* *Mean ± SD*	*Rested sleep* *Mean ± SD*
PVT RTT ($msec^{-1}$)	Main effect	2.853 ± 0.441	3.153 ± 0.342
KSS	Main effect	7.750 ± 1.585	3.150 ± 1.226
Mood	No effect		
Flexibility (IES)	Main effect	905.785 ± 151.227	818.877 ± 169.902
	Sleep × switch	Repeated: 623.162 ± 93.282	Repeated: 586.699 ± 91.851
		Switch: 1188.408 ± 279.603	Switch: 1051.055 ± 271.684
N-Back (IES)	Main effect	531.959 ± 98.383	499.503 ± 93.060
Stroop (IES)	No main effect		
	Sleep × congruency	Con: 661.092 ± 129.516	Con: 713.394 ± 90.938
		Neut: 729.843 ± 83.751	Neut: 806.856 ± 181.812
		Incon: 995.803 ± 222.552	Incon: 766.845 ± 158.547
VPT level 1 (IES)	Main effect	1382.903 ± 633.011	887.978 ± 276.320
	Sleep × congruency	Con: 1178.765 ± 458.077	Con: 825.219 ± 273.544
		Incon: 1587.042 ± 861.922	Incon: 950.737 ± 291.657
VPT level 2 (IES)	Main effect	1367.979 ± 525.226	1059.058 ± 343.254

PVT RTT: reciprocal reaction time in the Psychomotor Vigilance Task; KSS: Karolinska Sleepiness Scale; IES: Inverse Efficiency Scores (IES = reaction time (RT)/1-error rate (ER)]; VPT: Visual Perspective-taking Task; Con: congruent trials; Neut: neutral trials; Incon: incongruent trials; SD: standard deviation.

Inhibition task

A repeated 2 (Sleep: TSD vs. RS) x 3 (Congruency: Congruent vs. Neutral vs. Incongruent) ANOVA was conducted on the mean IES. One participant was excluded due to outlying performance in the TSD and RS conditions. The ANOVA showed no main effect of Sleep ($F_{1,18}$ = 2.017, P = .173), but a main effect of Congruency ($F_{1,18}$ = 23.441, P < .001), and a significant Sleep x Congruency interaction ($F_{1,18}$ = 27.967, P < .001).

Analysis of the Sleep x Congruency interaction showed that inhibition (Incongruent – Neutral trials) and congruency (Incongruent – Congruent trials) effects were significantly higher in the TSD condition (*critical* $P_{\text{Bonferroni}}$ = .017; t_{18} = 5.371, P < .001; t_{18} = 7.695, P < .001; respectively) (Figure 4). The facilitation effect (Neutral – Congruent trials) did not differ between conditions (t_{18} = .608, P = .551).

To sum up, TSD altered cognitive flexibility and inhibition but not working memory.

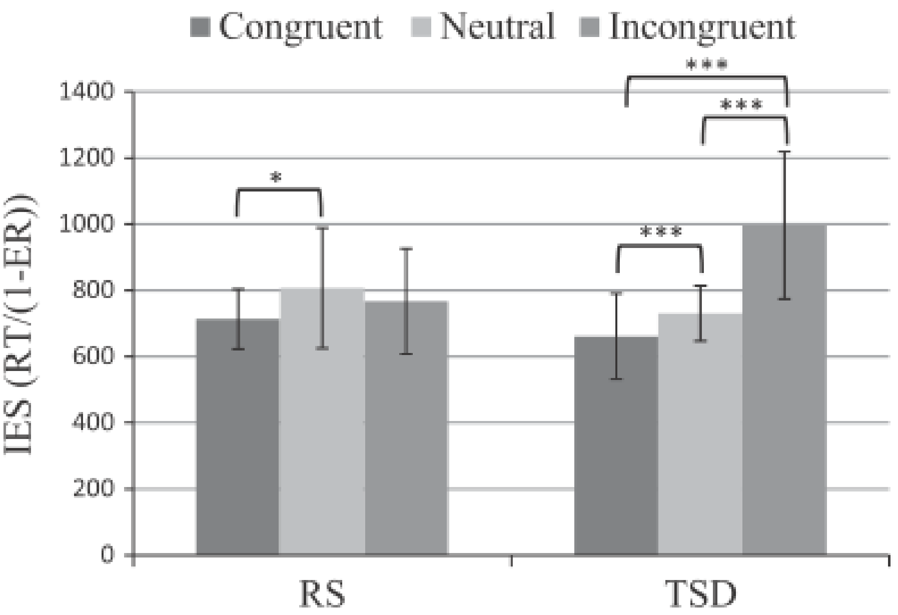

Figure 4. Performance in the Stroop task. Performance in the Stroop task computed on the inverse efficiency scores (IES) as a function of factors sleep (RS versus TSD) and congruency (congruent versus neutral versus incongruent). RS: regular sleep group; TSD: total sleep deprivation group. ***$P < 0.001$; *$P < 0.05$. Error bars indicate standard deviations.

Level-1 visual perspective taking task

A repeated 2 (Sleep: TSD vs. RS) x 2 (Perspective: Other- vs. Self-perspective) x 2 (Congruency: Congruent vs. Incongruent) ANOVA was conducted on the IES. Two participants were not included in the analyses for outlying performance (one in the TSD condition, one in the RS condition). The ANOVA showed a main effect of Sleep ($F_{1,17} = 15.647$, $P = .001$) with better performance in the RS condition, a marginally significant main effect of Perspective ($F_{1,17} = 3.302$, $P = .087$) with better performance on the Self-perspective trials, a main effect of Congruency ($F_{1,17} = 14.157$, $P = .002$) with better performance on Congruent trials, a significant Perspective x Congruency interaction ($F_{1,17} = 5.295$, $P = .034$) with a higher Congruency effect on Other-perspective trials, and a significant Sleep x Congruency interaction ($F_{1,17} = 5.295$, $P = .034$). Other interactions were non-significant (Ps > .121). The Congruency, Perspective, and Congruency x Perspective effects replicated previous studies (Samson et al., 2010; Surtees et al., 2016).

