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To cite this version:

Thomas Mangin, Nathalie André, Abdelrhani Benraiss, Benjamin Pageaux, Michel Audiffren. No ego-depletion effect without a good control task. Psychology of Sport and Exercise, 2021, 57, pp.102033. 10.1016/j.psychsport.2021.102033 . hal-03503465

HAL Id: hal-03503465

https://hal.science/hal-03503465

Submitted on 27 Dec 2021

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Psychology of Sport & Exercise 57 (2021) 102033

Contents lists available at ScienceDirect

Psychology of Sport & Exercise

journal homepage: www.elsevier.com/locate/psychsport

No ego-depletion effect without a good control task

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ARTICLE INFO

Keywords:
Boredom
Cognitive fatigue
Effortful control
Ego depletion
Motivation
Sequential protocol

ABSTRACT

The ego-depletion effect refers to a temporary failure of self-control exertion after first performing an effortful task. This phenomenon has experienced a replication crisis in the past few years. In the present series of experiments, we tried to replicate the ego-depletion effect using a 30-min modified Stroop task tapping two executive functions (inhibitory control and cognitive flexibility) as the depleting task. In the first study, we compared the performance of a handgrip endurance task after this depleting task or after a classic control task (i.e., reading color words) and failed to replicate the ego-depletion effect. We showed that the control task induced boredom and subjective fatigue. In a second study, we looked for a better control task and compared the color-word reading task to another possible control task used in the literature (i.e., watching a documentary). Controlling for boredom, subjective fatigue, motivation and affective state, we found that the video task was not boring and did not induce fatigue, drop in motivation or negative affective state, whereas the color-word reading task did. In a third study, we used the video task as the control task and the modified effortful Stroop task used in the first study as the depleting task and succeeded in replicating the ego-depletion effect. This series of experiments illustrates that the choice of an appropriate control task is crucial to observe an ego-depletion effect and that boredom is costly. Consequently, it appears necessary to control for boredom in any future replication study aiming to observe an ego-depletion effect.

1. Introduction

Self-control can be viewed as a high-level cognitive function drawing on some limited resources that play a crucial role in daily living (Muraven & Baumeister, 2000). A high capacity in self-control is generally associated with a good integration of individuals into society and a diminished risk of unhealthy and deviant behaviors (Baumeister, 2005; DeWall et al., 2011; Fischer et al., 2012; Muraven et al., 2002; Tangney et al., 2004). In the domain of sport and exercise, self-control plays a crucial role in performance (for reviews, Englert, 2016; Englert, 2017; Englert et al., 2020; for meta-analyses, Giboin & Wolff, 2019; Brown et al., 2020) and in exercise adherence (for reviews, Martin Ginis & Bray, 2010; Hagger et al., 2010a; Buckley et al., 2014).

When the self-control capacity is temporarily weakened by a first effortful task, it is frequent to observe a drop in performance in a subsequent effortful task (Baumeister et al., 1998, 2018). This phenomenon, which is well known as 'ego-depletion effect', is currently challenged regarding its actual existence (Carter, Kofler, Forster, & McCullough, 2015; Vadillo, 2019), replicability (Hagger et al., 2016; Lurquin et al., 2016; Osgood, 2017; Xu et al., 2014) and theoretical underpinnings (Inzlicht & Schmeichel, 2012; Kurzban et al., 2013). The principal aim of this series of experiments is to replicate the ego-depletion effect by using an adequate experimental protocol that is cohesive with several assumptions of the strength model of self-control (Baumeister et al., 2007, 2018).

This model proposes that self-control depends on limited resources that can be depleted by any act of self-control leading to the ego-depletion effect. The sequential task protocol, elaborated by Baumeister et al. (1998), is commonly used in the laboratory to observe this short-term detrimental effect. In this protocol, a first group of participants carries out an initial effortful task called the depleting task, which is assumed to weaken the capacity to exert self-control. Right after this first task, participants perform a second effortful task called the dependent task, which further weakens the capacity to exert self-control.

