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Research report

Cognitive fatigue: A Time-based Resource-sharing account

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ABSTRACT

Cognitive Fatigue (CF) is an important confound impacting cognitive performance. How CF is triggered and what are the features that make a cognitive effort perceived as exhausting remain unclear. In the theoretical framework of the Time-based Resource-sharing (TBRS) model (Barrouillet et al., 2004), we hypothesized that CF is an outcome of increased cognitive load due to constrained time to process ongoing cognitive demands. We tested this cognitive load-related CF hypothesis across 2 experiments manipulating both task complexity and cognitive load induced by the processing time interval. To do so, we used the TloadDback paradigm, a working memory dual task in which high and low cognitive load levels can be individually adjusted. In Experiment 1, participants were administered a high cognitive load (HCL, short processing time interval) and a low cognitive load (LCL, large processing time interval) conditions while complexity of the task was kept constant (1-back dual task). In Experiment 2, two tasks featuring different levels of complexity were both administered at the individual's maximal processing speed capacity for each task (i.e., short processing time interval). Results disclosed higher CF in the HCL than in the LCL condition in Experiment 1. On the contrary, in Experiment 2 similar levels of CF were obtained for different levels of task complexity when processing time interval was individually adjusted to induce a HCL condition. Altogether, our results indicate that processing time-related cognitive load eventually leads to the subjective feeling of CF, and to a decrease in alertness. In this framework, we propose that the development of CF can be envisioned as the result of sustained cognitive demands irrespective of task complexity.

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1. Introduction

Coping with sustained cognitive demands for extended periods of time represents a major challenge. Inescapably, a feeling of exhaustion and lack of energy will develop over time, which will eventually hamper cognitive performance. Having a break or shifting onto another, less demanding cognitive task may mitigate the subjective feeling of fatigue, at variance with a state of sleepiness that needs sleep to be relieved (Kumar, 2008). Mental or Cognitive Fatigue (CF) can be defined as the decrease in cognitive resources developing over time on sustained cognitive demands, independently of sleepiness (Trejo, Kochavi, Kubitz, Montgomery, Rosipal, & Matthews, 2005). CF is observed in various attentional and executive function areas with developing difficulties to suppress irrelevant information during selective attention (Faber, Maurits, & Lorist, 2012), increased perseverations and time needed to plan (van der Linden, Frese, & Sonnentag, 2003), weakened cognitive control (Lorist, Boksem, & Ridderinkhof, 2005) and decreased high-level information processing (Tanaka, Shigihara, Funakura, Kanai, & Watanabe, 2012) or even declining physical performance (Marcora, Staiano, & Manning, 2009). Notwithstanding, CF is not always associated with performance impairment (Ackerman & Kanfer, 2009) and can be modulated by individual traits such as personality, interests (Ackerman & Kanfer, 2009) and motivation (Ackerman & Kanfer, 2009; Boksem, Meijman, & Lorist, 2005; Lorist et al., 2005). In this respect, triggering CF is also a function of the self-predicted costs and rewards involved by the ongoing effort (Stewart, Wright, Azor Hui, & Simmons, 2009). Indeed, the more positive the benefit-costs an action entails, the lower the intensity of the mental effort perceived by the organism (Boksem & Tops, 2008). Nonetheless, even when costs and benefits are controlled (i.e., stable levels of cognitive demand and reward during the task), performance is often affected through time (Gergelyfi, Jacob, Olivier, & Zénon, 2015) suggesting the influence of other parameters such as the specificity of the cognitive demands or the availability of cognitive resources. Although CF arises from virtually any sustained cognitive effort, the determinants of CF (i.e., the mechanisms making a cognitive demand more exhausting) have been barely studied. This lack of knowledge raises a critical issue in experimental psychology, as CF can be a major confound in a wide variety of cognitively demanding situations.

1.1. *Current approaches to induce CF*

Most experimental investigations of CF have been conducted manipulating either task duration (Lorist, Klein, & Nieuwenhuis, 2000; Lorist et al., 2005; Mizuno, Tanaka, Fukuda, Imai-Matsumura, & Watanabe, 2011; van der Linden, Frese, et al., 2003) also known as Time-on-Task (ToT) (Ackerman & Kanfer, 2009; Lim, Wu, Wang, Detre, & Dinges, 2010), or task demands (Cook, O'Connor, Lange, & Steffener, 2007; Shigihara, Tanaka, Ishii, Kanai, et al., 2013). In the ToT approach, a stable cognitive demand is sustained over time. For instance, CF can be induced asking participants to reorganize fictional employee schedules for about 2 h (van der Linden, Frese, & Meijman, 2003), to perform mental arithmetic problems for up to 3 h (Trejo et al., 2005) or to achieve a range of cognitive tasks, including working memory, inhibition tasks, arithmetic problems and brainteasers during 90 min (Klaassen et al., 2014). This approach is rather successful in inducing CF, suggesting that any sustained cognitive effort will, sooner or later, lead to this phenomenon independently of the degree of cognitive demands requested by the task (Ackerman & Kanfer, 2009). However, other studies show that CF does not increase to the same extent in all demanding situations (Nakagawa et al., 2013; Shigihara, Tanaka, Ishii, Tajima, et al., 2013). These studies manipulate task demands to induce different levels of CF, under the assumption that higher cognitive demands will tax more on cognitive resources, eventually leading to higher CF levels. For example, varying the complexity of a working memory N-back task leads to different levels of CF after 30 min of practice (Shigihara, Tanaka, Ishii, Tajima, et al., 2013). In these studies, CF manifested at the behavioral level with more errors in a cognitive flexibility task (Trail Making Test) administered after the end of practice but also with post-task changes in spontaneous beta power in frontal regions (Shigihara, Tanaka, Ishii, Kanai, et al., 2013). Accordingly, higher task demands associated with higher subjective fatigue ratings were associated with a reduced P300 amplitude and increased alpha power in frontal and parietal areas (Käthner, Wriessnegger, Müller-Putz, Kübler, & Halder, 2014). Hence, along with ToT, the cognitive load arising from the features of the ongoing cognitive demands is also a strong modulatory factor in the induction of CF. Consequently, higher cognitive load should lead to faster and/or higher CF levels, which opens up the question on the variable(s) primarily subtending cognitive load.

1.2. *Determinants of cognitive load*

Cognitive load theories posit a limited processing capacity (Atkinson & Shiffrin, 1968; Moreno & Park, 2010; Sweller, 1988). At the perceptual level, this can be probed using interference paradigms where distractors are presented in different cognitive load situations. When the task condition involves a high perceptual load (e.g., by increasing complexity), distractors will cause less interference, an effect interpreted as reflecting the fact that the system does not have enough capacity to process irrelevant information (Lavie, 2010; Nilli Lavie, 2006). A common approach for intensifying cognitive load in a task is to increase the number of elements to process. For instance, in the N-back paradigm (Kirchner, 1958), increased cognitive load is associated with an increased number of elements to update in working memory to correctly perform comparisons between the ongoing and past elements in the series. Alternatively, the Time-based Resource-sharing model (TBRS; Barrouillet, Bernardin, & Camos, 2004) proposes that the available time to process ongoing cognitive demands is actually the major factor responsible for inducing cognitive load. More specifically, the TBRS model conceptualizes attention as a limited resource, which is needed to process incoming information. The model posits that the performance is related to the proportion of time needed for the attention to process ongoing information. Therefore, cognitive demand or mental effort is conceptualized as the "*function of the amount of work the activity requires divided by the time allowed to do it*" (Barrouillet et al., 2004). According to this definition, an individual will reach his/her maximal cognitive load without impaired performance when the time allowed to perform the cognitive operation equals the time needed to correctly cope with the cognitive demands. Therefore, limiting the time available to process task-associated cognitive demands should increase cognitive load, eventually resulting in higher CF. This idea, already captured by ancient literature in the field (see Arai, 1912), is still lacking empirical validation.

