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RESEARCH ARTICLE

Effects of total sleep deprivation on the perception of action capabilities

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Abstract Changes in a subject's state have been shown to modulate the perceptual update of his or her action capabilities. In parallel, sleep deprivation impairs in cognitive functions. It involves common neural structures that support the perception of successfully achieving a motor task. Thus, the study investigated the effect of 24 h of sleep deprivation on the perception of action capabilities. Twenty-four healthy participants were randomly separated into two groups (*control* group vs. 24 h *sleep deprivation* group). Participants in the *control* group slept at home according to their habitual sleep–wake schedule. The 24-h *sleep deprivation* group stayed awake in the laboratory. Participants estimated the limit of their maximal height of stepping-over a bar before and after the sleep intervention. These estimations were compared to each participant's actual maximal stepping-over height. Physical performance (measured by maximal voluntary quadriceps contraction and repetitive vertical jumping tests) and perceptual inhibition tests (measured by choice reaction time tasks) were also performed for three sessions at three time points t_0, t_{+12h}, and t_{+24h} with $t_0 = 8{:}00$ a.m. for all participants. Participants in the 24-h *sleep deprivation* group showed impairments in perceived over-stepping performance and impaired cognitive functioning (higher reaction time), while no changes were observed in actual performance in the over-stepping, voluntary quadriceps contraction, or jumping tasks. The cognitive processing of inputs that specify the estimated consequences of motor action is discussed as the main explanation for the inability to successfully update the perception of action capabilities after sleep deprivation.

Keywords Sleep deprivation · Perception · Action capabilities · Cognition

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Introduction

Human beings are flexible actors, quite capable of changing their intended action to produce alternative behaviors. However, performing a given behavior successfully requires one to perceive a specific action as possible to perform, and subsequently to understand the ways in which body movements must be controlled to actually perform that action. Such possibilities for behavior known as action "affordances" (Gibson 1979; Warren 1984) reflect the task-specific fit between the properties of the environment and the individual's capabilities for movement. Ellis and Tucker (2000) suggested that the brain representation of a whole action potentiated by the environment can be sub-divided into sensorimotor components. One main component specifically involving the dorsal neural pathway relates to perception of action capabilities (Binkofski and Buxbaum 2013; Borghi and Riggio 2009; Thill et al. 2013). Thus, the present study examined the effects of sleep deprivation on the perception of action capabilities in a judgment task of (successfully) stepping-over a bar (Burton 1992; Fajen and Matthis 2011; Jiang and Mark 1994).

Changes in one's perception of action capabilities

A plethora of studies suggest that people are adept at relating (updating) visual information to their action capabilities to

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promote the effective selection and execution of actions (Fajen et al. 2009; Higuchi et al. 2011; Malek and Wagman 2008; Ramenzoni et al. 2008; Regia-Corte and Wagman 2008; Stoffregen et al. 1999; Weast et al. 2011; Yu et al. 2011). However, numerous studies showed that changes in the perceiver-actor's state (e.g., fitness level, fatigue, pain, age, anxiety) influence the perception of action capabilities (Bhalla and Proffitt 1999; Deschamps et al. 2014; Graydon et al. 2012; Hackney and Cinelli 2013; Pijpers et al. 2006, 2007; Sakurai et al. 2013).

In spite of substantial evidence highlighting the relative difficulty to accurately update the perception of action capabilities during periods when perceivers experience altered adaptive/homeostatic needs, to the best of our knowledge, no study has directly investigated whether 24 h of total sleep deprivation (TSD) could have an effect on an individual's perception of his or her own action capabilities. Given the evidence that TSD attenuates a person's ability to perform a variety of psychomotor tasks (Frey et al. 2004; Patel et al. 2008; Scott et al. 2006), it could be suggested that the failure to update one's perception of his or her action capabilities could increase the risk of accidents in night shift work, decrease performance in military personnel or athletes, or decrease performance on a variety of everyday tasks (Graydon et al. 2012; Hackney and Cinelli 2013; Sakurai et al. 2013). Thus, this study aimed to investigate the effects of TSD on the perception of action capabilities, with assessments of performance across cognitive and physical domains as parallel outcome measures. Even if TSD did not establish adverse effects on participants' "meta-cognitive" ability to accurately assess their own cognitive performance (e.g., Baranski and Pigeau 1997; Baranski et al. 1994; Dorrian et al. 2000), this study addressed the role that the cognitive and/or sensory-motor functions may play in the expected adverse effects of TSD on the perception of action capabilities.

Consequences of total sleep deprivation on cognition

Consequences of TSD (defined as a case of sleep reduction in which the organism is awake for an unusually prolonged period of time) on cognitive abilities, executive performance, mood, behavior, and/or an organism's state are well established (see Killgore 2010; Orzel-Gryglewska 2010; Poudel et al. 2013, for recent reviews). Specifically, numerous studies have shown clear detrimental effects of TSD on cognitive functions, including decision-making, planning skills, and vigilant attention (Zhang and Liu 2008). For example, inhibition efficiency in a classic Go-No Go task is impaired following TSD (Drummond et al. 2006). Broadly speaking, such research has revealed that cognitive control, and specifically our executive mental function responsible for updating appropriate actions and for inhibiting inappropriate responses, declines as a function of time spent awake (Ratcliff and Dongen 2009). Beyond these consistent findings, it remains unclear whether the relationship between cognitive functioning and TSD affects the perception of action capabilities.