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https://doi.org/10.1016/j.psychsport.2021.102033
Received 15 February 2021; Received in revised form 22 July 2021; Accepted 4 August 2021
Available online 5 August 2021
1469-0292/© 2021 Published by Elsevier Ltd.

A second group of participants carries out the same sequence of tasks except that the first task is replaced with a less-effortful control task. The strength model of self-control predicts that the participants who performed the depleting task perform worse in the subsequent dependent task than the participants who perform the control task first. This drop in performance is proposed to be due to fewer available resources because of the first act of self-control.

Several authors interpret the ego-depletion effect as the result of mental or cognitive fatigue related to the feeling that people may experience after or during prolonged periods of cognitive activity (Inzlicht & Berkman, 2015; André et al., 2019). Throughout the present manuscript, we conceive cognitive fatigue as the weakening of the capacity to exert effortful control over time. Based on the integrative model of André and collaborators (2019), we define effortful control as the capacity of the salience network, which includes the dorsal anterior cingulate cortex and the anterior insula (Seeley et al., 2007), to generate theta rhythmic oscillations in order to help brain regions involved in the ongoing task to filter pertinent information. Finally, we assume that performing a self-control task requires the involvement of mental effort, an energetic mechanism anchored in the salience network and making decision about the need for effortful control according to the costs and benefits associated with the achievement of the task goal (André et al., 2019; Shenhav et al., 2017). In this perspective, cognitive fatigue is viewed as a cost of exerting effortful control (Boksem & Tops, 2008) accompanied by a difficulty to sustain attention and effort to optimize performance over time (Chaudhuri & Behan, 2004).

In accordance with the strength model of self-control (Baumeister et al., 2007), the level of effortful control required by the depleting task is an important determinant of the size of the ego-depletion effect. Numerous depleting tasks have been used in the ego-depletion literature, but some of them seem to be definitely not as effortful as required to deplete participants. For instance, the meta-analysis of Dang (2018) showed that the video viewing task failed to induce a significant ego depletion effect after imputing effect sizes by the trim and fill method. In the same way, replication studies failed to obtain a significant ego depletion effect with the letter-crossing task (Etherton et al., 2018; Hagger et al., 2016; Wimmer et al., 2019; Xu et al., 2014). In contrast, tasks strongly tapping executive functions, such as the Stroop task, seem to be very good candidates to elicit high effortful control costs (André et al., 2019; Hofmann et al., 2012) and induce an ego depletion effect (Dang et al., 2021).

According to the taxonomy of Miyake et al. (2000), core executive functions include inhibitory control, updating of working memory and cognitive flexibility. Thus, the use of tasks well known to require one or more executive functions seems more appropriate to observe an ego-depletion effect. Inhibitory control presents many similarities with the concept of self-control used in social psychology when the latter is more restrictively designated as the ability to follow rules or inhibit immediate desires so as to delay gratification (e.g., Muraven & Baumeister, 2000). Another important commonality between executive functions and self-control is that both these high-level cognitive functions require effortful control (André et al., 2019; Hofmann et al., 2012).

In the present experiment, we made the choice of a modified Stroop task as the depleting task. This task requires inhibiting a pre-potent automatic response in some trials (reading words that are in color) in order to name the color of the ink. In this case, the Stroop task requires the control over a dominant response. In addition, we introduce a possible switch between two response rules at each trial: (1) reading the word or (2) naming the color of the ink. This last methodological add-on makes the task more effortful by increasing the cognitive load and tapping cognitive flexibility. In addition, several authors successfully induced a drop in performance following the completion of a modified Stroop task by comparison to a less effortful cognitive control task (e.g., MacMahon et al., 2019; Pageaux et al., 2014). Moreover, two meta-analyses showed that the Stroop task is effective at inducing an ego depletion effect (Dang, 2018; Hagger et al., 2010). Finally, the Stroop task has a moderate replication rate of 41%, higher than for the e-letter task (33.3%) or the multi-source interference task (38.5%), but lower than the emotion suppression task (54.1%) (Wolff et al., 2018). In the same way, we chose the handgrip endurance task as dependent task since this task have been used in numerous studies and that meta-analyses find a medium to large effect associated with this dependent task (Giboin & Wolff, 2019; Hagger et al., 2010).