In the present study, we tested the evolution of CF in the theoretical framework of the TBRS model (Barrouillet et al., 2004). First, we hypothesised that increasing cognitive load by reducing the time available to process cognitive demands will induce higher CF levels even after a relatively short period of time (Experiment 1). To disentangle the respective contributions of processing time interval and task complexity in the induction of CF, we also predicted similar CF levels in two tasks featuring different levels of complexity, but in which the level of cognitive load (i.e., the processing time required by the task divided by the available processing time interval) was proportionally adjusted according to the TBRS model (Experiment 2). To test these hypotheses, we used the Time load Dual-back task (TloadDback; Borragán, Slama, Destrebecqz, & Peigneux, 2016) in which different levels of cognitive load can be induced and individually adjusted by modifying the time available to process the ongoing-task demands. Finally, two additional control experiments assessing the impact of the induced CF on alertness and test-retest effects respectively are proposed as supplementary information for the interested reader.

2. Experiment 1. Does cognitive load trigger CF?

In our first experiment, we aimed at inducing different levels of subjective and objective CF in conditions involving identical task complexity, but in which the time available to process ongoing information is manipulated to increase task demands. Thus, we predicted that cognitive load, and consequently CF, will be higher when the time allowed to process the task is reduced. Importantly, large inter-individual differences can be observed in net cognitive capacity (Gaillard, Barrouillet, Jarrold, & Camos, 2011), which makes the same task more or less demanding for different individuals. Given our assumption that CF is a consequence of the cognitive load experienced by the participant, it is essential to adapt cognitive demands to the capacities of each individual to ensure similar levels of cognitive load. Although it is most often simply not taken into account (e.g., Faber et al., 2012; Mizuno et al., 2011; Tanaka et al., 2012), inter-subject variability in cognitive capacity can be controlled, to some extent, by adapting task difficulty according to a prior cognitive assessment (Klaassen et al., 2013; 2014). In the present study, we used a novel approach, the TloadDback task (Borragán et al., 2016) that allows tailoring the specific task parameters for each participant by pre-assessing the minimal time needed to perform suitably on the task, hence providing an individual index of maximal cognitive load. This way, we ensured that even subjects exhibiting high innate cognitive capacity levels are challenged in a high cognitive load (HCL) condition.

2.1. *Methods*

2.1.1. *Participants*

Thirty-two French-speaking participants (21 women, 6 left-handed; mean age 23.37 ± 3.86 years) without reported history of psychiatric or neurological disease gave their informed consent to participate in the present study, conducted in accordance with the Declaration of Helsinki and approved by the ethics committee of the Faculty of Psychological Sciences at the Université Libre de Bruxelles (ULB). Subjects were naïve to the purpose of the experiment. All participants had a satisfying sleep quality during the month preceding the experiment (Pittsburgh Sleep Quality Index − PSQI score ≤ 9; *mean* ± *SD*; =4.69 ± 1.51; Buysse et al., 1989). Participants were also in the range of neutral chronotype (45.93 ± 10.46 at the Morningness-Eveningness Questionnaire, MEQ; Horne & Ostberg, 1976). Finally, participants obtained a mean score = 34.7 ± 7.47 at the Fatigue Severity Scale (FSS; Krupp, 1989), a brief questionnaire composed by 9 questions evaluating the impact of fatigue on people's daily life during the week before the experiment. Two participants were excluded from the study for not adhering to the exclusion criteria (i.e., having bad sleep quality and not finishing the whole experiment).

2.1.2. *Tasks and procedure*

2.1.2.1. TIME LOAD DUAL BACK (TLOADDBACK) TASK. The TloadDback task (Borragán et al., 2016) is a dual task featuring a classical N-back working memory-updating task (Kirchner, 1958) and an interfering second task (odd/even decision task). Combining two tasks with different information processing requirements aimed at ensuring a large recruitment of working memory resources. This involvement of working memory resources can be modulated with the pace at which the information needs to be processed or the complexity of the N-back task (e.g., 0 *vs* 1-back; see below). In the classical TloadDback task, digits and letters are displayed on the screen in alternation (letter/number/letter/...; Fig. 1b). Participants are instructed to either (a) press with their left hand the space key every time the displayed letter is the same than the previous letter (1-back task), or (b) indicate whether the displayed digit is odd or even by pressing with their right hand "1" or "2" on the numeric keypad. A total of 8 letters (A, C, T, L, N, E, U, and P) and 8 numbers (1, 2, 3, 4, 6, 7, 8 and 9) were used during the task. All letters had a frequency of occurrence >2.5% in the French Grammar (Boris New & Christophe Pallier, Lexique3). Letters visually similar to numbers were excluded (e.g., O, I, S, Z). The digit "5" was also excluded to have a same number of odd and even digits. All stimuli were presented in Arial font size 120, centrally on a 16-inch computer screen (refresh rate 60 Hz). The space key was covered with a white sticker and the "1" and "2" keys were covered with blue and green stickers to prevent possible associations between key number and parity judgements.

Each block comprised 30 letters and 30 digits displayed in alternation (see Fig. 1b). Digits and letters were pseudo-randomly presented. For letters, 10 consecutive repetitions

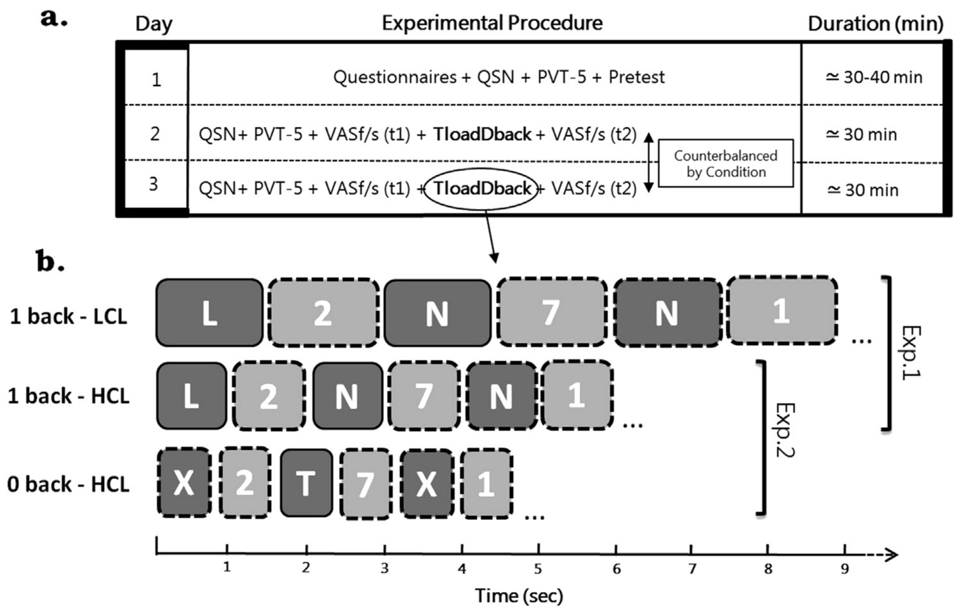

Fig. 1 – Experimental design. (a) Overview of the experimental procedure in Experiments 1 and 2. Testing was distributed over 3 days. On Day 1, after filling in with the questionnaires (PSQI: Pittsburgh Questionnaire, MEQ: circadian chronotype and FSS: Fatigue Severity Scale) a pre-test aimed at determining the individual maximal processing capacity (i.e., the shortest possible Stimulus Time Duration [STD] to keep performance >85%) on the respective TloadDback task version. On Days 2 and 3, task conditions were administered (counterbalanced). Subjective cognitive fatigue and sleepiness (Visual Analogic Scales) were measured before and after the task. Baseline vigilance levels (PVT-5) and subjective sleep quality (QSN) were measured at the beginning of each day session. (b) Illustration of processing rate featured by the STD in different TloadDback variants. The individual STD determines the number of stimuli that appear in the same time duration in each condition.