Analysis of the Sleep x Congruency interaction showed that the Congruency effect (Incongruent vs. Congruent trials) was significantly higher in the TSD than in the RS conditions

(t_{17} = 2.301, P = .034; Figure 5). A general effect of Sleep was also observed with better performance in the RS than in the TSD condition for both Congruent (t_{17} = 4.337, P < .001) and Incongruent (t_{17} = 3.545, P = .002) trials.

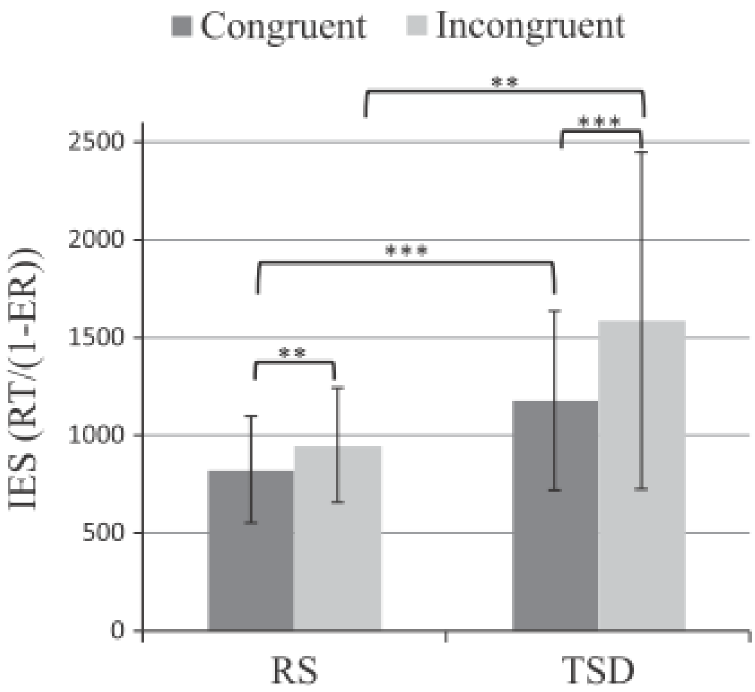

Figure 5. Level-1 visual perspective-taking performance. Level-1 visual perspective-taking performance computed on the inverse efficiency scores (IES) as a function of factors sleep (RS versus TSD) and congruency (congruent versus incongruent trials). RS: regular sleep group; TSD: total sleep deprivation group. ***P < 0.001; **P < 0.01; *P < 0.05. Error bars indicate standard deviations.

Contribution of executive functions and vigilance to the effect of TSD on the Congruency effect.

To investigate whether the impact of TSD on congruency effects is better explained by changes in executive functioning or vigilance, we computed correlations between the Congruency effect (Incongruent minus Congruent trials) in the level-1 VPT task, the executive functioning effects (switch cost in the flexibility task, inhibition and congruency effect in the Stroop task), and the level of vigilance (PVT RRT). Correlations between executive functioning effects and the congruency effect in the level-1 VPT task were not significant (all Ps > .663). However, the level-1 VTP congruency effect was negatively correlated with vigilance (r = -0.498, P =.035). We also conducted a within-participant mediation analysis (Montoya & Hayes, 2016) aimed at controlling whether the change in level-1 VTP congruency effects from RS to

TSD conditions is mediated by the change in vigilance level. A simple mediation model was computed with the factor Sleep Condition (RS vs. TSD) and the level-1 VTP congruency effect as the dependent variable, and the PVT RRT as the mediator variable. The indirect effect was not significant (Sobel's test $P = .124$), suggesting that the change in congruency effect between RS and TSD is not significantly mediated by the change of vigilance. For more information about the correlational and mediation analyses, see supporting information section 4).

Level-2 visual perspective taking task

A repeated 2 (Sleep: TSD vs. RS) x 2 (Perspective: Other- vs. Self-perspective) x 2 (Congruency: Congruent vs. Incongruent) ANOVA was conducted on the IES. Two participants were excluded from the analysis (one due to missing data, one with outlying performance in the TSD condition). The ANOVA showed a main effect of Sleep ($F_{1,17} = 17.929$, $P = .001$) with better performance in the RS condition, a non-significant main effect of Perspective ($F_{1,17} = .510$, $P = .824$), and a main effect of Congruency ($F_{1,17} = 23.019$, $P < .001$) with better performance on Congruent trials. All interactions were non-significant (ps > .213). Thus, unlike in the level-1 VPT task, no interaction was found between Sleep and Congruency. To quantify evidence in favor of the null hypothesis (i.e. no interaction) as compared to the alternative hypothesis (i.e. interaction), complementary Bayesian analyses were performed and suggest that the lack of interaction was 3.597 times more likely than the alternative hypothesis and that this was not driven by a smaller Congruency effect (see Supporting information section 5).

Discussion

This study examined the impact of one night of TSD on level-1 and -2 visual perspective taking, which are pivotal skills for successful social interactions. Results revealed poorer global performance in the level-1 and -2 VPT tasks after a TSD night. In addition, TSD was found to impact perspective-taking performance specifically when self- and other-centered visual perspectives are conflicting with each other in the level-1 VPT task. This increased congruency effect reflects a higher difficulty in handling the conflict between perspectives after TSD and thus go against the "state instability" theory which claims that vigilance drop leads to an overall decrease in performance with indirect effects on executive functions. These results are in line with a previous study showing a similar increase in the consistency effect for level-1 visual perspectives when participants simultaneously completed a task taxing executive function (Qureshi et al., 2010). The authors concluded that executive functions are needed to handle perspectives conflicts but not to compute the perspectives *per se*. In the current study, results from our executive tasks indicated that TSD also alters cognitive flexibility and inhibition. Our results might thus give some credence to the idea that sleep loss directly hampers executive functioning. Importantly however, we did not find any linear association between the reduction of performance at handling conflicting level-1 visual perspectives following TSD and reductions of performance across the executive tasks. Hence, we cannot conclude that the increased difficulty at conflict handling after TSD (vs. a night of sleep) is directly or solely linked to impaired executive functioning.