A second theoretical determinant of the size of the ego depletion effect is the duration of the depleting task (Hagger et al., 2010). According to the strength model of self-control, it can be assumed that the longer the duration of the depleting task is, the higher the amount of depleted resources and larger the size of the ego-depletion effect are. The short duration of the depleting task, which is commonly used in the ego-depletion experiments, has probably been part of the replication crisis. Hagger et al. (2010) mentioned in their meta-analysis that many of the depleting tasks used were relatively brief. Most of the replication studies used depleting tasks that lasted less than 9 min with an average of 6 min. In a sport context, a recent meta-analysis pointed out that the mean task duration for the depleting task in ego-depletion paradigm with physical dependent task is 5.37 ± 3 min (Giboin & Wolff, 2019). To be depleted, healthy participants have to exert their self-control long enough (e.g., Blain et al., 2016). Cognitive fatigue, also known as mental fatigue, which can be indexed by a decrement in performance in a cognitive or physical task, generally occurs after a long and continuous effortful cognitive activity (e.g., Guo et al., 2018; Pageaux & Lepers, 2018). In this respect, Wolff et al. (2019) reported that until 16 min, the effect of the task on fatigue was nonsignificant. In a systematic review, Van Cutsem et al., 2017 proposed that cognitive tasks lasting more than 30 min consistently and negatively affected performance of a subsequent physical task, except for maximal and supramaximal exercises (Pageaux & Lepers, 2018). However, two meta-analyses recently showed that the duration of the depleting task does not seem to be a crucial parameter in the occurrence of the ego depletion and/or cognitive fatigue effect (Brown et al., 2020; Giboin & Wolff, 2019). In spite of the disturbing results of these two meta-analyses, we made the choice to use a depleting task with a long duration (i.e., 30 min), which is longer than most of the task durations generally used in ego-depletion studies. Our methodological choice was guided, on the one hand, by the theory (i.e., longer the depleting task is, higher the cognitive fatigue should be) and, on the other hand, by two sets of data. First, numerous vigilance studies examining the effect of cognitive fatigue as a function of time-on-task reported that performance deteriorates over time in long tasks requiring sustained attention (e.g., Boksem et al., 2005; Lorist, 2008). Second, a recent study manipulating the duration of the depleting task (4, 8 and 16 min) showed that spending longer time on the initial self-control task led to greater detrimental effects on a subsequent physical task (Boat et al., 2020).

A third determinant of the effect size of ego depletion could be trait self-control. Trait self-control refers to the self's capacity to exert control over thoughts, emotions, and behaviors (Baumeister et al., 2007) and is linked to many positive adaptive behaviors such as weight control, healthy eating, as well as school and work performance (de Ridder et al., 2012). Importantly, trait self-control is also a crucial aspect of participation in physical activity (Buckley et al., 2014), adherence to exercise (Gerdtham et al., 2020) and sport and exercise performance (Englert, 2016). Specifically, self-control in sport and exercise has been examined through trait self-control or the dispositional tendencies displayed by people who report to have higher or lower self-control or implicit beliefs that self-control is limited or unlimited. Overall, it has been shown that high trait self-control individuals are more physically active (Allom et al., 2016), invest more time in their training regimens (Toering & Jordet, 2015) and perform better under pressure (Landman et al., 2015). In the present study, we make the hypothesis that trait self-control could moderate gradients of state self-control, such as self-control deployment. For instance, high trait self-control individuals could be less impacted by situational high demands in self-control than low trait self-control

individuals (Lindner et al., 2018; Muraven et al., 2005).