(target responses) were presented in each block. Performance per block was computed using a weighted formula where accuracy for letters and digits represented 65% and 35% of the total score, respectively. This choice was made to emphasize the information-retrieval component of the task, based on existing literature showing that encoding, maintenance, and manipulation functions of working memory have a higher attentional cost than encoding and manipulation alone (Fougnie, 2008). Raw scores for letters and digits are separately reported in Table 1. Performance per block was computed as a performance percentage.

2.1.2.2. Individual adjustment of high and low cognitive load conditions. The manipulated variable in this task is the available processing time during which each item is presented on the screen, i.e., the Stimulus Time Duration (STD). This manipulation is in line with the TBRS hypothesis that the available time to process information, or processing time pressure, is the determinant of cognitive load (Barrouillet et al., 2004) and, according to our assumption, the determinant of the level of CF. Individual STD was adjusted before the experimental condition in a pre-test session, and calculated for each participant as the shortest STD to keep accuracy performance >85%. The pre-test session included two parts. In the first part, participants practiced separately the odd/even judgements and a 1-back task, using the right hand for parity judgements and the left hand for the 1-back task. The STD was set at 1500 msec during this phase. Once the two separate tasks were satisfactorily mastered (correct responses >85%), they were administered together during several dual-task blocks, again with an STD of 1500 msec. The training session was interrupted when participant's performance reached the

Table 1 – Accuracy performance for composite score and for letters and digits computed separately on the TloadDback task computed by temporal intervals (quartiles t1 to t4) during the 16 min of practice in Experiment 1.

Performance scores		t1		t2		t3		t4	
Condition	Component	M ± SD	CI	M ± SD	CI	M ± SD	CI	M ± SD	CI
1 back-HCL	Composite score	90 ± 7	(93–88)	88 ± 7	(90–85)	85 ± 8	(88–82)	85 ± 9	(89–82)
	Letters	89 ± 10	(93–85)	86 ± 11	(90–82)	83 ± 12	(88–78)	84 ± 13	(88–79)
	Digits	93 ± 5	(95–91)	91 ± 6	(93–88)	89 ± 8	(92–86)	89 ± 7	(92–86)
1 back-LCL	Composite score	96 ± 3	(97–95)	96 ± 4	(97–95)	95 ± 5	(97–93)	93 ± 6	(95–91)
	Letters	96 ± 5	(98–93)	95 ± 6	(97–93)	94 ± 8	(97–91)	91 ± 9	(95–88)
	Digits	97 ± 2	(98–96)	97 ± 13	(98–96)	96 ± 4	(97–94)	96 ± 4	(97–94)

85% weighted accuracy threshold (see above). They usually achieved this goal within 90–360 sec. Participants were then allowed a resting period to recover before beginning the second part of the pre-test. In this pre-test session, they were told that task complexity would progressively increase and that the aim of the pre-test was to measure their maximal cognitive capacity. They were successively presented full blocks (60 trials each) in a horse-race adaptive STD. To minimise the triggering of CF during the pre-tests session, participants were invited to take as much time as they needed before starting the next block. In the first block, STD was fixed at 1400 msec for all participants (total block duration = 84 sec). If performance for this block was >85%, the STD for the next block was set at the prior STD minus 100 msec. The procedure was then repeated until performance in the task declined below the threshold of 85%, meaning that the participant's cognitive load limit had been reached. To improve the goodness of adjustment of the pre-test (e.g., to consider variables as the learning of strategies), participants were given 3 accumulative errors. Errors allowed them to perform again at the same STD level when they were unable to maintain a performance >85%. The participant's last successful STD was assigned to the HCL condition. To determine the STD in the Low Cognitive Load condition (LCL), STD was made 50% longer than in the HCL (i.e., $STD_{(LCL)} = STD_{(HCL)} + 1/2\ STD_{(HCL)}$). Hence, a linear relation was kept between HCL and LCL levels for each individual. In both HCL and LCL conditions, blocks of stimuli were presented for 16 min (with a slight variation to allow completing the ongoing block after 16 min elapsed). Hence, participants with a shorter STD processed more stimuli within the allotted time, but the ratio between $STD_{(HCL)}$ and $STD_{(LCL)}$ was kept constant, ensuring a proportional change in cognitive load.

2.1.2.3. Evaluation of cognitive load-related effects

Subjective CF was measured before and after the TloadDback-task (Fig. 1a) using the Visual Analogic Scale of Fatigue (VASf; Lee, Hicks, & Nino-Murcia, 1991). Likewise, subjective sleepiness was assessed using the Visual Analogic Scale for Sleepiness (VASs; see e.g., Tanaka, Ishii, & Watanabe, 2014). To control for potential differences in the subjective notions of CF and sleepiness between participants, CF was defined to them as the need to stop an ongoing cognitive effort, whereas sleepiness was explained as excessive sleep pressure leading to the need to close the eyes and fall asleep.

Objective CF was measured computing the evolution of performance throughout the duration of the TloadDback task (Campagne, Pebayle, & Muzet, 2004; Faber et al., 2012; Lorist et al., 2000; van der Linden et al., 2003). Performance level (i.e., weighted accuracy) was computed over four successive time periods (t1, t2, t3, t4) including each ±20% of total trials, with an approximate duration of 3 min by time period. Time periods t1 and t2 were used to assess performance at the beginning of the experiment (40% of trials). Time periods t3 and t4 were used to assess performance at the end of the experiment (40% of trials).

Additionally, delta (Δ) indexes were computed to analyse the relationships between objective and subjective indicators of CF. The Δ Subjective Fatigue index reflects the differential increase of subjective fatigue between HCL and LCL conditions. To compute this index, we first calculated the increase of subjective fatigue [differential score, i.e., VASf after the task (post) minus VASf before the task (pre)] for both conditions. We then computed the difference between increases in HCL and LCL conditions (differential score in HCL minus differential score in LCL condition). Thus, positive values indicate that CF increased more in the HCL than in the LCL condition. Similarly, we computed Δ Performance t1, Δ Performance t2, Δ Performance t3 and Δ Performance t4 to capture the differential evolution of performance within the task between the HCL and LCL conditions [i.e., (Performance HCL–Performance LCL) for the 4 time periods]. Negative values indicate a worse performance in the HCL condition. If subjective and objective measures of CF are associated, then significant associations (i.e., negative correlation) between Δ Subjective and Δ Performance indexes are more likely to be observed at the end of the task (t3 and t4) when CF has been triggered, than at the beginning (t1 and t2) (see e.g., Lim et al., 2010; Gershon et al., 2009).

2.1.2.4. Vigilance and sleep measures

At the beginning of each experimental session, participants were administered a 5 min version of the psychomotor vigilance task (PVT; Dinges & Powell, 1985). A visual countdown started at random intervals (2–10 sec) during a 5-minutes session in which participants were instructed to stop the countdown as fast as possible by pressing a key. Reciprocal reaction times (1/RT; Basner & Dinges, 2011) omission and commission errors were recorded.

Participants were then administered the St-Mary Hospital Questionnaire (QSN; Ellis, Johns, Lancaster, Raptopoulos, Angelopoulos, & Priest, 1981) to assess sleep quality for the night preceding the experimental day (results are reported as Supplemental information).

2.1.2.5. General procedure

The experiment took place on three consecutive days (see Fig. 1a for an overview). To avoid circadian confounds, participants were always tested at the same time of the day for the three sessions. The time periods between 12:00 and 14:00 and after 18:00 were also excluded to avoid post-lunch dip and sleep pressure at the end of the day, respectively. Participants were asked to maintain regular sleep habits and avoid alcohol and drug consumption during the experimental days and the night before the start of the experiment. Nicotine and stimulant (e.g., coffee, tea, energizers…) consumption was banned for at least two hours before the beginning of each testing session. Each experimental session started with the administration of the PVT and QSN (see above). Thus on Day 1, the Pretest was administered to compute the maximal individual cognitive load [$STD_{(HCL)}$]. Participants were also administered the PSQI, MEQ and FSS. On Days 2 and 3, participants were administered the HCL and LCL conditions in a counterbalanced order. The VASf and the VASs were also administered before (pre) and after (post) the TloadDback task both in the HCL and LCL conditions. To avoid possible comparisons between fatigue or sleepiness reports, participants did not see their prior responses when filling in again with the VASf and VASs.