Another potential explanation is that the increased difficulties in handling perspectives conflict after TSD result from a decline of vigilance. Congruently, performance at conflict handling difficulties was negatively correlated with vigilance levels. However, the reduction of performance for conflict handling was not significantly mediated by the drop in vigilance.

The reduction of conflict handling was observed in the level-1 VTP task but not in the level-2. This is further evidence that these two abilities are distinct and separable (as proposed by Flavell et al., 1981). One key difference between the two forms of perspective taking is that inferring someone's level-1 visual perspective is effortless (Qureshi et al., 2010) whereas it is effortful to infer a level-2 perspective (Surtees et al., 2016; Surtees et al., 2012). Hence, the absence of an effect of TSD specifically affecting conflict handling in the level-2 VPT task raises the possibility that performance on congruent and incongruent perspectives trials was similarly impacted by TSD. This would result in a general reduction of performance on the level-2 VPT task, which is what we observed.

An alternative explanation stems from the higher difficulty of the level-2 VPT task compared to the level-1 (indicated by higher IES, longer RT, and higher consistency effect, see also Supplementary sections S2 and S5). Indeed, performance in complex working memory tasks often seems less affected by TSD than performance in simpler tasks (Terán-Pérez et al., 2012). This finding is explained by the fact that performing a challenging task temporarily increases arousal, thus minimizing the TSD-related decline in performance (Wilkinson, 1965). Congruently, in the TSD condition, vigilance level and conflict handling performance were correlated in the level-1 but not in the level-2 VPT. However, as mentioned before, mediation analyses showed that the difference between the Congruency effect in the sleep and TSD conditions is not fully explained by vigilance.

The only study that investigated the impact of sleep loss on cognitive perspective taking showed slower reaction time on a sarcasm detection task after TSD but no difference in the congruency effect (Deliens et al., 2015a). However, the sarcasm detection task included Other's perspective trials only. Not having to switch from one perspective to another across trials may release cognitive resources and make handling the conflict between perspectives less effortful.

To conclude, we show with this study that TSD modulates VPT ability; which further supports the view that perspective taking is not a wholly static trait-like characteristic (Bukowski & Samson, 2017). Besides a general decline of performance on both level-1 and level-2 VPT, level-1 was particularly affected in situations where one's own and another person's perspectives were conflicting. Sleep problems are a frequent complaint in people presenting social-emotional difficulties (e.g. autism spectrum disorder, Deliens et al., 2015b ; schizophrenia, Monti et al., 2013). Our findings suggest that sleep loss often resulting from sleep disorders might mediate part of their social-emotional difficulties, an hypothesis to be investigated in future studies.

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Supporting information

Data S1. Mood and personality questionnaires

Table S1. Personality traits

Data S2. Supplementary results: Reaction times and error rates results

Table S2. Report of statistically significant effects of sleep through within-subject comparison Sleep-deprivation vs. Regular-sleep on RT and ER

Data S3. Sleep variables the days before the testing sessions and during the TSD night

Data S4. Contribution of executive functions and vigilance to the effect of TSD on the Congruency effect

Table S4. Correlations the Congruency effect in the level-1 VPT task, executive functions and vigilance

Figure S4a. Relation of level-1 VTP and vigilance in the TSD condition

Figure S4b. Diagram of the mediation model.

Data S5. Bayesian analyses

Supporting information

Data S1. Mood and personality questionnaires

Happiness, anxiety, shame and guilt were self-rated at the start of each testing session on a 7-point Likert. The mood questionnaire contains four target questions (here marked with an asterisk) and nine fillers:
Instruction: *How much do you feel…*

1. Happy, thrilled, blooming? *
2. Sad, depressed, blue?
3. Angry, annoyed, outraged at yourself?
4. Angry, annoyed, outraged toward somebody else?
5. Scared, afraid, frightened ?
6. Disdainful, scornful?
7. Anxious, tensed, nervous? *
8. Disgusted, repulsed?
9. Amused, joyful, cheerful?
10. Surprised, stunned, astonished?
11. Attentive, concentrating, alert?
12. Ashamed, disgraced, humiliated? *
13. Guilty, blameworthy, responsible? *

To assess the link between VPT performances and personality traits and mood disorders, questionnaires were administered. Depressive tendencies were assessed using the Beck's Depression scale (Beck et al., 1988). Empathy and perspective-taking abilities were assessed using the Interpersonal Reactivity Index (IRI; Davis, 1983), a self-report questionnaire measuring interpersonal reactivity on four subscales: perspective taking (PT), fantasy (FS), empathic concern (EC), and personal distress (PD). Participants also completed the Empathy Quotient (EQ; Baron-Cohen and Wheelwright, 2004) as a measure of subject's cognitive and affective perspective taking. Autistic traits and Alexithymia were assessed using the Autism Spectrum Quotient (AQ; Baron-Cohen et al., 2001, Sonie et al., 2011) and the Toronto Alexithymia Scale (TAS; Bagby et al., 1994, Loas et al., 1997), respectively.
The table below indicates descriptive statistics for these questionnaires. The maximum score observed in our sample for the Beck's Depression scale was 6, which corresponds to the "normal ups and downs" category. No participant scored in the alexithymic range on the Toronto Alexithymia scale (cut-off: TAS-20 < 61) or on the autistic range on the Autism Spectrum Quotient (cut-off: AQ < 32).