The mechanism underpinning the ego-depletion effect is still in debate. According to the strength model of self-control, the ego-depletion effect would be caused by the depletion of brain resources (Baumeister et al., 1998, 2007). However, the exact nature of these resources has not yet been clearly established. Other models, such as the process model of self-control (Inzlicht & Schmeichel, 2012) assume that effort is aversive and that the exertion of effortful control leads to a subsequent reorientation of attention and motivation toward more pleasant cues and less effortful activities. This model predicts that after the depleting task, participants will be less motivated to perform another self-control task or the same depleting task another time. Furthermore, in studies that already explore this variable, the motivation to perform the mental task has been shown to be a moderator of the ego-depletion effect (Hagger et al., 2010; Muraven & Slessareva, 2003). For all these reasons, we decided to measure the motivation to perform each task throughout the sequential task protocol in order to control for the role of motivation in the drop of performance after the depleting task.

In the same way, recent works suggest than boredom could play a determinant role in the occurrence of the ego depletion effect (Wolff & Martarelli, 2020; Wolff, Bieleke, Stähler, & Schüler, 2021). According to Eastwood et al. (2012), boredom can be defined as an aversive state that occurs when people want but are unable to engage in a satisfying activity. For instance, a typical vigilance task is long and monotonous and requires participants to continuously monitor a display for detecting rare signals. Maintaining a good level of performance in such a task is generally perceived as highly boring. In the sport domain, athletes often perceive the repetition of sequences of the same training exercises as boring. In their Meaning and Attentional Components (MAC) model of boredom, Westgate and Wilson (2018) proposed that the state of boredom provides people with information about their current attentional and meaning states which they then use to form judgments and make decisions about what to do and how much effort to engage in the ongoing activity. In that perspective, boredom present several commonalities with cognitive fatigue: (1) they are associated with negative mood states; (2) they inform our brain about the state of the system induced by the ongoing activity; (3) they depend on the duration and the cognitive load of the task; (4) they participate to effort-based decision-making. More interestingly, Wolff and Martarelli (2020) proposed that boredom might affect results of ego depletion research by placing an unwanted demand on effortful control deployed by the participant and signaling that he/she should explore behavioral alternatives. Considering these recent advances on the possible mediating influence of boredom in the ego-depletion effect, we decided to control the boredom induced by the depleting and the control tasks.

The main purpose of this article is to replicate the ego-depletion effect using a long depleting task (30 min) strongly tapping executive functions. During a long task, time-on-task may change the inhibitory control demand in the depleting task because of learning, and then the characteristics of the task (Wolff & Martarelli, 2020). However, a modification of task parameters, such as an increase of the frequency of incongruent stimuli (Dulaney & Rogers, 1994) or the addition of a switch between two rules of action according to the preparatory signal, can limit learning effects. In this case, the demand of inhibitory control should remain high throughout the Stroop task. First, we hypothesize that performance of the dependent task (i.e., a handgrip endurance task) will be worse after the depleting task (i.e., a modified Stroop task tapping inhibitory control and cognitive flexibility) rather than after the control task (i.e., a color-word reading task). Second, we hypothesize that the depleting task will induce a decrease in motivation and an increase in subjective fatigue in comparison to the control task. As suggested by the literature on ego-depletion and cognitive fatigue, prior mental exertion impacts negatively the perception of effort and pain in a subsequent task, we also monitored these two perceptions during the handgrip endurance task (Boat & Taylor, 2017; Schmeichel & Vohs, 2009; Vohs et al., 2008).