2.1.3. Statistics

Statistical analyses were computed following Fritz, Morris, and Richler (2012) recommendations. Kolmogorov–Smirnov tests were used to assess assumption of normality. Single t-tests against the null value, paired t-tests between conditions and repeated-measures ANOVAs were used to analyze the evolution of CF and sleepiness. Pearson correlation analyses were used to investigate relationships between relevant variables. Tukey tests were used for post-hoc comparisons. Mean (*m*) ± Standard Deviation (*SD*) are reported as measures of central tendency and variability, and effect sizes reported either as Cohen's d (d) or partial eta squares (η^2). Mean squared errors (*MSE*) were reported for the ANOVAs as well. Significance level was set at $p < .05$ (two-tailed). Additionally, we use Bayesian analysis as a confirmatory approach to test the reliability of null results, which is not possible with usual statistics.

2.2. Results

2.2.1. Sleep quality and vigilance on experimental days

Repeated-measures ANOVAs were computed on subjective sleep quality scores (from 1 [bad] to 6 [good]) and sleep duration (hours) as derived from the QSN (Ellis et al., 1981) for the three nights of the experiment. Sleep quality (Night 1 = 4.45 ± 1.02, Night 2 = 4.29 ± .86 and Night 3 = 4.45 ± .81) or sleep duration (Night 1 = 7.62 ± 1.34, Night 2 = 7.93 ± 1.13 and Night 3 = 7.84 ± 1.14 h), were similar for the three experimental nights (all $ps > .4$).

Vigilance levels were also measured at the beginning of each experimental session using the PVT. A repeated-measures ANOVA computed on reciprocal reaction times (mean 1/RT, see Basner & Dinges, 2011) failed to disclose significant differences between the 3 experimental days [$F_{(2, 58)} = .11$, $p > .8$; Day 1 = 3.33 ± .004, Day 2 = 3.32 ± .005 and Day 3 = 3.31 ± .005]. The same analysis computed on the RT coefficient of variation (CV = SD/Mean) also failed to disclose significant differences between the 3 experimental days [$F_{(2, 58)} = .2$, $p > .9$; Day 1 = .17 ± .08, Day 2 = .17 ± .07 and Day 3 = .17 ± .07]. These results indicate that sleep on the preceding night and vigilance levels are not confounding factors in the evaluation of CF induction in this experiment.

2.2.2. Pre-test

As mentioned above, the minimal STD to ensure task performance >85% was computed for each individual separately. Mean $STD_{(HCL)}$ was 963 ± 173 msec (range = 600–1400). A Kolmogorov–Smirnov test disclosed a normal distribution across participants ($p > .2$).

2.2.3. Subjective measures of CF and sleepiness

As a measure of subjective fatigue and sleepiness induced by the TloadDback task, we computed differential scores between pre- and post-task on VASf and VASs scores, respectively.

2.2.3.1. CF. We performed a 2 (Cognitive Load: HCL *vs* LCL; within subject-factor) by 2 (Order: HCL–LCL *vs* LCL–HCL; between subject-factor) mixed-design ANOVA on differential (i.e., pre minus post) VASf scores. Results disclosed a main effect of Cognitive Load [$F_{(1, 28)} = 7.98$, $p = .01$, $MSE = 3.22$; $\eta^2 = .22$]. As expected, CF increased more in the HCL (2.45 ± 1.89) than in the LCL (1.27 ± 1.43) condition. The Order or Order × Cognitive Load condition interaction factors did not reach significance ($Fs < 1$; all $ps > .4$). Additionally, t-tests on VASf differential scores against the constant value 0 disclosed a significant increase in CF after both the HCL [$t_{(29)} = 7.08$, $p < .001$, $d = 2.63$] and the LCL [$t_{(29)} = 4.85$, $p < .001$, $d = 1.80$] conditions (Fig. 2a).

2.2.3.2. Sleepiness. A similar 2 by 2 mixed-design ANOVA was computed on differential VASs scores. The analysis disclosed a main effect of Cognitive Load condition [$F_{(1, 28)} = 4.40$, $p < .05$; $MSE = 2.07$; $\eta^2 = .14$]. Contrarily to subjective fatigue, subjective sleepiness increased more in the LCL (1.73 ± 2.35) than in the HCL condition (.97 ± 2.2). The Order or Order × Cognitive Load interaction effects did not reach significance ($Fs < 1.5$; all $ps > .25$). t-Tests on VASs differential scores against 0 also disclosed increased sleepiness in both the *HCL* [$t_{(29)} = 2.47$, $p < .05$, $d = .92$] and the *LCL* [$t_{(29)} = 4.05$, $p < .001$, $d = 1.50$] conditions (Fig. 2b).

2.2.3.3. Correlations between CF and TloadDback performance. Pearson correlation analyses between VASf (fatigue) difference scores in the HCL and LCL conditions failed to reach significance ($p > .5$). The same analysis conducted on VASs (sleepiness) difference scores disclosed a significant correlation between the two conditions ($r = .62$, $p < .001$). These results suggest that whereas increments in sleepiness could be modulated by intra-individual factors, increments in fatigue might be driven by the task condition.

2.2.4. Objective measurement of CF during task performance

A mixed-design ANOVA computed on weighted accuracy scores with Cognitive Load (HCL *vs* LCL) and Time on Task (ToT) (t1 *vs* t2 *vs* t3 *vs* t4) as within subject factors and Order (HCL–LCL *vs* LCL–HCL) as the between-subject factor disclosed a main effect of the Cognitive Load condition [$F_{(1, 28)} = 29.60$, $p < .001$; $MSE = .97$; $\eta^2 = .51$], with higher performance levels in the LCL (94.6 ± 7%) than in the HCL (87.6 ± 3%) condition, and a main effect of ToT [$F_{(3, 84)} = 11.63$, $p < .001$; $MSE = .19$; $\eta^2 = .29$]. Tukey's post-hoc tests disclosed a higher performance at the beginning than at the end of practice [t1 > (t3 = t4) and t2 > t4; all $ps < .01$]. The Cognitive Load condition × ToT interaction was also significant [$F_{(3, 84)} = 3.78$, $p < .05$; $MSE = .10$; $\eta^2 = .12$]. Tukey's post-hoc analyses indicated that although performance decreased in both the HCL and LCL conditions from the beginning to the end of the task (t1 > t4; Tukey's post-hoc $ps < .05$), it decreased faster in the HCL condition in which performance decreased from t1 to t2 and from t2 to t3 (all $ps < .05$) as compared to the LCL condition in which performance was only different between t1 and t4. These results suggest that, as expected, cognitive demands and resulting CF were higher in the HCL condition (see Table 1).