Table S1. Personality traits

	TAS	Beck	IRI PT	IRI FS	IRI PD	IRI EC	AQ	EQ
Mean	43.30	2.900	19.05	22.05	13.95	20.80	15.35	41.40
Std. Deviation	7.733	1.917	4.286	3.034	4.904	3.172	3.787	9.976
Minimum	29.00	0.000	11.00	17.00	5.000	15.00	10.00	24.00
Maximum	57.00	6.000	25.00	26.00	22.00	27.00	24.00	57.00

Data S2. Supplementary results: Reaction times and error rates results

Table S2. Report of statistically significant ($p < .05$) effects of sleep through within-subject comparison Sleep-deprivation vs. Whole-sleep on RT and ER

Measure	**Effects of Sleep**	**Sleep Deprivation** M±SD	**Rested Sleep** M±SD
N-back (ER)	Main effect	.107 ± .075	.057 ± .054
VPT level 1			
RT	Main effect	977.22 ± 287.43	820.69 ± 263.71
	Sleep X Congruency	Con: 914.89 ± 259.72	Con: 783.63 ± 259.45
		Incon: 1039.54 ± 320.35	Incon: 857.76 ± 272.70
	Sleep X Perspective	Self: 939.07 ± 288.51	Self: 817.38 ± 285.82
		Other: 1015.36 ± 288.51	Other: 824.01 ± 246.26
ER	Main effect	.208 ± .176	.064 ± .072
VPT level 2			
RT	Main effect	1146.81 ± 381.39	920.03 ± 231.65
ER	Main effect	.123 ± .109	.062 ± .086
Mental rotation			
RT	Main effect	1174.70 ± 311.54	987.55 ± 188.66
ER	Main effect	.180 ± .107	.139 ± .106

Mental flexibility

Reaction times

A repeated ANOVA was computed on the RTs of the correct responses with Sleep (RS vs TSD) and Switching (Repeat vs Switch trials) as within-subject variables. The ANOVA showed an non-significant effect of Sleep [$F(1, 19) = 2.960$, $p = .102$, $\eta_p^2=.135$], a main effect of Switching [$F(1, 19) = 118.415$, $p < .001$, $\eta_p^2=.862$], with better performance on Repeat trials, and a non-significant Sleep x Switching interaction [$F(1, 19) = 1.326$, $p = .264$, $\eta_p^2=.065$].

Numerical differences indicate however better performance in RS condition than TSD condition (RS: 781.25 ± 163.32; TSD: 834.06 ± 107.38) and a non-significantly higher Switching effect in the TSD condition (Repeat: 607.20 ± 85.54; Switch: 1060.93 ± 185.01) than in the RS condition (Repeat: 575.65 ± 93.22; Switch: 986.85 ± 254.12).

Error rates

A repeated ANOVA was computed on the ERs with Sleep (RS vs TSD) and Switching (Repeat vs Switch trials) as within-subject variables. The ANOVA showed an non-significant effect of Sleep [$F(1, 19) = 2.010$, $p = .172$, $\eta_p^2=.096$], a main effect of Switching [$F(1, 19) = 20.009$, $p < .001$, $\eta_p^2= .513$], with better performance on Repeat trials, and a non-significant Sleep x Switching interaction [$F(1, 19) = 1.565$, $p = .226$, $\eta_p^2=.076$].

Numerical differences indicate however better performance in RS condition than TSD condition (RS: .038 ± .035; TSD: .058 ± .061) and a non-significantly higher Switching effect in the TSD condition (Repeat: .024 ± .032; Switch: .092 ± .101) than in the RS condition (Repeat: .018 ± .026; Switch: .058 ± .056).

In sum, results from RTs and ERs are consistent in indicating a trend towards an higher Switching effect following sleep deprivation.

Working memory

One participant's data could not be analyzed and for two participants the mean IES performance was 2 SD outside the mean of the group; these 3 participants were not included in the analyses.

Reaction times

A repeated 2 (Sleep: TSD vs. RS) x 2 (Load: 0- vs 2-back) ANOVA was conducted on the RTs of correct responses. The ANOVA disclosed a non-significant main effect of Sleep [$F(1, 16) = 1.409$, $p = .253$, $\eta_p^2= .081$] and a main effect of Load [$F(1, 16) = 31.795$, $p < 0.001$, $\eta_p^2= .665$], with better performance on low working memory load trials, and a non-significant Sleep x Load interaction [$F(1, 19) = 0.008$, $p = .931$, $\eta_p^2 =.001$].

Error rates

A repeated 2 (Sleep: TSD vs. RS) x 2 (Load: 0- vs 2-back) ANOVA was conducted on the ERs. The ANOVA disclosed a main effect of Sleep [$F(1, 16) = 13.600$, $p = .002$, $\eta_p^2= .459$], with better performance in the RS condition, a main effect of Load [$F(1, 16) = 39.903$, $p < 0.001$, $\eta_p^2= .714$], with better performance on low working memory load trials, and a marginally significant Sleep x Load interaction [$F(1, 16) = 4.423$, $p = .052$, $\eta_p^2 =.217$].

Analysis of the Sleep x Load interaction through paired t-tests showed better performance for 0-back trials (TSD: .038 ± .057; RS: .015 ± .029) than 2-back trials (TSD: .176

± .116; RS: .100 ± .087) in both the TSD (t(16) = 5.487, p < .001) and RS conditions (t(16) = 4.859, p < .001). This working memory load effect (2-back vs. -back trials) was marginally significantly higher in the TSD than the RS conditions (t(16) = 2.103, p = .052, *d* = 0.510). A general effect of Sleep was also observed with better performance in the RS than in the TSD condition for both 2-back trials (t(16) = 3.305, p = .004) and 0-back trial but the difference is marginally significant for the latter condition (t(16) = 1.926, p = .072).

Stroop Task

One participant's mean IES performance was 2 SD outside the mean of the group, his performance was not included in the analyses.