2. Experiment 1

2.1. Methods

2.1.1. Participants

One hundred eighteen students (60 females, Mean age = 20.42 years, SD = 2.87) in psychology and sport sciences from the University of Poitiers took part in this experiment in exchange for course credit. The sample size was determined using G*Power 3.1.9.2 (Faul et al., 2007; Universität Kiel, Germany) with $d = 0.30$, alpha = .05, and power = .80. Because the correlation among repeated measures was unknown at this time, $r = .50$ was retained. We chose a d-value of 0.30 because we thought that the overall effect size (i.e., d = 0.62) calculated in the meta-analyses of Hagger et al., (2010) was overestimated. More specifically, the effect size for the Stroop task was d = 0.40 in the meta-analysis of Hagger et al., (2010), and g = 0.44 in the meta-analysis of Dang (2018). More recent meta-analyses found an effect size ranging between 0.29 and 0.50 (Brown et al., 2020; Giboin & Wolff, 2019; Holgado, Sanabria, Perales, & Vadillo, 2020; McMorris, Barwood, Hale, Dicks, & Corbett, 2018). We made this choice to increase the likelihood to observe the effect. According to G*Power, 90 participants were sufficient to detect the effect. Using random.org, participants were randomly assigned to the experimental and control groups.

The participants signed an informed consent form after they had received a verbal explanation about the procedure. The local ethics committee approved the procedures of the three experiments presented in this manuscript (n ° CER2018-09-04).

2.1.2. Procedure

This experiment included two sessions spaced by one to four weeks. At the beginning of the first session, participants completed a sociodemographic questionnaire. During each session, they also had to answer some questions about substances use (cigarettes, caffeine, drugs, and sleeping pills), physical activities practiced, possible traumatic events experienced within few hours before the session, and the amount of sleep the night preceding the session. If one undesirable event was detected (e.g., a sleepless night just before the session), the session was postponed when possible, otherwise the participant was excluded from the analysis. During the first session (Fig. 1A), participants performed a handgrip endurance task and then 48 trials of a cognitive task (i.e., the incongruent Stroop task or color-word reading task) as a training. During the second session (Fig. 1B), participants first performed the cognitive task (the same as the first session), lasting approximately 30 min, and then the handgrip endurance task. The cognitive task differed in the experimental and the control groups: the experimental group performed an effortful depleting task and the control group a less-effortful control task. Before and after each task, participants had to answer questions displayed on a screen using a visual analog scale (VAS) ranging from 0% to 100%. At the beginning of each session, participants indicated their motivation to perform the first task (i.e., the handgrip endurance task for the first session and the mental task for the second) and their level of fatigue. After the tasks, they reported their motivation to perform the task again, to accomplish another more pleasant task and to perform the handgrip endurance task (only for the second session). They also had to assess the difficulty of the task, their feelings of boredom during the task, the amount of mental resources they used during the task and their level of fatigue. Wewers and Lowe (1990) validated this type of VAS and Brown and Bray (2017) used similar VAS to measure mental fatigue and motivation to perform the task in a similar experiment. At the end of the 2nd session, trait self-control was measured with the Brief Self-Control Scale (Tangney et al., 2004). We decided to assess this personality variable because individuals with a low self-control trait tend to show a larger ego-depletion effect than individuals with a high self-control trait (DeWall, Baumeister, Stillman, & Gailliot, 2007). Answering the questions and performing the handgrip maximal voluntary contraction (MVC) task after the first task did not