An additional analysis was performed to assess separately the evolution within time for the two components of the task (i.e., parity judgment on numbers and N1-back on letters). A

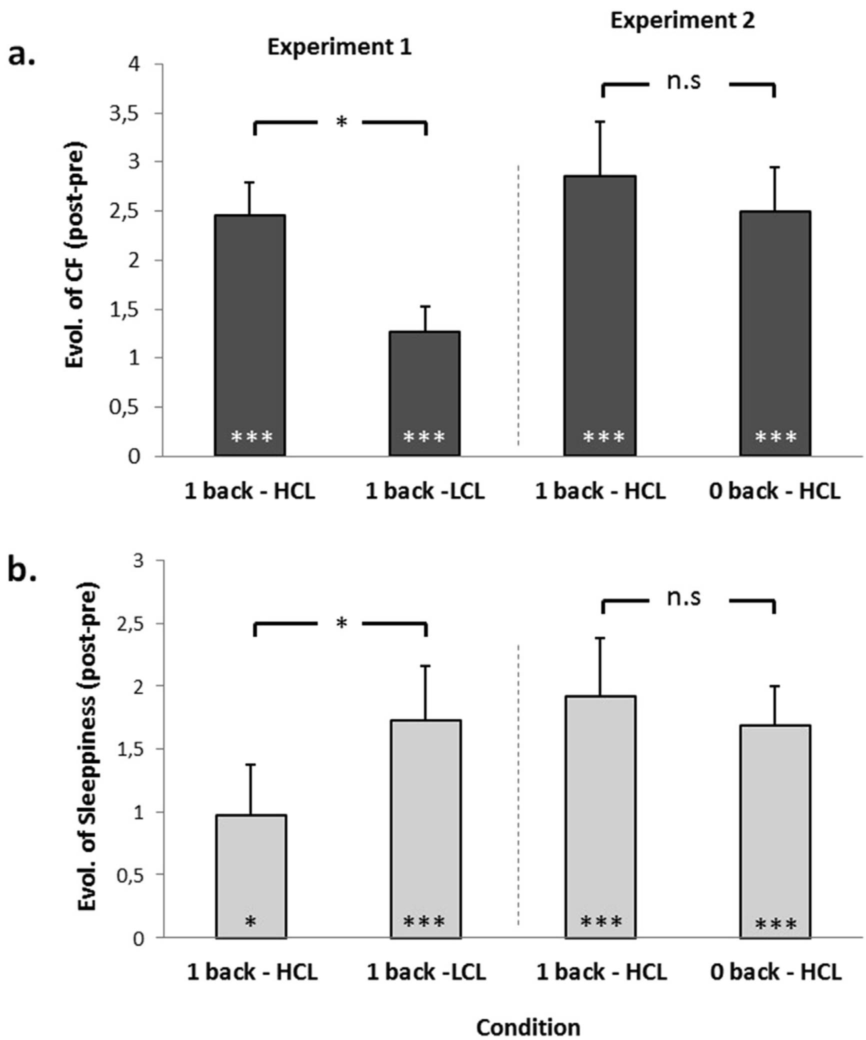

Fig. 2 – Cognitive fatigue (CF) and sleepiness before and after the TloadDback task in Experiments 1 (on the left) and 2 (on the right). Error bars represent standard errors. Asterisks reflect *p*-values after Tukey post-hoc correction: * = *p* < .05; ** = *p* < .01 and * = *p* < .001; "*n.s.*" is non-significant and "*tend*" reports a tendency (.1 < *p* > .05).**

mixed-design ANOVA was computed with Component (Letter *vs* Digits), Condition (HCL *vs* LCL) and Time (t1–t4) as within-subject factors and Order as a between subject factor. The analysis confirmed the previously observed main effects of Time ($F = 13$, $p < .001$), Condition ($F = 47$, $p < .001$) and the interaction Time × Condition ($F = 5$, $p < .005$). Furthermore, there was a main effect of Component ($F = 6$, $p < .05$), with higher performance value for digits than letters (93 ± 35 *vs* 90 ± 7%), indicating the slightly higher complexity featured by the working memory component (1-back task on letters) compared to the interfering task (odd/even task on digits), which justifies the computation of a weighted composite score emphasizing the working memory component.

2.2.5. *Correlation between subjective and objective markers of CF*

In line with our predictions, Pearson coefficient analyses disclosed positive correlations between Δ Subjective Fatigue and Δ Performance scores during the second half (t3: $r = -.5$; $p < .01$, t4: $r = -.42$; $p < .025$) but not during the first half (t1: $r = -.27$; $p = .15$, t2: $r = -.16$; $p = .4$) of the task (see Fig. 3). These negative correlations suggest that the higher differences in performance between conditions at the end of the experiment reflect increased CF, as estimated with subjective scales.

Regarding the evolution of sleepiness, the correlations between Δ Subjective Sleepiness and Δ Performance were non-significant at all time periods (all *ps* > .4), suggesting that differences in performance are not explained by a differential increase of sleepiness over the task.

2.2.6. *Relationships with habitual fatigue levels (trait-fatigue)*

Individual scores on the FSS questionnaire (mean score = 34.7 ± 7.47) were not correlated with the increase of CF or Δ Fatigue or Δ Sleepiness scores (all *ps* > .25), suggesting that measurement of trait fatigue is independent of state fatigue as measured over task practice, at least in healthy young participants. Similar results were found in a recent study (Sandry et al., 2014).

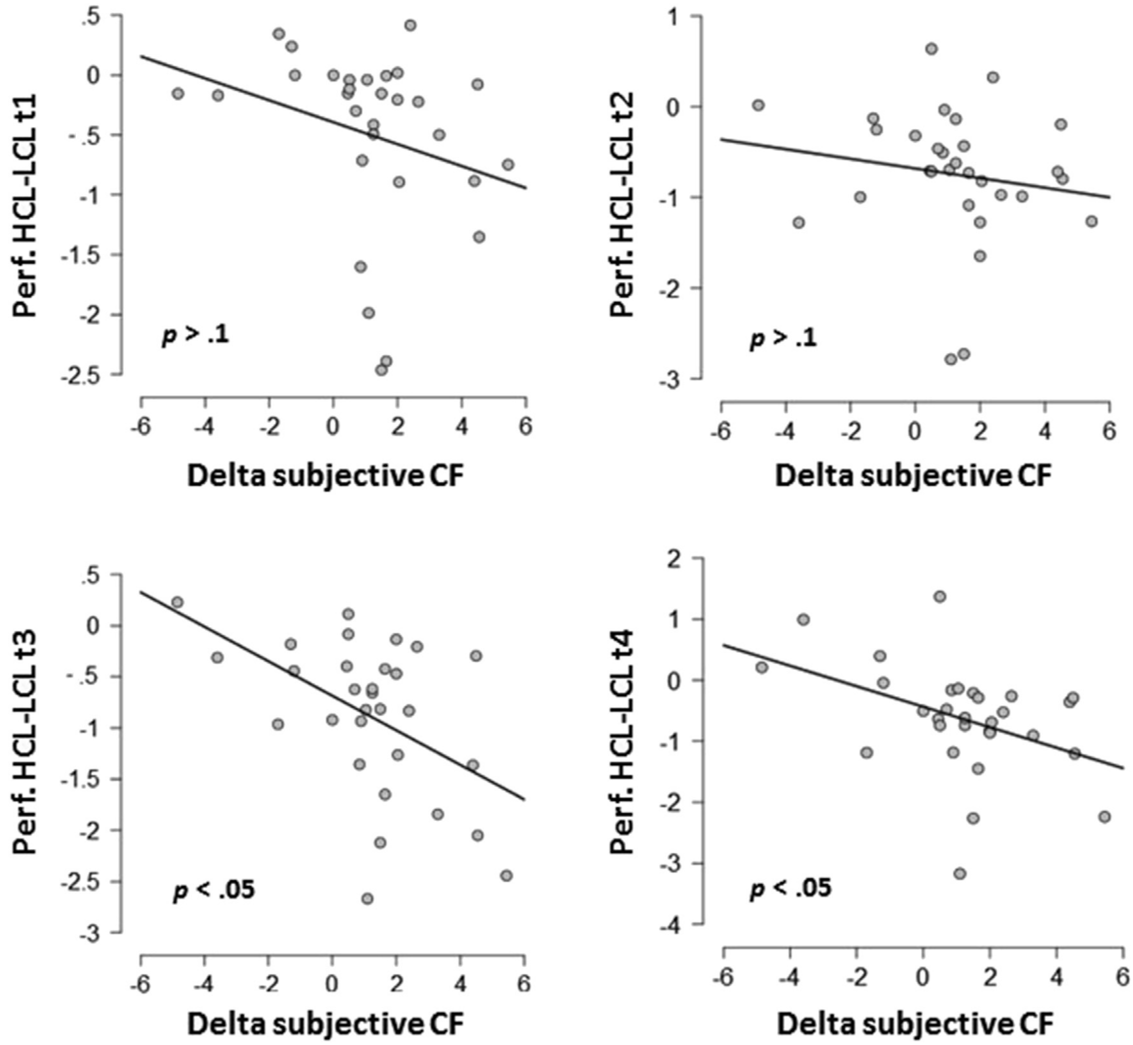

Fig. 3 – Correlations between (delta) differences in subjective scores of cognitive fatigue and differences in objective performance at the four quartiles of the TloadDback (t1–t4). Confidence interval = .95.