Even if not directly investigated, knowledge about the neurophysiological mechanisms involved in the perception of action capabilities and TSD-related cognitive impairment might guide our hypotheses. Indeed, Thill et al. (2013) presented a recent review of neurophysiological models of neuronal systems involved in the selection and specification of the perceived appropriate action. This selection is accomplished based on top-down processes that mainly occur within the prefrontal cortex (PFC) and act on various stages of the dorsal neural pathways, including the premotor cortex, which is involved in the preparation/execution of actions (Cisek 2007). Along with these recent studies, the effect of TSD on cerebral responses to cognitive performance (e.g., response inhibition) has been found to be associated with activation in the PFC and premotor areas, among others (Chuah et al. 2006; Smith et al. 2013). Considering all these arguments, we predict that the adverse effects of TSD on cognitive control would also influence the perception of action capabilities because of the significant role of PFC.

Consequences of total sleep deprivation on physical performance

Total sleep deprivation (TSD) of up to 24 h has not been shown to influence physical performance capabilities or cardiovascular responses to exercise (Oztürk et al. 2007; Souissi et al. 2003; Vardar et al. 2007). Nevertheless, the effect of TSD on muscular capabilities remains unclear. Meney et al. (1998) reported that one night of TSD did not decrease the strength in the muscles of the hand, leg, or back on the day right after TSD; on day 2, only a significant decrease in back strength was observed. On the other hand, some studies have found that maximal voluntary contraction of quadriceps decreased more in a TSD condition than in a control condition (without sleep deprivation) when subjects performed previously intermittent sprints (Skein et al. 2011). Because the integration of sensory-motor inputs might guide the perception of action capabilities, the effects of TSD on performance were assessed in a force production task (quadriceps maximal voluntary contraction) and an inter-limbs coordination task (repetitive vertical jumping). As the extensors of lower limbs are the main muscles activated when actually performing our experimental task of stepping-over a bar, these two aforementioned performances are functionally relevant to participants' stepping-over capabilities. Thus, we predicted that physical performance would be not altered by sleep deprivation because the selected tasks did not require a long exhausting engagement of participants, unlike Skein et al. (2011), but rather an assessment of muscular qualities of force, velocity, and coordination at a given time.

Aims of the study and hypotheses

In short, prior research has shown that sleep deprivation has various effects on human performance at different levels of functioning (see Boonstra et al. 2007 for an integrated review) and has main effects on executive function. However, the effects of exercise on cognitive functioning and motor performance after TSD still need to be clarified. Therefore, in the current experiment, we aimed to characterize the effects of TSD on the perception of action capabilities in a task of stepping-over a bar. We hypothesized that a TSD of 24 h would be associated with a decrease in the perceived ability to perform the task (but not a decrease in actual performance) because of the adverse effects of TSD on the efficiency of cognitive functioning. Inhibitory function, assessed by two-choice reaction time tasks, was also expected to be vulnerable to 24-h TSD (i.e., highest reaction times at t_{+24h}).

Methods

Participants

Twenty-four students (50 % females) at the University of Nantes (France) aged 21.4 ± 5.3 years (mean ± SD) (height = 171.5 ± 0.09 cm, weight = 67 ± 12.78 kg) volunteered to participate in the present experiment. Participation included a 2-day protocol and three sessions (at t_0, t_{+12h}, and t_{+24h}). Participants were equally and randomly divided into two experimental groups: a "control" group (mean age 20.08 ± 2.23 years; six women; body mass index 21.41 ± 5.39 kg m^{-2}) and a 24-h *sleep deprivation* group ($G_{24\text{-}SD}$) (mean age 22.66 ± 7.15 years; six women; body mass index 23.05 ± 1.82 kg m^{-2}). Independent sample *t* tests revealed no difference in age or body mass index between groups [$t(22) = 1.19$, $p = 0.24$, $t(22) = 0.99$, $p = 0.32$, respectively]. No participants exhibited any visual (or corrected vision) or physical impairment, any psychiatric or neurological disorders, or took long-term medications. Participants were asked to avoid the intake of caffeine, nicotine and alcohol the day before and during the experiment. Students were not paid for their participation in the experiment, and they had no previous experience with the experimental tasks. They were clearly informed of the experimental tasks before providing written consent. This study was conducted according to the Helsinki Statement (1964).

Tasks and apparatus

Self-estimated or actual stepping-over capabilities

The apparatus consisted of two separate poles (120 cm in height) and a bar (120 cm long, 1.6 cm diameter) laid across them. The experimenter manually laid the bar on wedges. The wedges were hidden from subjects and could be adjusted at intervals of 2.5 cm (Fig. 1).

For each of three experimental sessions, a series of performance estimates and actual performance was recorded. Participants were first asked to estimate the maximum height of the bar that they could step over (perceived H_{max} in cm). The criteria for the stepping-over action were that participants had to step over the bar without holding onto anything else and without jumping (i.e., they always had to keep at least one foot on the ground). As the experimenter moved the bar in randomized discrete steps (excluding hysteresis effect), the participants were asked to say "yes" or "no" as they judged whether or not they would be able to cross the bar according to the aforementioned criteria. Two blocks of estimates were performed, with a random presentation of eleven bar positions ranging from 70 to 95 cm. Then, the actual maximum height of stepping-over the bar (actual H_{max} in cm) was measured. The bar's height was successively increased until the participant could not step over the bar without holding on to something or jumping for two consecutive trials, or when the bar dropped or the participant refused to step over. As soon as the experimenter judged that the maximal height was reached, the same bar height was tested a second time to assess the consistency of actual performance.