Reaction times

A repeated 2 (Sleep: TSD vs. RS) x 3 (Congruency: Congruent vs. Neutral vs. Incongruent) ANOVA was conducted on the RTs of correct responses. The ANOVA showed a non-significant main effect of Sleep [F(1, 18) = 0.985, p = .334, η_p^2=.052], a main effect of Congruency [F(1, 18) = 41.183, p<0.001, η_p^2=.696], with better performance on Congruent trials, and a non-significant Sleep x Congruency interaction [F(1, 18) = 0.009, p = .926, η_p^2=.001].

Numerical differences indicate however better performance in RS condition than TSD condition (RS: 692.34 ± 102.37; TSD: 716.33 ± 109.93), a non-significantly (slightly) higher Congruency effect (Incongruent vs. Congruent trials) in the TSD condition (Congruent: 650.75 ± 118.39; Incongruent: 803.99 ± 150.63) than in the RS condition (Congruent: 620.03 ± 87.04; Incongruent: 770.66 ± 177.86), and a non-significantly higher Inhibition effect (Incongruent vs. Neutral trials) in the TSD condition (Neutral: 694.24 ± 82.81) than in the RS condition (Neutral: 686.34 ± 80.06).

Error rates

A repeated 2 (Sleep: TSD vs. RS) x 3 (Congruency: Congruent vs. Neutral vs. Incongruent) ANOVA was conducted on the ERs. The ANOVA showed a non-significant main effect of Sleep [F(1, 18) = 0.019, p = .891, η_p^2=.001], a main effect of Congruency [F(1, 18) = 36.366, p<0.001, η_p^2=.669], with better performance on Congruent trials, and a non-significant Sleep x Congruency interaction [F(1, 18) = 0.419, p = .526, η_p^2=.023].

Numerical differences indicate almost identical performance in RS condition and TSD condition (RS: .081 ± .053; TSD: .079 ± .042), a non-significantly higher Congruency effect (Incongruent vs. Congruent trials) in the TSD condition (Congruent: .013 ± .026; Incongruent: .178 ± .114) than in the RS condition (Congruent: .025 ± .043; Incongruent: .174 ± .121), and an almost identical Inhibition effect (Incongruent vs. Neutral trials) in the TSD condition (Neutral: .048 ± .061) and the RS condition (Neutral: .044 ± .044).

In sum, results from RTs and ERs are consistent in indicating a trend towards a higher Congruency effect following sleep deprivation.

Level-1 visual perspective taking task

For two participants, the mean IES performance was at least 2SD outside from the mean of the group; these participants were not included in the analyses.

Reaction times

A repeated 2 (Sleep: TSD vs. RS) x 2 (Perspective: Other- vs. Self-perspective) x 2 (Congruency: Congruent vs. Incongruent) ANOVA was conducted on the RTs of correct responses. The ANOVA showed a main effect of Sleep [$F(1, 17) = 19.917$, $p < .001$, $\eta_p^2=.540$], with better performance in the RS condition, a main effect of Perspective [$F(1, 17) = 4.895$, $p = .041$, $\eta_p^2=.224$], with better performance on the Self-perspective trials, a main effect of Congruency [$F(1, 17) = 30.645$, $p < .001$, $\eta_p^2=.643$], with better performance on Congruent trials; a significant Sleep x Perspective interaction [$F(1, 17) = 4.619$, $p = .046$, $\eta_p^2= .214$], a significant Sleep x Congruency [$F(1, 17) = 7.059$, $p = .017$, $\eta_p^2= .293$], a significant Perspective x Congruency interaction [$F(1, 17) = 33.637$, $p < .001$, $\eta_p^2= .664$], with a higher Congruency effect on Other-perspective trials, and a non-significant Sleep x Perspective x Congruency interaction [$F(1, 17) = 0.007$, $p = .935$, $\eta_p^2= .001$].

Analysis of the Sleep x Perspective interaction through paired t-tests showed better performance on Self- than Other-perspective trials in the TSD condition ($t(17) = 2.592$, $p < .019$) but not the RS conditions ($t(17) = 0.348$, $p = .732$). A general effect of Sleep was also observed with better performance in the RS than in the TSD condition for both Other ($t(17) = 5.702$, $p < .001$) and Self trials ($t(17) = 2.822$, $p = .012$). The Self-perspective advantage was significantly higher in the TSD than the RS conditions ($t(17) = 2.149$, $p = .046$). This barely significantly higher egocentric advantage following sleep privation is to interpret with caution as it is partly driven by the co-occurring increased Congruency effect, and more specifically, the increased egocentric interference.

Analysis of the Sleep x Congruency interaction through paired t-tests showed better performance for Congruent than Incongruent trials in both the TSD ($t(17) = 5.377$, $p < .001$) and RS conditions ($t(17) = 4.368$, $p < .001$). This Congruency effect (Incongruent vs. Congruent trials) was significantly higher in the TSD than the RS conditions ($t(17) = 2.657$, $p = .017$, $d = 0.626$). A general effect of Sleep was also observed with better performance in the RS than in the TSD condition for both Congruent ($t(17) = 3.933$, $p = .001$) and Incongruent trials ($t(17) = 4.651$, $p < .001$).

Error rates

A repeated 2 (Sleep: TSD vs. RS) x 2 (Perspective: Other- vs. Self-perspective) x 2 (Congruency: Congruent vs. Incongruent) ANOVA was conducted on the ERs. The ANOVA showed a main effect of Sleep [$F(1, 17) = 10.397$, $p = .005$, $\eta_p^2= .380$], with better performance in the RS condition, and a main effect of Congruency [$F(1, 17) = 14.187$, $p = .002$, $\eta_p^2= .455$], with better performance on Congruent trials. The main effect of Perspective and all interactions were not significant [Perspective: $F(1, 17) = 0.281$, $p = .603$, $\eta_p^2 =.016$; Sleep x Perspective: $F(1, 17) = 0.794$, $p = .385$, $\eta_p^2= .045$], Sleep x Congruency: $F(1, 17) = 0.890$, $p = .359$, $\eta_p^2= .050$; Perspective x Congruency: $F(1, 17) = 1.312$, $p = .268$, $\eta_p^2= .072$; Sleep x Perspective x Congruency interaction: $F(1, 17) = 0.031$, $p = .863$, $\eta_p^2= .002$].