2.3. *Summary discussion of Experiment 1*

In line with our predictions derived from the TBRS model (Barrouillet et al., 2004), we have found in Experiment 1 that shortening the available time to process ongoing information while keeping a similar level of complexity and the same task duration increases cognitive load, eventually resulting in higher levels of CF, as assessed using both subjective and objective measurements. On a methodological note, it must be emphasized that manipulating STD to increase cognitive demands while keeping constant the duration of the task logically leads to a higher number of stimuli to be processed in the HCL than in the LCL condition. One may therefore argue that CF originates from a higher number of items to process during a same time interval, an argument germane to the TBRS approach. In this respect, Barrouillet et al. (2004) showed that increasing the number of stimuli actually do not lead to higher cognitive load, if supplementary time is allotted to process this information. Thus, it is likely not the number of items in itself that increases cognitive load, but the time left available to process these items.

A second observation is that subjective feelings of sleepiness and CF appeared to be dissociated. Indeed, higher levels of CF tended to be associated with lower levels of sleepiness. It suggests that a higher state of arousal is triggered when cognitive demands are high and strongly solicit available resources. As a result, the subjective feeling of sleepiness is reduced, and increases at a slower rate in the HCL/high CF condition. A complementary explanation is that participants might have found the LCL condition too easy to process, leading them into an under-stimulation state and to a feeling of boredom accompanied by higher subjective sleepiness. These interpretations are in line with the Facilitation–Inhibition model of fatigue (Ishii, Tanaka, & Watanabe, 2014) which suggests that there is no need to keep a high amount of cognitive resources constantly active when the demands are not high enough.

3. Experiment 2: CF: time or complexity?

The results of Experiment 1 suggest that increasing processing time pressure can induce CF in conditions where the task features identical complexity. However, the inherent complex and demanding character of the TloadDback (i.e., dual task processing and working memory updating) raises the possibility that complexity also contributed to the induction of CF. To investigate this issue, in Experiment 2 we compared two task conditions differing by their complexity demands, but in which a similarly high time pressure was ensured. If our prediction that CF is due to processing time pressure more than to task complexity in itself holds true, then a similar increase in CF should be observed in the two experimental conditions, both at the subjective and objective measurement levels.

3.1. *Methods*

3.1.1. *Participants*

Thirty-four French-speaking participants (21 women, 5 left-handed; average of age 23.72 ± 3.79) participated in Experiment 2, under the same conditions as in Experiment 1. None of them participated in Experiment 1. They were not informed in advance about the aim of the experiment, and were pseudo-randomly assigned to the experimental conditions order (see below). Participants presented a good quality of sleep within the month preceding the experiment (all PSQI scores ≤ 9; *mean* ± *SD* was 5.75 ± 1.96; Buysse et al., 1989). Participants were also in the range of neutral chronotype (50.81 ± 7.97 at the MEQ; Horne & Ostberg, 1976). Average of participant's FSS score of general fatigue was 34 ± 7.96. Five participants were excluded from the analyses for not respecting the inclusion criteria (i.e., having bad sleep quality or too extreme circadian chronotype or not participating in the whole experiment).

3.1.2. *Task and procedure*

Two conditions involving different cognitive demands were used in this experiment. The first condition was identical to the HCL condition of Experiment 1. In the second condition, the complexity of the TloadDback was reduced by suppressing the memory retention component of the task, using a 0-back instead of a 1-back task. In contrast with the original HCL condition where participants are asked to keep in mind and update prior information to perform a comparison between the ongoing and the prior letter (1-back task), participants were simply asked to signal the presentation of the target letter “X” (0-back). Digits (odd/even decision) and letters (“X” detection) alternated like in Experiment 1, and the material was identical. Time pressure was individually adjusted in a pre-test session to involve similar cognitive load demands in the high (1-back) and low complexity conditions (0-back) according to the framework of the TBRS model (Barrouillet et al., 2004). The stimulus time duration (STD) needed to achieve accuracy performance >85% was computed separately for both conditions. Therefore, both tasks were considered to involve HCL demands (1-back HCL and 0-back HCL). Pre-tests for high and low complexity conditions were administered on Day 1 following a counterbalanced order. The STD was determined using exactly the same procedure as in Experiment 1. In order to prevent a potential impact of CF due to pre-testing in the other condition, participants were invited to take as much as time they needed to recover between the two pre-test assessments.

Apart from the determination of optimal STD for both conditions on Day 1, the procedure and additional material (questionnaires, scales, PVT) were identical to Experiment 1. The 1-back HCL and 0-back HCL conditions were counterbalanced between Day 2 and Day 3.

3.2. *Results*

3.2.1. *Sleep quality and vigilance on experimental days*

Repeated-measures ANOVAs were computed for subjective sleep quality scores [from 1 (bad) to 6 (good)] and sleep duration (hours) as derived from the QSN (Ellis et al., 1981) for the three nights of the experiment. Sleep quality (Night 1 = 4.3 ± 1.37, Night 2 = 4.41 ± 1.22 and Night 3 = 4.15 ± 1.64) and sleep duration (Night 1 = 7.9 ± 1.6, Night 2 = 8.4 ± 1.8 and Night 3 = 7.7 ± 1.3 h) were similar for the three experimental nights (all *ps* > .15). Vigilance levels were also measured at the beginning of each experimental session using the 5 min version of the PVT (Dinges & Powell, 1985). No significant differences were found for the mean 1/RT index ($F < 1$, $p > .4$; Day 1 = 3.16 ± .004, Day 2 = 3.16 ± .005 and Day 3 = 3.15 ± .006). No significant differences were found for the CV ($F < 1$, $p > .2$). These results indicate that sleep on the preceding night and vigilance levels cannot be considered as confounding factors in the evaluation of CF induction in this experiment.

3.2.2. *Pre-test*

The minimal STD to ensure task performance >85% was computed in each individual for both 1-back HCL (high) and 0-back HCL (low) complexity conditions. Mean STD was 934 ± 215 msec (range = 600–1400) in the 1-back HCL condition and 676 ± 130 msec (range = 500–1100) in the 0-back HCL condition. Kolmogorov–Smirnov tests disclosed a normal distribution across participants in the 1-back HCL condition (*ps* > .2) but a positive skewed distribution in the 0-back HCL condition. An ANOVA computed on logarithmic transformed STD with Complexity (High: 1-back HCL *vs* Low: 0-back HCL) as the within-subject factor and Order (High–Low *vs* Low–High) as the between subjects factor disclosed a main effect of Complexity with smaller STD in the low than in the high complexity condition [$F_{(1,\ 27)} = 53.2$, $p < .001$; $MSE = .005$; $\eta^2 = .66$], indicating two different levels of complexity. No other effects were significant (*ps* > .4).

3.2.3. *Subjective measures of CF and sleepiness*

As in Experiment 1, task-related increases in subjective fatigue and sleepiness were computed as difference scores between pre-task and post-task in both 1-back HCL and 0-back HCL conditions on VASf and VASs (respectively).