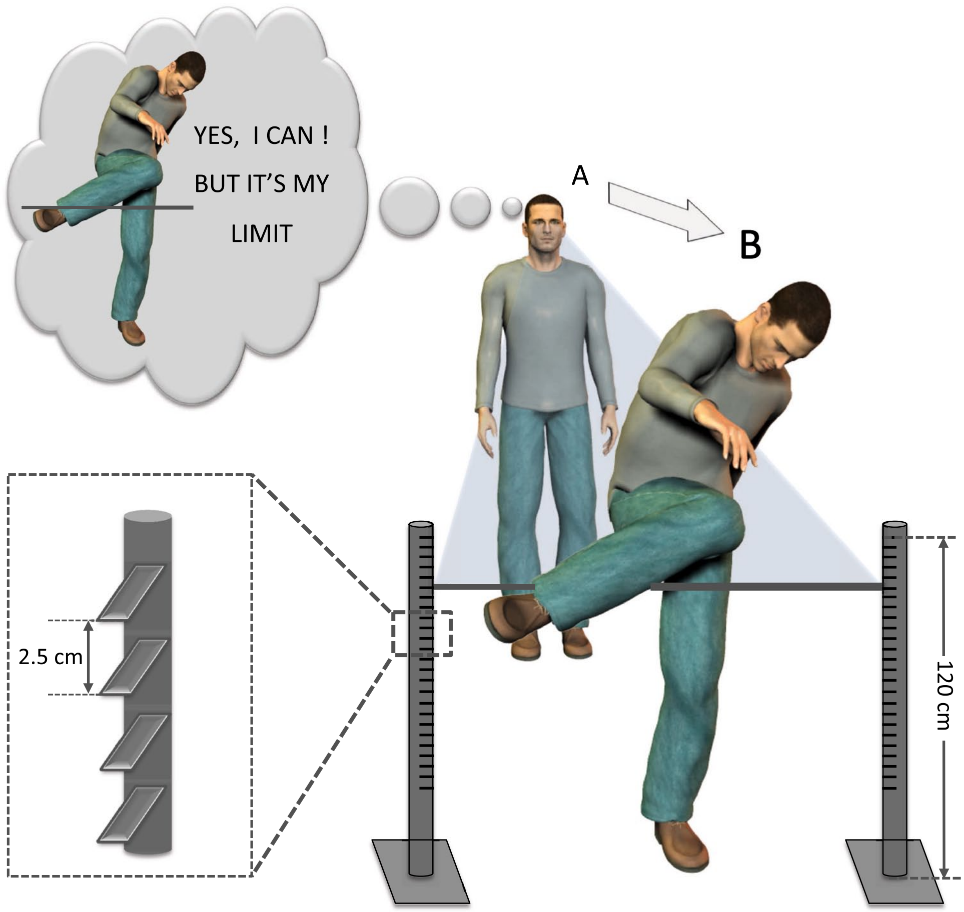
Quadriceps maximal voluntary contraction

During each experimental session, the participants performed maximal voluntary isometric contractions (MVCs) of the *quadriceps femoris* muscles to quantify the maximal force production for their dominant leg. Force production was performed on a Biodex® System 3 Pro dynamometer (Biodex Medical Systems, Shirley, NY), with the angle of the knee joint set at 70° (Blazevich et al. 2007). After a warm-up of 5 min, participants received encouragement while performing two MVC trials (about 5 s each), separated by 2 min of rest. The best performance was considered.

Vertical jumping test

An infrared timing system (Optojump, Microgate SRL, Rome, Italy) was used to conduct a functional vertical jumping test. In each session, participants were required to perform five consecutive countermovement vertical jumps,

Fig. 1 Experimental set-up



with instructions to reach and maintain a maximal height with each jump. No time constraint was imposed.

Cognitive tasks

Based on reaction times to specific stimuli on a computer screen, a test of perceptual inhibition was performed by exactly replicating the MAPIT protocol (see Redfern et al. 2009 for details). For this perceptual task, participants saw a black arrow pointing either to the left or to the right and were instructed to press a corresponding key assigned either to left- or right-pointing arrows. Participants viewed two types of trials: congruous and incongruous. In congruous trials, the spatial location of the 2-cm-long arrow (which appeared 15 cm to the right or left of the central fixation point on the screen) corresponded with the direction the arrow pointed (e.g., a left-pointing arrow appeared to the left of fixation). In incongruous trials, participants were instructed to inhibit processing the arrow's spatial location and to focus only on the direction it pointed. Thus, the arrow pointed to the direction that did not correspond with its location (e.g., a right-pointing arrow appeared to the left side of central fixation point). Two blocks each included 20 congruous and 20 incongruous randomly intermixed trials, for a total of 80 trials. The participants' reaction time (RT) was measured as the time elapsed between the presentation of the arrow and the onset of the key press. A trial started with the presentation of a black central fixation cross for 300 ms followed by the arrow's display, which was presented for 300 ms. The interval between the warning signal (the cross) and the response signal (the arrow) was preset and varied randomly between 1 and 2 s so that the participant could not anticipate stimulus onset (Mendelson et al. 2010). Participants were allotted a maximum of 2 s to respond and were given no feedback about their reaction time, even in the case of a response error. The inter-trial interval was fixed at 2 s after the participant's response.