Numerical differences indicate however a non-significantly higher Congruency effect in the TSD condition (Congruent: $.174 \pm .039$; Incongruent: $.242 \pm .047$) than in the RS condition (Congruent: $.042 \pm .014$; Incongruent: $.087 \pm .0233$) and also a non-significantly larger Self-perspective advantage but this time in the RS condition (Self: $.053 \pm .015$; Other: $.076 \pm .024$) than in the TSD (Self: $.209 \pm .041$; Other: $.207 \pm .047$).

In sum, results from RTs and ERs are consistent in indicating a trend towards a higher Congruency effect following sleep deprivation but are inconsistent for the Perspective effect.

Level-2 visual perspective taking task

For one participant, data could not be analyzed and for one participant, mean IES performance was at least 2 SD outside from the mean of the group; these participants were not included in the analyses.

Reaction times

A repeated 2 (Sleep: TSD vs. RS) x 2 (Perspective: Other- vs. Self-perspective) x 2 (Congruency: Congruent vs. Incongruent) ANOVA was conducted on the RT of correct responses. The ANOVA showed a main effect of Sleep [$F(1, 17) = 14.318$, $p = .001$, $\eta_p^2 = .457$], with better performance in the RS condition, a non-significant main effect of Perspective [$F(1, 17) = 1.620$, $p = .220$, $\eta_p^2 = .087$], a main effect of Congruency [$F(1, 17) = 25.265$, $p < .001$, $\eta_p^2 = .598$], with better performance on Congruent trials, a non-significant Sleep x Perspective interaction [$F(1, 17) = 1.551$, $p = .230$, $\eta_p^2 = .084$], a non-significant Sleep x Congruency [$F(1, 17) = 0.078$, $p = .784$, $\eta_p^2 = .005$], a non-significant Perspective x Congruency interaction [$F(1, 17) = 0.572$, $p = .460$, $\eta_p^2 = .033$], and a non-significant Sleep x Perspective x Congruency interaction [$F(1, 17) = 0.001$, $p = .978$, $\eta_p^2 = .001$].

Error rates

A repeated 2 (Sleep: TSD vs. RS) x 2 (Perspective: Other- vs. Self-perspective) x 2 (Congruency: Congruent vs. Incongruent) ANOVA was conducted on the ERs. The ANOVA showed a main effect of Sleep [$F(1, 17) = 9.700$, $p = .006$, $\eta_p^2 = .363$], with better performance in the RS condition, a non-significant main effect of Perspective [$F(1, 17) = 1.226$, $p = .284$, $\eta_p^2 = .067$], a main effect of Congruency [$F(1, 17) = 20.591$, $p < .001$, $\eta_p^2 = .548$], with better performance on Congruent trials, a non-significant Sleep x Perspective interaction [$F(1, 17) = 0.036$, $p = .852$, $\eta_p^2 = .002$], a non-significant Sleep x Congruency [$F(1, 17) = 1.015$, $p = .328$, $\eta_p^2 = .056$], a non-significant Perspective x Congruency interaction [$F(1, 17) = 1.085$, $p = .312$, $\eta_p^2 = .060$], and a non-significant Sleep x Perspective x Congruency interaction [$F(1, 17) = 1.106$, $p = .749$, $\eta_p^2 = .006$].

The Congruency, Perspective, and Congruency x Perspective effects observed on RTs and ERs replicated the previous studies using this paradigm (Surtees, et al., 2012; Surtees, et al., 2016).

Rotation task

For one participant, mean IES performance was at least 2 SD outside from the mean of the group; his performance was not included in these analyses.

Reaction times

A repeated 2 (Sleep: TSD vs. RS) x 2 (Verticality: Horizontal vs. Vertical position) x 2 (Rotation: No-Rotation vs. 90° Rotation) ANOVA was conducted on the RTs of correct responses. The ANOVA showed a main effect of Sleep [$F(1, 18) = 11.049$, $p = .004$, $\eta_p^2 = .380$], with better performance in the RS condition, a significant main effect of Verticality [$F(1, 18) = 4.429$, $p = .0496$, $\eta_p^2 = .197$], with better performance in the horizontal position condition, a main effect of Rotation [$F(1, 18) = 13.566$, $p = .002$, $\eta_p^2 = .430$], with better performance in the No-rotation condition, a non-significant Sleep x Verticality interaction [$F(1, 18) = 0.885$, $p = .359$, $\eta_p^2 = .047$], a non-significant Sleep x Rotation [$F(1, 18) = 0.286$, $p = .599$, $\eta_p^2 = .016$], a non-significant Verticality x Rotation interaction [$F(1, 18) = 0.145$, $p = .708$, $\eta_p^2 = .008$], and a non-significant Sleep x Verticality x Rotation interaction [$F(1, 18) = 0.037$, $p = .849$, $\eta_p^2 = .002$].

Error rates

A repeated 2 (Sleep: TSD vs. RS) x 2 (Verticality: Horizontal vs. Vertical position) x 2 (Rotation: No-Rotation vs. 90° Rotation) ANOVA was conducted on the ERs. The ANOVA showed a main effect of Sleep [$F(1, 18) = 7.132$, $p = .016$, $\eta_p^2 = .284$], with better performance in the RS condition, a significant main effect of Verticality [$F(1, 18) = 12.848$, $p = .002$, $\eta_p^2 = .416$], with better performance in the horizontal position condition, a main effect of Rotation [$F(1, 18) = 29.705$, $p < .001$, $\eta_p^2 = .623$], with better performance in the No-rotation condition, a non-significant Sleep x Verticality interaction [$F(1, 18) = 0.063$, $p = .804$, $\eta_p^2 = .003$], a non-significant Sleep x Rotation [$F(1, 18) = 0.991$, $p = .333$, $\eta_p^2 = .052$], a non-significant Verticality x Rotation interaction [$F(1, 18) = 2.736$, $p = .115$, $\eta_p^2 = .132$], and a non-significant Sleep x Verticality x Rotation interaction [$F(1, 18) = 1.392$, $p = .253$, $\eta_p^2 = .072$].