3.2.4. *CF*

We computed a 2 (Complexity: 1-back HCL *vs* 0-back HCL; within subject-factor) by 2 (Order: 1-back HCL − 0-back HCL *vs* 0-back HCL − 1-back HCL; between subject-factor) mixed-design ANOVA on the VASf scores. Results failed to disclose a main effect of Complexity ($p > .3$). We conducted a Bayesian analysis (Eidswick, 2012) using JASP-software (Love et al., 2016) to probe the reliability of this null result (see Fig. 4a and b). Bayesian paired samples t-test computed upon subjective delta scores of CF for the two conditions (i.e., 1-back HCL *vs* 0-back HCL) disclosed a Bayes Factor of .23. This value, below the standard threshold of 1/3 suggests that evidence is in favour of the null hypothesis. Main effects of Order and Cognitive Load did not reach significance (all $ps > .13$). The interaction Complexity × Order disclosed a trend for significance ($p > .06$) which was disconfirmed by post-hoc analysis (*all* $ps > .2$). CF increased both in the 1-back HCL (2.85 ± 3) and in the 0-back HCL (2.5 ± 2.4) condition. Additional t-tests on VASf difference scores against the constant value 0 disclosed a significant increase in CF both after the 1-back HCL [$t_{(28)} = 4.98$, $p < .001$, $d = .93$] and the 0-back HCL [$t_{(28)} = 5.64$, $p < .001$, $d = 1$] conditions.

3.2.5. *Sleepiness*

A mixed-design ANOVA on VASs difference scores also did not disclose a main effect of Complexity, Order or Order × Complexity interaction effects ($Fs < 2.4$; all $ps > 1.3$). Calculation of a Bayes Factor for sleepiness evolution disclosed a value of .20, supporting again the null hypothesis. Subjective sleepiness increased both in the 1-back HCL (1.6 ± 2.27) and in the 0-back HCL condition (1.8 ± 1.7). t-Tests on VASs difference scores against 0 also disclosed an increase in sleepiness in both the 1-back HCL [$t_{(28)} = 3.92$, $p < .001$, $d = .73$] and the 0-back HCL [$t_{(28)} = 5.4$, $p < .001$, $d = 1$] conditions.

3.2.6. *Objective measurement of CF during task performance*

A new mixed-design ANOVA computed on weighted accuracy scores with Complexity (1-back HCL *vs* 0-back HCL) and ToT (t1 *vs* t2 *vs* t3 *vs* t4) as within subject factors and Order (1-back HCL – 0-back HCL *vs* 0-back HCL – 1-back HCL) as the between-subject factor disclosed a main effect of ToT [$F_{(3, 81)} = 18.2$, $p < .001$; $MSE = .002$; $\eta^2 = .40$]. Tukey's post-hoc tests disclosed a higher performance at the beginning than at the end of practice (t1 > (t2 = t3); (t1, t2) > t4; $ps < .05$; see Table 2). No other main effects or interaction were significant (*all* $Fs < 2.1$, *all* $ps > .16$). A Bayesian repeated-measure ANOVA disclosed a Bayes Factor of .084 for the Complexity × ToT interaction, confirming a similar decrease in performance in the two conditions.

3.3. *Summary discussion of Experiment 2*

Experiment 2 aimed at comparing two conditions that differed by their level of complexity, but in which the cognitive load was similar according to the TBRS model (Barrouillet et al., 2004). Results evidenced a comparable evolution of CF and Sleepiness when the two conditions featuring different complexity were equalized in processing time pressure. Similarly, accuracy performance during task practice concurrently decreased in both conditions suggesting similar task demands. These results confirm that it is not the number of stimuli presented *per se* that is responsible for the triggering of CF since the number of stimuli presented in the 0-back HCL was higher than in the 1-back HCL, but rather the time available to process them. In both cases participants were at the edge of their capacity, explaining why CF increased

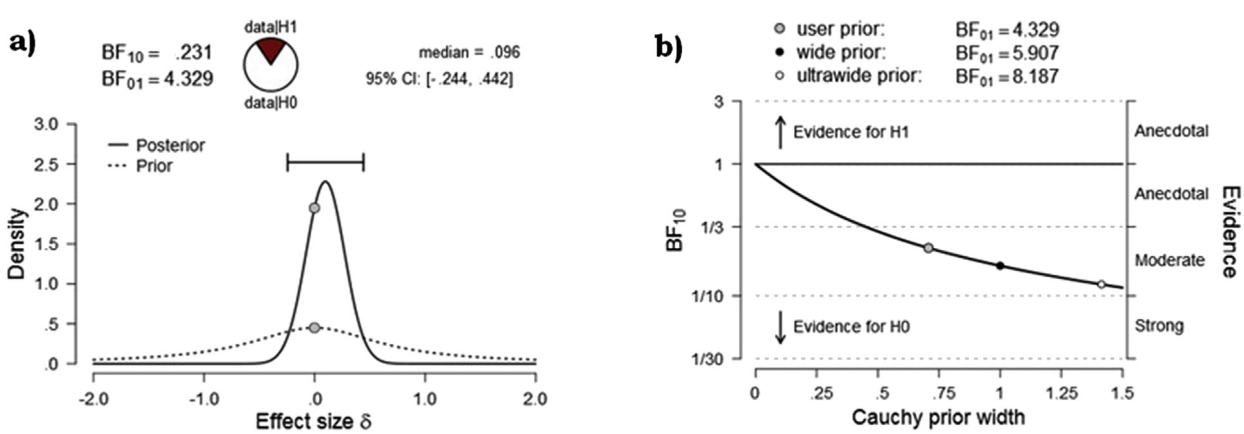

Fig. 4 – Bayesian analyses (Experiment 2). Evolution of the subjective feeling of CF. (a) Density plot shows how after all evidence is presented, the distribution narrows around an effect size of 0 (i.e., arguing for no difference between conditions). (b) Evidence in favor of H0 or H1 given our data and the Cauchy width of our prior distribution set at .707. The Bayes Factor$_{10}$ (grey dot) is lower than 1/3, arguing in favor of the H0 of similar CF evolutions within the conditions.

Table 2 – Performance evolution for the two variants of the HCL TloadDback in the Experiment 2.

Performance scores		t1		t2		t3		t4	
Condition	Component	M ± SD	CI	M ± SD	CI	M ± SD	CI	M ± SD	CI
1 back-HCL	Composite score	88 ± 15	(95–87)	84 ± 17	(94–84)	83 ± 18	(93–83)	83 ± 19	(92–82)
0 back-HCL	Composite score	83 ± 20	(82–70)	81 ± 19	(80–69)	78 ± 23	(78–67)	78 ± 23	(77–64)

similarly in the two conditions. Consequently, these results support the hypothesis that task complexity in itself is not the main responsible for the induction of CF, which rather is cognitive load as estimated by the TBRS model (Barrouillet et al., 2004).

4. General discussion

4.1. *A time-based model for the induction of CF*

This study aimed at investigating whether increased CF after a highly demanding cognitive situation can be explained in the framework of the TBRS model (Barrouillet et al., 2004). We used a paradigm adapted from a classical N-back paradigm (Kirchner, 1958) in line with the TBRS's concept of attentional limited resources, the TloadDback task (Borragán et al., 2016), which allows computing individually tailored high- and low-cognitive demand situations. Two experiments were carried out to estimate CF and the induction of sleepiness in high- versus low-demanding situations. In Experiment 1, the processing time interval defined the high-demanding condition. In Experiment 2, the influence of complexity on CF and sleepiness was investigated in two conditions featuring different levels of complexity but in which processing time pressure was adjusted to induce a similar level of cognitive load.