As in previous studies (Nassauer and Halperin 2003; Redfern et al. 2009), the spatial response tendency was reinforced just prior to congruous/incongruous blocks by presenting 40 visuo-spatial two-choice RT trials in which participants responded to a black rectangle presented in either the right or the left of the computer screen with the congruous key (i.e., *a two-choice RT with spatial uncertainty*). In addition, two separate blocks of 40 two-equiprobable choice RT baseline trials were presented just prior to and after these blocks. In these baseline trials, arrows were presented in the center of the screen, randomly pointing either to the left or to the right, and participants responded with the key corresponding to the direction of the arrow (i.e., *a two-choice RT with directional uncertainty*). The inter-trial interval was fixed at 2 s.

In sum, participants completed 200 two-choice reaction time trials in about 25 min.

Subjective self-assessments

Before and after each session, participants were asked to answer three questions (via a 100 mm visual analogue scale calibrated from 0, "not at all," to 100, "absolutely") about their physical fitness ("I am feeling physically in great shape"), attentional fatigue ("I am feeling mentally and attentionally fit"), and sleepiness ("I am feeling sleepy"). The three items were presented successively in random order, and participants had to draw a vertical mark on the 100 mm line. The distance of the vertical mark from the left extremity ("not at all") was measured manually in centimetres and considered for analysis.

Experimental protocol

For all participants, the 2-day protocol included three sessions, at about 8:00 a.m. and 8:00 p.m. ± 15 min on the first day (day 1) and at 8:00 a.m. ± 15 min the next morning (day 2). Note that the 8:00 a.m. assessments did not require participants to awaken earlier than they would normally to arrive for testing because their courses started at 8:00 a.m. every day. For the *control* group, participants slept at home in their bed according to their habitual sleep–wake schedule (mean sleep duration of 6.8 ± 0.6). The 24-h *sleep deprivation* group was sleep deprived for about 25.9 h ± 0.4, while three experimenters took turns observing participants in order to ensure that they did not fall asleep. Participants were allowed to engage in non-strenuous activities, such as reading, listening to music, watching videos, and conversing. Participants performed all aforementioned tasks in a random order within each session with the exception that the cognitive tasks were always completed last.

Data analysis and statistics

All data were normally distributed; thus, values are reported as mean ± SD (or SE) throughout the text and the figures. Note that all estimates made at t_0 were considered as the baseline performance of participants. Specifically, we assumed that the baseline over- or under-estimation (i.e., differences between perceived and actual H_{max}) can be derived from individuals' inability to consider experimental restrictions when making judgments regarding actions (Fischer 2000; Graydon et al. 2012) and/or from individual characteristics (such as expertise or fitness level), which have also been shown to influence perception of action capabilities (Bhalla and Proffitt 1999; Higuchi et al. 2011; Weast et al. 2011). Focusing on the dynamics of the perception of action capabilities as a function of sleep deprivation conditions, the baseline difference between perceived H_{max} and actual H_{max} at t_0 was thus removed from the perceived H_{max} collected at t_0, t_{+12h}, and t_{+24h}.

Stepping-over capabilities

To test the effects of time-of-day and sleep deprivation on the perception of action capabilities, we compared maximum estimate and actual performance during the three sessions as a function of Group. Thus, an analysis of variance (ANOVA) with 3 within-participants factors (Session—t_0, t_{+12h}, and t_{+24h}) and 2 (Group) between-participants factors was performed for each dependent variable. To provide additional insight into the effect of sleep deprivation on the relationship between the perception of action capabilities and actual performance, the ratio of perceptual estimation divided by the actual performance was calculated. A ratio of one indicates a perfect match, whereas a ratio greater or less than one indicates an over- or under-estimation, respectively. As the data were normalized as a function of the baseline difference between perceived H_{max} and actual H_{max} at t_0, only the ratios were compared at t_{+12h}, and t_{+24h}, using Mann–Whitney U tests.

Physical measures

For the mean vertical jumping performance (mean height in cm of five consecutive jumps) or the maximal voluntary quadriceps contractions, similar 3 (Session) × 2 (Group) two-way ANOVAs were carried out to verify that participants' physical abilities were similar across groups, even though one group of participants was sleep deprived.

Reaction time measures

Mean RTs for each task (i.e., the two-choice RT with spatial uncertainty, the two-choice RT with directional uncertainty, and the perceptual congruous or incongruous RT) were computed for each participant. For all these four tasks, a 3 (Session) × 2 (Group) ANOVA was carried out with each mean RT as dependent variable.

Self-assessments

For each item ("sleepy," "physically fit" and "attentionally fit"), a 3 (Session) × 2 (Group) ANOVA was conducted using the mean scores (in cm) as the dependent variable.

For each analysis, the level of significance was $p < 0.05$. Following significant effects, the least significant difference comparisons were used as post hoc tests. Whenever the sphericity assumption in a repeated-measures ANOVA was violated (Mauchly's test), the corrected tests of significance were used. In that case, paired *t* tests were used as post hoc comparisons (with alpha levels corrected for multiple comparisons). Partial eta squared (${}_{p}\eta^2$) values are reported as measures of effect size, with moderate and large effects considered for ${}_{p}\eta^2 = 0.07$ and ${}_{p}\eta^2 \geq 0.14$, respectively (Cohen 1988).