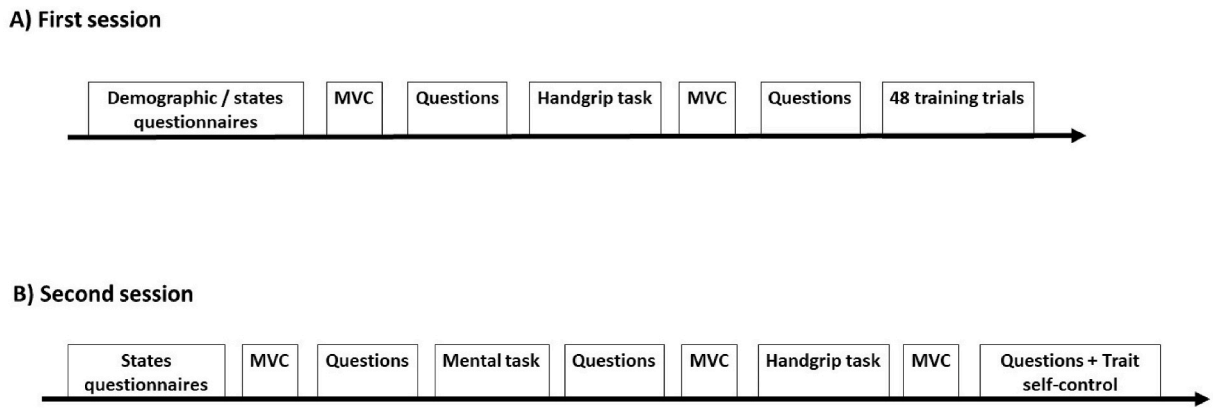

Fig. 1. Experimental design. A, time course of the first session; B, time course of the second session. MVC: Measure of maximal voluntary contraction in the handgrip task.

exceed 7 min (M = 4.23 min, SD = 0.65 min).

2.1.3. Experimental set-up of handgrip tasks

Isometric handgrip force of the dominant hand was measured using a hand dynamometer (TSD121C, BIOPAC). During the MVC and the endurance task described below, the participant seated on the same chair with an arm support imposing an elbow angle of ~90 deg. During each contraction, participants were asked to maintain their forearm in an anatomical neutral position. The force signal was recorded with the data acquisition unit MP160WSW and AcqKnowledge 4.2 software (BIOPAC Systems Inc., Goleta, USA). We digitized the force signal online at a sample frequency of 1000 Hz using a computer and stored it for off-line analysis.

2.1.4. Handgrip MVC task

In session 1, MVC was measured before and immediately at exhaustion of the endurance task. In session 2, including either the depleting or the control task, MVC was measured before and after the cognitive task, as well as immediately at exhaustion of the endurance task. In the MVC task, participants were asked to squeeze the dynamometer with their dominant hand as strong as possible for 3 s. To ensure obtaining participants' true maximal force, the measurement of MVC was repeated, with 30 s rest between contractions, until the force does not increase in comparison to the previous contraction peak force. The value of the first MVC in session 1 was used as the reference for determining the force feedback used in the subsequent endurance task in both sessions. The comparison of MVC peak force before the endurance task and immediately at exhaustion of the same task allowed us to assess the extent of muscle fatigue induced by the endurance task.

2.1.5. Handgrip endurance task

The endurance task was used to investigate the ego-depletion effect. To do so, we asked the participants to maintain a submaximal isometric handgrip contraction until exhaustion. This time-to-exhaustion test has been used in the ego-depletion and mental fatigue literature to investigate the effects of prior mental exertion on subsequent physical performance (Brown & Bray, 2019; Pageaux & Lepers, 2018). In our task, participants had to maintain 13% of their MVC peak force until exhaustion. In that way, the relative submaximal force was identical between sessions for the same participant.

A force feedback was provided to the participant during the whole endurance task. A circular gauge was displayed on a computer screen placed in front of him/her (see Fig. 2). The gauge was calibrated in such a way that the perimeter of the gauge (i.e., 360 deg.) corresponds to 100% MVC of the participant. A pointer moved along the calibrated circular scale according to the force produced by the participant. A green arc ranging from 12 to 14% of his/her MVC peak force, which is named