Data S3. Sleep variables the days before the testing sessions and during the TSD night

Concordance between actimetric recordings and self-reported sleep logs was controlled by visual inspection. Habitual sleep duration within the month preceding the testing session, indicated by the PSQI (mean 8h00 ± 55 min) did not differ from those reported in the SMHS questionnaire, all ps > .5, excepted a trend for a shorter experimental night (N) in the sleep condition (7h16 min ± 42 min), $t(19) = 2.921$; $p = .009$; p-value corrected for multiple comparisons = .063. These results show that participants maintained their sleep habits during the nights preceding the testing sessions. Similarly, a repeated measures ANOVA conducted on mean sleep duration as reported in the SMHS questionnaire with within-subjects factors Night (N-3, N-2, N-1) and Sleep (RS vs. TSD) failed to reveal main effects of Sleep, $F(1, 19) = .800$; $p = .382$, $\eta_p^2 = .040$, Night of sleep, $F(2, 38) = .246$; $p = .783$, $\eta_p^2 = .013$, or interaction, $F(2, 38) = .126$; $p = .882$, $\eta_p^2 = .007$.

During the TSD night, self-reported sleepiness (KSS) increased over successive hours (from well awake [2.650 ± 1.496] at 7 pm to very tired [7.750 ± 1.585] at 9 am), $F(14, 266) = 57.176$, $p < .001$, $\eta_p^2 = .751$. Repeated ANOVA conducted on PVT RRT data showed smaller RRT (from 3.160 ± 0.359 at 19:00 to 2.853 ± .441 at 9:00), $F(14, 266) = 10.480$, $p < .001$, $\eta_p^2 = .355$, across the TSD night.

At 9:00, before the testing session, participants in the TSD condition reported more sleepiness (KSS = 7.750 ± 1.585), $t(19) = 10.971$, $p < .001$, and presented smaller vigilance level (RRT = 2.853 ± .441), $t(19) = 5.658$, $p < .001$, than in the RS condition (KSS = 3.150 ± 1.226, RRT = 3.153 ± .342).

Data S4. Contribution of executive functions and vigilance to the effect of TSD on the Congruency effect.

To test whether the impact of TSD on level-1 VPT congruence effect is associated to changes in executive functioning or vigilance, we computed correlations between this effect, the executive functioning effects (switch cost in the flexibility task, inhibition and congruency effect in the Stroop task), and the level of vigilance (PVT RRT). Correlations between executive functioning effects and the congruency effect in the level-1 VPT task were not significant (all Ps > .663, see Table S4). However, the level-1 VTP congruency effect was negatively correlated with vigilance (r = -0.498, P =.035, Figure S4a). Grounded on this significant correlation, we run a Mediation analysis. Mediation analysis is a statistical method used to determine how some causal agent X (i.e., here the Condition variable, RS vs. TSD) transmits its effect on Y (i.e., the congruency effect in the level-1 VPT task). That is, what is the mechanism by which X (i.e., sleep deprivation) influences Y (i.e., the congruency effect)? The most basic mediation model possible consists of a causal antecedent variable linked to a single consequent variable through a single intermediary variable or mediator (M; i.e. here vigilance level). The simple mediation model is represented in conceptual diagram form (Figure S4b). This model contains two consequent variables (M) and (Y) and two antecedent variables (X) and (M), with X causally influencing Y and M, and M causally influencing Y. A simple mediation model is thus any causal system in which at least one causal antecedent X variable is proposed as influencing an outcome Y through a single intervening variable M. In such a model, there are two distinct pathways by which a specific X variable is proposed as influencing Y. One pathway leads from X to Y without passing through M and is called the direct effect of X on Y. The second pathway from X to Y is the indirect effect of X on Y through M. It first passes from antecedent X to consequent M and then from antecedent M to consequent Y. The indirect effect represents how Y is influenced by X through a causal sequence in which X influences M, which in turn influences Y. Mediation is, thus, ultimately a causal explanation. It is assumed that the relationships in the system are causal, and, importantly, that M is causally located between X and Y. It must be assumed, if not also empirically substantiated, that X causes M, which in turn causes Y. M cannot possibly carry X's effect on Y if M is not located causally between X and Y (Hayes, 2013). This is exactly the case in this study since TSD has been found to disturb vigilance level in numerous studies, and vigilance loss might influence perspective-taking abilities. Our hypothesis is a causal one because we hypothesized that the increase in the consistency effect for level-1 visual perspectives in TSD could be caused by attentional dysfunctions. However, since we are in a two-condition within-subject design, we had had to use a specific mediation analysis for within-participant, which has been recently developed by Montoya and Hayes (2016). As shown on Figure S4c, the principle is similar to the classical, between-subject Mediation analysis except that (1) the mediator (M) is the difference between vigilance level in the TSD and RS conditions; (2) the outcome is the difference in the congruency effect (Y) in the TSD and RS conditions; (3) the grand mean-centered means of the mediator is added as covariates in the model of $Y_2 - Y_1$.