Results

Stepping-over capabilities

Perceptual boundaries

The mean maximal perceived H_{max} was used as the perceptual boundary in that condition. Overall, the perceptual boundary was equivalent across groups (main effect of Group: $F(1, 22) = 2.025$, $p = 0.169$, ${}_{p}\eta^2 = 0.084$), with a perceived H_{max} at 79.09 ± 6.59 versus 83.06 ± 7.81 cm for $G_{24\text{-SD}}$ and G_{CONT}, respectively. Moreover, the H_{max} was identical across sessions (main effect of session at t_0, t_{+12h}, and t_{+24h}: $F(2, 44) = 0.446$, $p = 0.598$, ${}_{p}\eta^2 = 0.02$), indicating that participants estimated their maximal height consistently over time. Finally, a decrease in perceptual boundary was apparent at t_{+24h} as compared to t_0, but only for the $G_{24\text{-SD}}$ [Group × Session interaction: ($F(2, 44) = 3.895$, $p = 0.027$, ${}_{p}\eta^2 = 0.15$)]. Precisely, participants in the $G_{24\text{-SD}}$ estimated a shorter height at t_{+24h} compared to t_0 (−3.58 cm, i.e., 4.42 %; $p = 0.01$). For the G_{CONT}, equivalent values at t_0 and t_{+24h} were found (+1.77 cm, i.e., 2.15 %; $p = 0.201$) (Fig. 2).

Actual behavioral boundaries

Behavioral boundaries were equivalent across sessions (main effect of Session: $F(2, 44) = 2.543$, $p = 0.09$, ${}_{p}\eta^2 = 0.104$), with similar actual H_{max} performances at t_0 (81.56 ± 5.35 cm), t_{+12h} (81.66 ± 5.29 cm), and t_{+24h} (82.91 ± 4.87 cm). The analysis indicated identical perceived performance between groups [$F(1, 22) = 0.26$, $p = 0.608$, ${}_{p}\eta^2 = 0.012$; 81.52 ± 5.86 cm for $G_{24\text{-SD}}$ versus 82.56 ± 4.32 for G_{CONT}]. In addition, no significant Group × Session interaction was found [$F(2, 44) = 0.34$, $p = 0.713$, ${}_{p}\eta^2 = 0.015$], evidencing no change in actual stepping-over performance as a function of sessions.

Ratio

The ratio of perceptual boundary divided by the actual boundary was statistically equivalent between the G_{CONT} (1.01 ± 0.09) and the $G_{24\text{-SD}}$ (0.97 ± 0.05) at t_{+12h} ($Z = 1.38$; $p = 0.16$). But the $G_{24\text{-SD}}$ underestimated their action capabilities at t_{+24h}, with a lower ratio (0.93 ± 0.05) than participants in the G_{CONT} (1.00 ± 0.08) ($Z = 2.10$; $p = 0.03$).

Functional measurements

Vertical jumping performance

The ANOVA for jumping mean height revealed a main effect of Session [$F(2, 44) = 7.83$, $p < .001$, ${}_{p}\eta^2 = 0.272$], with a significant improvement at t_{+12h} (26.73 ± 5.17 cm) as compared to t_0 (25.48 ± 5.3 cm) and t_{+24h} (25.44 ± 5.2 cm). The performances were statistically equivalent between groups (no main effect of

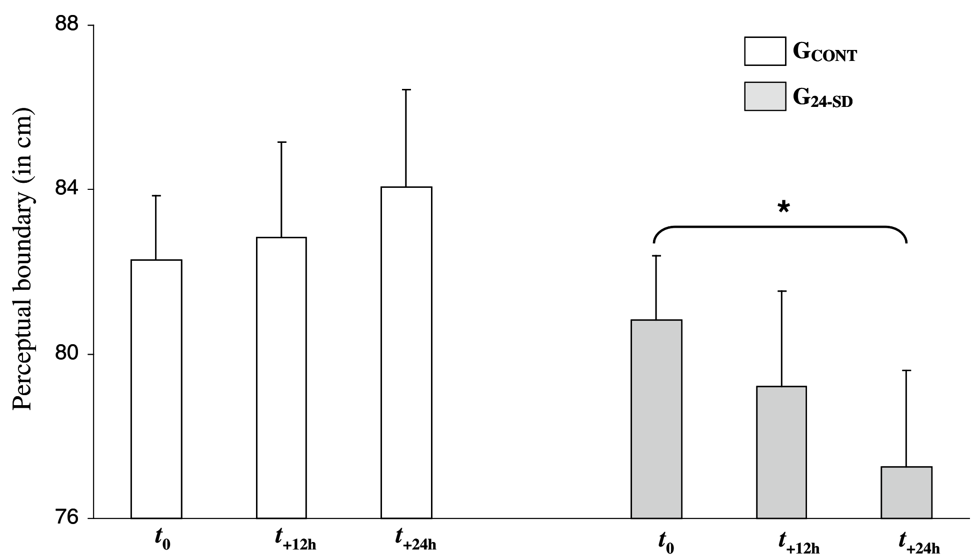


Fig. 2 Group × Session interaction for perceptual boundaries (in cm), namely the perceived maximal height of stepping-over the bar. *Error bars* correspond to the SE. Significant differences at *$p < .05$

Group: $G_{24\text{-SD}}$ versus G_{CONT}: $F(1, 22) = 0.025$, $p = 0.87$, ${}_p\eta^2 = 0.001$), and no significant Session × Group interaction ($F(2, 44) = 0.028$, $p = 0.97$, ${}_p\eta^2 = 0.001$), indicating that participants maintained their jumping performance regardless of the sleep deprivation condition.

Maximal voluntary quadriceps contraction

The analysis of variance revealed similar MVC scores at t_0 (185.21 ± 53.22 N m^{-1}), t_{+12h} (192.43 ± 56.69 N m^{-1}), and t_{+24h} (189.73 ± 52.84 N m^{-1}): $F(2, 44) = 0.894$, $p = 0.416$, ${}_p\eta^2 = 0.047$. Overall, both groups performed similarly [$F(1, 22) = 0.64$, $p = 0.431$, ${}_p\eta^2 = 0.044$], with 198.27 ± 44.8 N m^{-1} and 180.75 ± 59.88 N m^{-1} for $G_{24\text{-SD}}$ and G_{CONT}, respectively.