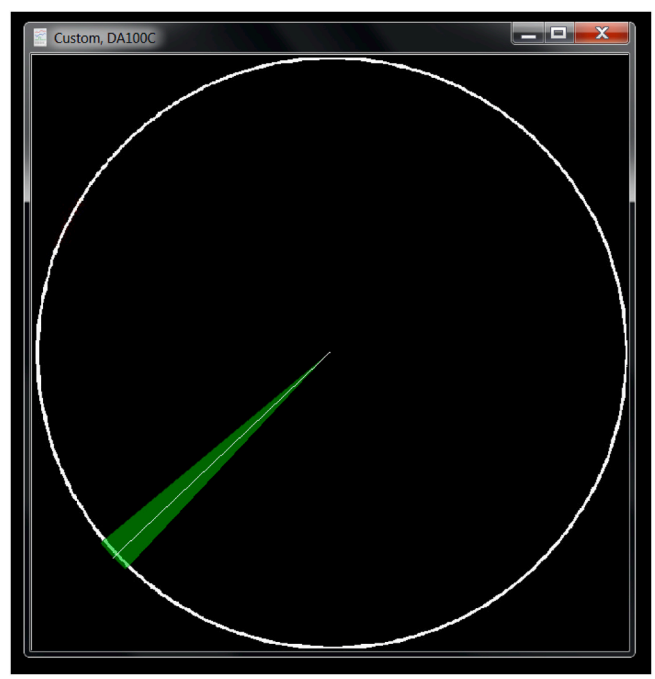

Fig. 2. Force gauge presented on the screen in front of the participant. The perimeter of the circular dial represents 100% of the participant's maximal voluntary contraction (MVC) and the green arc indicates the target zone (i.e. a range between 12 and 14% of MVC) in which the participant has to maintain the gauge indicator throughout the duration of the task. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

'green zone' hereafter, was constantly visible on the gauge. The green zone indicated the target zone in which the participant had to maintain the pointer throughout the duration of the endurance task (see Fig. 2). Exhaustion was defined as the participant not being able to maintain the pointer in the green zone, and staying out the green zone for more than 2 s despite the reminder of the researcher saying "Up". The time-to-exhaustion was determined offline by measuring the duration of the isometric contraction from the onset of the force signal to the exhaustion time as previously defined.

2.1.6. Perceptions of effort and muscle pain

During the endurance task, we measured perceptions of effort and muscle pain every 30 s. Perception of effort was measured with the CR100 scale (Borg & Kaijser, 2006), and participants were asked to rate

the "intensity of effort required to squeeze the dynamometer and breathe while staying in the green zone". Perception of muscle pain was measured with the Cook scale (O'Connor & Cook, 2001), and participants were asked to rate "the intensity of hurt they feel in their forearm muscles while performing the endurance task". Importantly, participants were asked not using the rating of effort as an expression of pain and vice-versa (Pageaux, 2016). Effort and muscle pain were analyzed using the "individual isotime" method (Nicolò et al., 2019). The "individual isotime" method has been shown to be efficient to analyze the effects of an experimental manipulation and performance ranking on physiological and psychological variables measured during a time to exhaustion test; i.e., the endurance task performed in the current study (Nicolò et al., 2019). According to this method, the shortest time-to-exhaustion recorded during the different experimental sessions carried out by a participant represents 100% of his/her individual isotime. Then, three other time points corresponding to 0%, 33%, and 66% of the 100% individual isotime were calculated for each participant and session. The time point corresponding to 0% of individual isotime was systematically the first measurement of perception of effort or muscle pain during the time-to-exhaustion test.

2.1.7. Cognitive tasks

The first task of the sequential task protocol was either a modified version of the incongruent Stroop task (i.e., the depleting task) or a color-word reading task (i.e., the control task). Participants, while comfortably seated in front of a screen, had to react as quickly and accurately as possible to a visual signal (i.e., a color word) by giving a vocal response in a microphone in both tasks. The two cognitive tasks, the presentation of stimuli and the recording of verbal responses were performed with E-Prime software 2.0 (Psychological Software Tools, Pittsburgh, PA).