Results from Experiment 1 indicate that cognitive load due to faster processing time is responsible for the increase in CF. Indeed, constrained processing time induced higher levels of CF at equal task complexity. This finding supports the TBRS's proposal that the available time to process incoming information is an important element to take into account when defining the limited attentional resources of human cognition (Atkinson & Shiffrin, 1968; Barrouillet et al., 2004; Gillie & Broadbent, 1989; Lavie, 2010). Results from Experiment 2 strengthen this idea, indicating that task complexity or specific cognitive demands involved in the task are not as crucial as the available processing time to induce CF (Barrouillet, Bernardin, Portrat, Vergauwe, & Camos, 2007; Lépine, Bernardin, & Barrouillet, 2005). Indeed, when processing time pressure was adjusted to induce a similar cognitive load in the two conditions differing by their complexity, the levels of CF were not different between the high and the low complexity conditions. Hence, it confirms that "*complexity is not required per se (...) what is needed is a steady capture of attention*" (Barrouillet et al., 2004). Our study further supports the proposal that attentional capture is mostly responsible for increased CF.

Although it is well documented that ToT generally leads to CF (i.e., the *Temporal fatigue hypothesis*; Ackerman & Kanfer, 2009; Boksem et al., 2005; Lim et al., 2010; Sandry et al., 2014; Trejo et al., 2005), only few studies have investigated whether the demands involved in a cognitive effort lead to different states of CF (*Cognitive load hypothesis*; Bailey, Channon, & Beaumont, 2007; Sandry et al., 2014; Shigihara, Tanaka, Ishii, Tajima, et al., 2013). Our study not only provides evidence to support this statement, but is also, to the best of our knowledge, the first to evidence that cognitive load defined according to the TBRS model is mostly responsible for the CF phenomenon. These results are also in line with the idea of a limited resource system in which CF is triggered by the unavailability of sufficient mental resources (Gergelyfi et al., 2015). Altogether, these results provide supporting evidence for the CF hypothesis, which explains performance decrements as the outcome of an overloaded attentional system (Grier et al., 2003; Holtzer, Shuman, Mahoney, Lipton, & Verghese, 2011; Stuss, Shallice, Alexander, & Picton, 1995). Furthermore, our results corroborate prior reports associating the development of CF with increased feelings of subjective fatigue and impaired performance (Boksem et al., 2005; Faber et al., 2012; Kato, Endo, & Kizuka, 2009; Lorist et al., 2005; van der Linden et al., 2003).

Finally, during the pre-test sessions, there was a high inter-individual variability in terms of the minimal time needed to achieve 85% accuracy performance, which further emphasizes the necessity to adapt task demands according to each individual's own capacity level when inducing cognitive load and/or CF (Holtzer et al., 2011).

4.2. *Differentiating between sleepiness and CF states*

Results of Experiment 1 disclosed a dissociation between the evolution of CF and the evolution of sleepiness through sustained practice, supporting the assumption that these states are not equal and need to be distinguished (Neu et al., 2010, 2011). Unfortunately, sleepiness and fatigue states have been often intermingled in the general conception of fatigue (Pigeon, Sateia, & Ferguson, 2003). In Experiment 1, although subjective CF and sleepiness increased during the TloadDback task both in the HCL and LCL conditions, we observed that CF increased faster in the HCL condition. Conversely, sleepiness increased more in the LCL condition. Such dissociation between the evolution of CF and sleepiness supports the assumption of two different states of "fatigue," likely regulated by different neural mechanisms (Ishii et al., 2014). More increased sleepiness in low-demanding task situations was previously reported (Shigihara, Tanaka, Ishii, Tajima, et al., 2013), a finding interpreted by the authors as the consequence of a situation of cognitive "under-load". In other terms, an insufficient workload would lead to increased boredom and/or sleepiness. In a low-demanding situation indeed, ongoing demands do not require the involvement of the whole system, which in response would slowly switch off. As proposed in the dual regulation system model (Ishii et al., 2014), if there is no need to keep a high amount of cognitive resources constantly active, then the system will activate an inhibition mechanism ordering the system to rest (Shigihara, Tanaka, Ishii, Tajima, et al., 2013). Accordingly, decreased performance is often reported when subjects perform in situations featuring lower cognitive demands (Pattyn, Neyt, Henderickx, & Soetens, 2008; Richter, Marsalek, Glatz, & Gundel, 2005; Wallace, Vodanovich, & Restino, 2003). The fact that CF and sleepiness decreases exhibit different patterns of evolution between HCL and LCL conditions in Experiment 1 may also support the idea that different brain systems are related to each of them (Shigihara, Tanaka, Ishii, Kanai, et al., 2013).

4.3. Correlation between subjective and objective measures of CF

In the present study, we found positive associations between the evolution of subjective CF and the evolution of performance during task practice. Currently, the relationships between subjective and objective parameters of CF are not well understood. Prior studies reported an absence of a correlation between the subjective perception of CF and objective behavioural measures (Bailey et al., 2007; Bryant, Chiaravalloti, & DeLuca, 2004; Krupp & Elkins, 2000; Lim et al., 2010), or a lack of association between subjective CF and decreased performance (Ackerman & Kanfer, 2009; Schwid et al., 2003). A possible explanation for an absent association between subjective and objective (performance) measures may be the fact that participants are not precisely aware of their degree of performance impairment. Therefore, they experience difficulties to relate perceived performance with the subjective perception of an increased mental effort (Lim et al., 2010). In daily life, people are used to signal that they are exhausted, but rarely specify the exact degree of this sensation. Furthermore, there is no universal metric for the feeling of exhaustion, and individuals may widely differ in their response to a cognitive challenge, as indicated by the range of pre-test values recorded in our experiments. To better account for inter-individual differences in the subjective experience of CF, we compared pre- to post-task differences (delta scores) or the within-task evolution of performance between the different experimental conditions, hence looking at individual, proportional changes. Correlation analyses indicate that the higher was the subjective CF reported at the end of the experiment in the HCL as compared to the LCL condition, the higher was the performance difference between conditions. Hence, these results suggest that a decrease in performance is associated with an increase in the feeling of CF. Further studies should investigate in more detail the causality in this relationship, i.e., whether the subjective feeling of CF is driven by changes in performance, or alternatively whether the change in performance is driven by the subjective feeling of CF.

4.4. Limitations and perspectives

A potential limitation of this work concerns the assessment of motivation within the task. Indeed, the feeling of CF also varies as a function of the continuous evaluation of the cost/benefits ratio during the task, which in turn influences the perceived level of cognitive effort (Boksem & Tops, 2008). Although we designed our experiment with the aim to equate task settings between conditions (i.e., identical time duration and rewards), we did not assess the evolution of motivation within the experiment. Another limitation is related to a potential influence of gender on CF. Indeed, due to a recruitment bias in psychology students, there are more women than men in our Experiments. However, the proportion is similar in both Experiments, which should have limited the impact of this variable. Finally, the duration of the TloadDback was arbitrary settled to 16 min. Although other experiments have shown that protocols of similar duration are efficient to induce CF effects (Gui et al., 2015; Lim et al., 2010), a more systematic manipulations of task duration and resting intervals should be investigated in future experiments. Likewise, future research should also investigate how the brain recovers from CF as well as the difference in the time needed to recuperate full processing capacity after high and low cognitive load situations.

5. Conclusion

We have shown across two main experiments that CF is triggered by the cognitive load related to the available processing time. These results strengthen the hypothesis of a limited attentional resource system, and highlight a close association between the amount of resources involved in a specific cognitive demand and the triggering of CF. Most importantly, our experiments suggest that it is not the complexity of the cognitive effort, but the continuous mental effort induced by the processing time pressure which is mostly responsible for the triggering of CF. Therefore, along with studies proposing that the triggering of CF depends on factors such as motivation, drive or personality traits (St Clair Gibson et al., 2003), CF can be envisioned as a mechanism influenced by the amount of depleted cognitive resources, and a function of the time available to process information as proposed in the TBRS model (Barrouillet et al., 2004). In this context and in line with physical models of fatigue (Baudry, Sarrazin, & Duchateau, 2013), CF can be interpreted as a natural warning-signal prompted by the organism to warn that a high cognitive demand is at risk to collapse the system.

Conflicts of interest

The authors declare no conflicts of interest in this work.

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Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.cortex.2017.01.023.

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