Reaction time measures (RT)

All mean RTs collected during the perceptual inhibitory test protocol are summarized in Table 1. Considering all participants and all cognitive tasks, relatively few errors were made: 5.75 % of the RTs (i.e., 276 of 4,800 RTs). Note also that the $G_{24\text{-SD}}$ made more errors than the participants in G_{CONT}, especially in the congruous/incongruous RT conditions at t_{+24h} (6.35 vs. 2.08 %, respectively).

All ANOVAs revealed similar RT scores between groups. However, these analyses also revealed a main effect of Session (except for the choice reaction time task with directional uncertainty) and a systematic Session × Group interaction for all RT tasks (see Table 2 for all statistical results). Overall, these findings indicate that mean RTs

Table 1 Mean reaction time performances (RTs) for the four probe reaction time tasks as a function of group (the "24-h sleep deprivation" group—$G_{24\text{-SD}}$—and the "Control" group—G_{CONT}), and Session (at t_0, t_{+12h} and t_{+24h})

Mean RTs (95 % confidence limits)	t_0		$t_{+12\,h}$		t_{+24h}	
	$G_{24\text{-SD}}$	G_{CONT}	$G_{24\text{-SD}}$	G_{CONT}	$G_{24\text{-SD}}$	G_{CONT}
Two-choice RT with spatial uncertainty (ms)	347.83 (327.98; 367.68)	352.16 (327.98; 367.68)	346.25 (319.22; 373.27)	333.91 (316.06; 351.76)	395.34 (327.57; 463.12)	334.67 (312.34; 356.98)
Two-choice RT with directional uncertainty (ms)	414.51 (389.46; 439.56)	404.75 (383.7; 425.79)	404.5 (379.8; 429.21)	387.9 (362.01; 413.78)	440.08 (397.3; 482.86)	387.14 (354.78; 419.49)
Perceptual congruous RT (ms)	470.38 (435.18; 505.59)	474.38 (433.97; 514.8)	443.24 (410.47; 476.01)	449.46 (411.46; 487.47)	489.94 (434.47; 545.41)	439.82 (402.66; 476.97)
Perceptual incongruous RT (ms)	531.26 (492.69; 569.83)	523.9 (478.86; 568.94)	499.06 (456.93; 541.19)	491 (452.18; 529.81)	576.42 (500.38; 652.47)	490.73 (450.41; 531.04)

Table 2 Analysis of variance results (F values) for all the choice RT measures for the different factors

Mean RTs	Group (1, 22)	Session (2, 44)	Session × Group (2, 44)
Two-choice RT with spatial uncertainty (ms)	1.509 (${}_p\eta^2 = 0.07$)	**3.887***[(3)] (${}_p\eta^2 = 0.163$)	**5.99****[(a, b)] (${}_p\eta^2 = 0.231$)
Two-choice RT with directional uncertainty (ms)	2.66 (${}_p\eta^2 = 0.108$)	2.28 (${}_p\eta^2 = 0.094$)	**3.70***[(a, b)] (${}_p\eta^2 = 0.144$)
Perceptual congruous RT (ms)	0.314 (${}_p\eta^2 = 0.014$)	**4.205***[(1, 3)] (${}_p\eta^2 = 0.16$)	**5.961****[(b)] (${}_p\eta^2 = 0.231$)
Perceptual incongruous RT (ms)	1.516 (${}_p\eta^2 = 0.064$)	**5.033***[(1, 3)] (${}_p\eta^2 = 0.186$)	**5.929****[(a, b)] (${}_p\eta^2 = 0.212$)

Factors were Group and Session. Degrees of freedom are shown in parentheses

RT reaction time

* $p < .05$, ** $p < .01$

[1] Significant difference between t_0 and t_{+12h}

[2] Significant difference between t_0 and t_{+24h}

[3] Significant difference between t_{+12h} and t_{+24h}

[a] Significant difference between t_0 and t_{+24h} for the $G_{24\text{-SD}}$

[b] Significant difference between the $G_{24\text{-SD}}$ and the G_{CONT} at t_{+24h}

Bold values are statistically significant at $p < 0.05$

increased from the first session (t_0) to the third (t_{+24h}) for participants in the G_{CONT}, but not for participants in the $G_{24\text{-}SD}$. Moreover, RTs were significantly higher for the $G_{24\text{-}SD}$ than the G_{CONT} at t_{+24h} (Table 1). For example, when considering the perceptual inhibition tests, participants from $G_{24\text{-}SD}$ obtained higher RTs at t_{+24h} compared to the G_{CONT} for perceptual congruous trials (+50.12 ms, i.e., 11.13 %; $p < .01$) and perceptual incongruous trials (+85.69 ms, i.e., 17.46 %; $p < .04$) (Fig. 3). When combined with the error data, these results were not due to a speed–accuracy trade off.

Self-assessments

For each question ("physical fit," "attentionally fit," and "sleepiness"), the analyses revealed a main effect of Group (all $Fs > 6.85$; $p < 0.02$), a main effect of Session (all $Fs > 9.45$; $p < 0.001$), and a systematic Session × Group interaction (all $Fs > 9.97$; $p < 0.001$). Overall, the participants in the $G_{24\text{-}SD}$ felt more physically and attentionally tired and perceived a higher level of sleepiness compared to the participants in the G_{CONT}, especially at t_{+24h} (Fig. 4).