Table S4. Correlations the Congruency effect in the level-1 VPT task, executive functions and vigilance

		PVT RRT	Flexibility Switch cost	Stroop Inhibition	Stroop Congruency effect
Level-1 VPT Congruency effect	*R*	-0.498	-0.073	0.026	0.114
	p-value	0.042	0.780	0.922	0.663

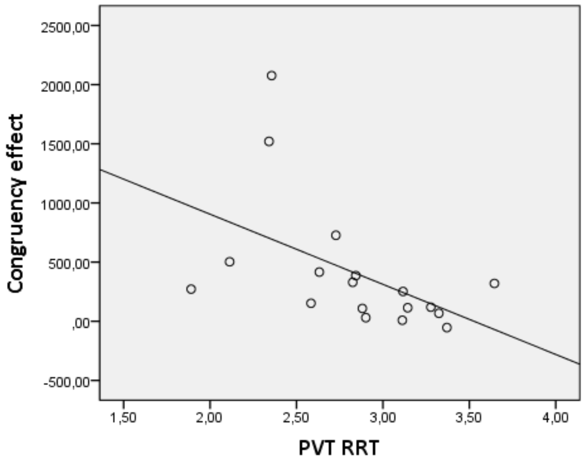

Figure S4a – Relation of level-1 VTP and vigilance in the TSD condition. Correlation between the level-1 VTP congruency effect (Incongruent minus Congruent trials) and the Reciprocal Reaction Time in the Psychomotor Vigilance Task (PVT RRT) in the Total Sleep Deprivation condition.

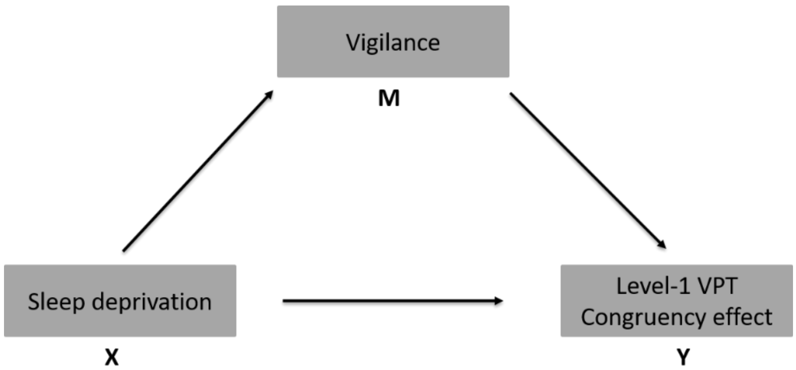

Figure S4b – Diagram of the classical between-subject mediation model. This model contains two consequent variables (M) and (Y) and two antecedent variables (X) and (M), with X causally influencing Y and M, and M causally influencing Y.

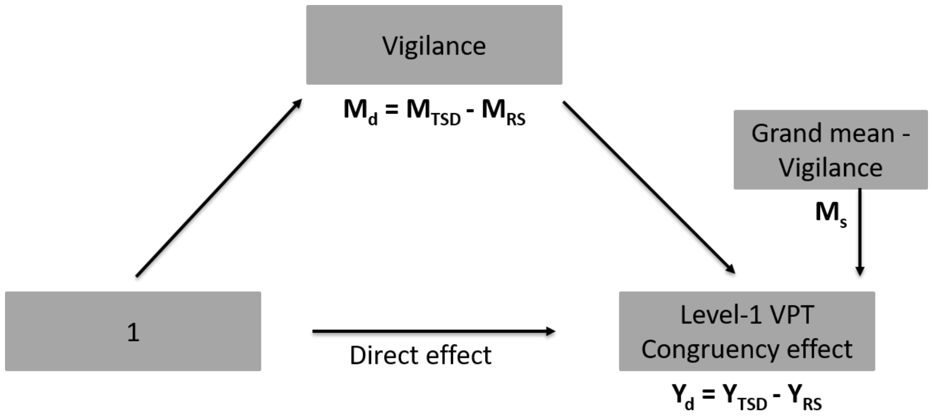

Figure S4c – Diagram of the two-condition within-subject mediation model.

Data S5. Bayesian analyses

Unlike in the level-1, the level-2 VPT congruency effect did not differ in the TSD and RS conditions ($p = 0.59$). Such a p-value leads usually to the interpretation that the null hypothesis (i.e. there is no effect of sleep conditions on the level-1 VPT congruency effect) cannot be rejected in favors of the alternative hypothesis (i.e. there is a difference in the level-1 VPT congruency effect between the TSD and RS conditions). However, null-hypothesis significance testing is a frequentist statistical approach grounding its conclusion on *"the extremeness of the data under the null hypothesis, with no consideration of the alternative hypothesis"* (Wagenmakers, 2007). Consequently, this statistical approach allows to make a statement about the null hypothesis but not about the alternative one. Concretely, a frequentist approach does not allow to preclude the possibility that neither the null nor the alternative hypothesis are good fits for the data. To assess the likelihood of our data under both the null (i.e. sleep deprivation has no impact on the Congruency effect) and alternative (i.e. sleep deprivation has no impact on the Congruency effect) hypotheses, we conducted a comparative method called Bayes factor analysis (Rouder et al., 2009) using JASP software (Love et al., 2015). The Bayes Factor (BF) is a ratio between the likelihood of the data fitting under the alternative hypothesis and the likelihood of the data fitting under the null hypothesis. A Bayes Factor greater than 3 is considered as substantial evidence for the alternative hypothesis (H1), values less than 1/3 indicate substantial evidence for the null (H0), and values between 1/3 and 3 indicate lack of sensitivity (Dienes, 2011). Here, the Bayes Factor (BF_{10}) favored the null hypothesis H0 with an evidence ratio of .278 ($BF_{10} < 1/3$) suggesting substantial support for the phenomenological absence of a sleep deprivation impact on the Congruency effect. The null hypothesis was 3.597 times more likely than the alternative hypothesis.

Finally, we compared the baseline Congruency effects between VPT level-1 and level-2 in RS condition to clarify whether the lack of Sleep x Congruency interaction in level-2 could originate from a smaller Congruency effect in level-2. Outliers both from the level-1 and level-2 tasks were not analyzed. The paired t-test revealed a significantly bigger Congruency effect in level-2 ($M = 383$, $SD = 284.89$) than level-1 ($M = 123.28$, $SD = 123.17$), $t(16) = 4.678$, $p < .001$, which does not support the latter interpretation.

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