Discussion

Our aim in the current study was to investigate the effects of 24 h of acute TSD on the perception of action capabilities by examining the perceptual and behavioral boundaries (perceived or actual H_{max}) in a task of stepping-over a bar. The current study also tests for parallel changes in cognitive functioning (assessed through choice reaction time)

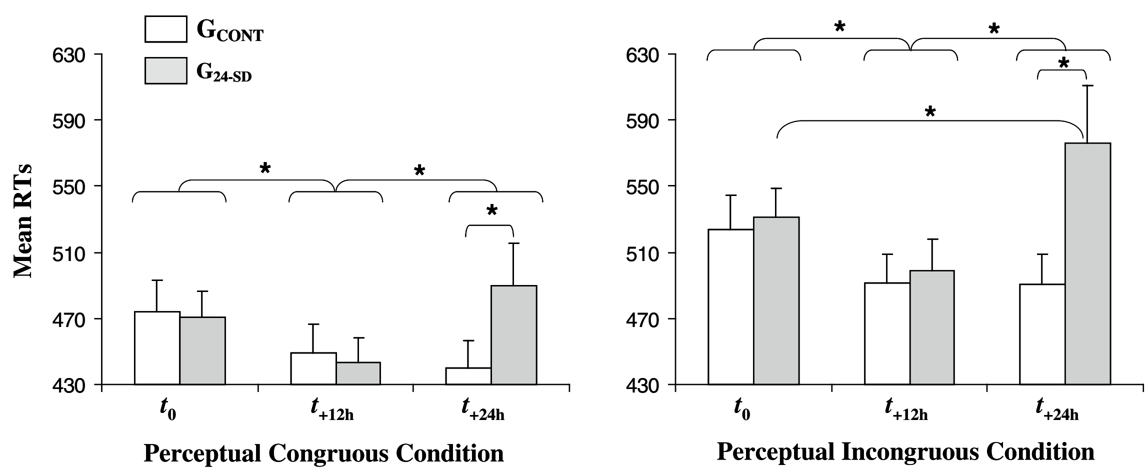


Fig. 3 Group × Session interaction for the reaction time performance (RTs) for both perceptual congruous and incongruous inhibition tests. *Error bars* correspond to the SE. Significant differences at $^*p < .05$

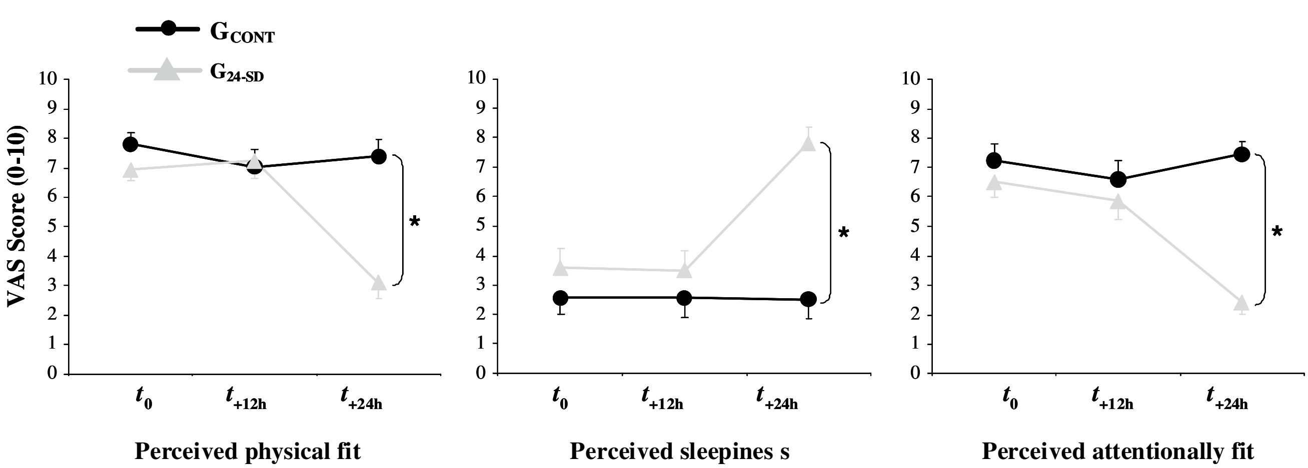


Fig. 4 Group × Session interaction for the mean self-reported scores (in cm) (via a 10-cm visual analogue scale—VAS—calibrated from 0 score "not at all" to 10 score "absolutely") for the three items ("physically fit", "sleepiness", and "attentionally fit"). *Error bars* correspond to the SE. Significant differences at $^*p < .05$

and/or in physical performance and motor skills (assessed with force production and vertical jumping tests).

As expected, participants exhibited lower perceived H_{max} after one night of sleep deprivation (at t_{+24h}) but no concomitant change in actual performance over time was observed. This means either that individuals had rather conservative estimates of their action capabilities at t_{+24h} (Dorrian et al. 2000; Graydon et al. 2012) or they showed a misperception of their stepping-over action capabilities, evidencing their *cognitive* vulnerability to extended wakefulness periods when relating visual information to their action capabilities. Indeed, no change in physical performance (i.e., vertical jumps and maximal voluntary contractions of the *quadriceps femoris* muscles) was found in either the 24-h sleep deprivation group or the control group, while an impairment in inhibitory process was only observed only in the *deprivation* group. Contrary to the findings of Baranski et al. (1994), evidencing that cognitive performance self-assessments are unaffected by TSD, this is the first study to demonstrate that the "sensory-motor" ability to estimate one's own motor ability is vulnerable to extended wakefulness.

This study cannot distinguish with certainty which of these alternatives (i.e., intentionally conservative estimates or altered cognitive functioning) explains the results. The potential for participants in the TSD condition to modify their performance to increase a "safety margin" is particularly relevant when motor tasks may induce risky behaviors (i.e., falling) and a high risk of accident (Comalli et al. 2013; Jones et al. 2006). Thus, it could be assumed that participants in the TSD group moderate their performance estimates to expose the system to less risk as a protective mechanism (Deschamps et al. 2014) and their ability to accurately assess the cognitive performance impairment (Dorrian et al. 2000; Baranski and Pigeau 1997). But we assume that the present experimental stepping-over task did not induce a highly risky context. As outlined in the introduction, it can be reasonably hypothesized that sleep deprivation led to a misperception of action capabilities because of impaired cognitive functioning.

Are the changes in perceptual performance independent (or not) from changes in actual performance?

Above all, the findings on perceptual boundaries have to be discussed regarding the dynamics of actual boundaries (Comalli et al. 2013). Previous research has shown that the perception of action capabilities can vary (or not) in a concomitant way with changes in actual performances (Deschamps et al. 2014; Hackney and Cinelli 2013; Malek and Wagman 2008; Regia-Corte and Wagman 2008). For example, Noël et al. (2011) investigated the perceptions of their ability to cross over a bar among both young and elderly adults. The updating of perceptual boundaries was consistent with changes in actual action capabilities, although they were inaccurate. Indeed, whereas the older adults perceived that their actual performance was lower compared to young adults, they overestimated their action capabilities (i.e., 12.5 cm difference between estimated performance and real performance). These findings support two possible mechanisms to specify changes in perceptual boundaries: (1) the accurate update of new action capabilities (dynamically modified by the experimental context and/or environmental properties) (e.g., Comalli et al. 2013) and/or (2) a perceptual impairment (i.e., inaccurate perception of the extent of changes in action capabilities as the actual performance effectively changed, or only a perceptual impairment without change in actual performance). In our study, actual H_{max} performances did not vary over time, arguing that perceptual alterations might be closely attributable to changes in the perceptive updating process over time for the $G_{24\text{-}SD}$.

Thus, it is important to determine the impairment sources that are responsible for inefficient cognitive updating of perception of action capabilities. We argue that the perception of motor action features, anticipation of the consequences of actions (i.e., the way individuals perceive the environment in terms of the costs of acting within it; Deschamps et al. 2014; Witt et al. 2004, 2009), and perceptive cognitive process are all involved in the perception of action capabilities.

Perception of motor action features as a source of perceptual alterations in action capabilities

Clearly, after 24 h of wakefulness, individuals are much less likely to perform actions that they believe will be uncomfortable, painful, and/or unachievable. As supported by the self-assessment results, participants' evaluation of their own physical fitness was significantly lower at t_{+24h} of sleep deprivation, which is consistent with their conservative behaviors, as revealed by lower H_{max} estimates. Again, related to a protective mechanism assumption, it may be suggested that individuals in the $G_{24\text{-}SD}$ have self-assessed a decrease (not found in the present case) in physical capacities from kinesthetic inputs or from incorrect self-expectations of sleep deprivation's effects. Whatever the explanation, subjects deprived of sleep for 26.5 h underestimated their maximum over-stepping height without changes in their actual performance.

These findings reinforce the relevance for characterizing the effects of TSD on both force production by using an MVC test and lower limb synergy abilities through the functional CMJ test. As reported, the effect of TSD on both tests was not significant, which is in accordance with previous studies (Meney et al. 1998; Souissi et al. 2003;

Vardar et al. 2007). This first key result suggests that the dynamic properties of the body and individuals' motor potential necessary for action performance may not be at the origin of the decrease in the assessment of physical fitness and consequently in perceptual boundaries. As a plausible alternative, although indirectly supported by the current findings, we suggest that conservative perceptual behavior is a direct consequence of sleep-deprivation-induced impairments in cognitive processing of kinesthetic inputs. Further investigation should specify which cortical structures, and neurophysiological processes could support this assumption (Babkoff et al. 2005; Thill et al. 2013).

Is the alteration in cognitive processes a source of changes in the perception of action capabilities?

Similar to previous studies, sleep deprivation was associated with a decrease in attention, as shown by an increase in reaction time performance and lower scores on attention self-assessment. With respect to attentional processing requirements, consistent findings underlined the importance of considering the interplay of cognitive load (or attentional cost), fatigue, and motor performance (Deschamps et al. 2011; Murian et al. 2008). Accordingly, our present results strongly suggest that perceptual output for action capabilities is altered during prolonged wakefulness because TSD impairs the central executive processes, with adverse effects on attention and response inhibition. Further research is required to test the specific relationship between changes in the perception of action capabilities and TSD-related cognitive impairment.

Conclusion

This study demonstrated deleterious effects of acute sleep deprivation on the sensory-motor ability necessary to consider one's action capabilities to insure safe and efficient motor control. We argue that the cognitive processing of external (i.e., environmental cues) and internal (i.e., the subject's physical state) inputs that specify the estimated consequences of motor action could be the explanation for the inability to successfully update the perception of action capabilities after sleep deprivation. Future research on these specific assumptions should provide further neurophysiological support for the failure of updating the perception of action capabilities with TSD.

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Conflict of interest The authors declare that they have no competing interests.

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