In the incongruent Stroop task, a trial began by the occurrence of a fixation point (i.e., a cross) enclosed in a square or a circle for 50 ms in the middle of the screen. Then, the fixation cross alone remained in the middle of the screen for 400 ms. Just after the end of this preparatory signal, a word appeared at the center of the screen (i.e., the response signal) until the response of the participant. In the case of an omission, the response signal lasted 1250 ms and was followed by a fixation cross that lasted 300 ms. If a participant answered before the end of the 1250 ms, a fixation cross occurred in the middle of the screen and lasted to complete the 1250 ms plus 300 ms. Therefore, every trial lasted 2 s. The words (i.e., response signals) displayed on the screen were the name of colors (red, blue, yellow or green) written in another color (e.g., red written in blue). In this task, the color corresponding to the meaning of the word is always incongruent with the color of the ink used to write the word. When a square surrounded the fixation cross, participants had to read the word, and when it was a circle, they had to name the color of the ink. The answers were recorded using two microphones, one to measure response time and the other to record the voice of the participant while answering. The choice of vocal responses was made to create more interference and to increase the strength of the automatic prepotent response (i.e., reading the word) by comparison to manual responses on a keyboard (MacLeod, 1991). The incongruent Stroop task included a unique block of 888 trials and lasted 29.6 min. In 50% of trials, participants had to read the word and in the remaining 50%, they had to name the color of the ink. We chose a proportion of 50/50, first to limit the learning effect during the incongruent Stroop task (Dulaney & Rogers, 1994) and second to make this task more difficult by engaging cognitive flexibility in addition to inhibitory control. The order of presentation of the two categories of trials was completely random.

In the color-word reading task, the time course of a trial was identical to that of the incongruent Stroop task except in two points. First, the participants had to read the color word in 100% of trials whatever the nature of the preparatory signal (i.e., a square or a circle). Second, the response signal was always a color word written in the same color as the meaning of the word (e.g., red written in red).

2.1.8. Exclusion criteria

Participants having had a stressful event before a session were removed (e.g., an emotional or stressful separation just before arriving or a sister who was admitted to the hospital). Participants that did not respect the handgrip task instructions were also excluded, i.e., those who stayed below the 12% limit continuously for more than 2 s but did not drop out. Finally, we excluded outliers using 2.5 median absolute deviation (MAD; Leys et al., 2013). Twenty-eight participants were excluded because of these various reasons (Seven were exposed to a stressful event before a session, 10 did not respect the handgrip instructions, 11 were outliers). Statistical analyses were conducted with and without these excluded participants. Analyses with excluded participants are presented in supplementary materials.

2.1.9. Statistical analyses

The statistical analyses were made using Jamovi 1.2.27 and Jasp 0.14.0.0. The graphics were created using GraphPad Prism 9.0.0. The alpha level for statistical significance was set at $\alpha = .05$. Effect sizes were calculated only for significant and marginal results by partial eta square (η^2_p) when using an ANOVA and by Cohen's *d* when using a *t*-test. All the t-tests performed in this article were Student t-test. When a repeated-measures factor with more than two levels was included in the F-test, the Mauchly's sphericity test was used to evaluate whether the sphericity assumption has been violated. When the Mauchly's test was significant, degrees of freedom were systematically corrected using Huynh-Feldt adjustments (Huynh & Feldt, 1976). Results of the Mauchly tests are reported in the supplementary material section. Because the violation of the sphericity assumption increases the type-I error rate, we conducted the Mauchly test only when the F-test leads to significant results. All post-hoc comparisons were corrected according to the Bonferroni procedure. In this series of experiment, we reported all pertinent measures, manipulations and exclusions in direct relationship with our hypotheses. This section also applies to experiments 2 and 3.

2.2. Results

2.2.1. Ego-depletion effect

An ANOVA with Group (experimental group vs control group) as a between-subjects factor and Session (first vs second) as a within-subjects factor was conducted on the time-to-exhaustion in the handgrip endurance task. We expected the following Group by Session interaction: the time to exhaustion should decrease in the experimental group from session one to session two, whereas it should remain stable between the two sessions in the control group. The interaction between Group and Session did not reach significance (see Fig. 3A) showing that we failed to observe an ego depletion effect: $F(1, 88) = 0.08$, $p = .782$, $\eta^2_p = .001$, CI_{95} [0, 0.047]. The simple effects of Group and Session also did not reach significance: $F(1, 88) = 3.75$, $p = .056$, $\eta^2_p = .041$, CI_{95} [0, 0.145] and $F(1, 88) = 0.30$, $p = .583$, $\eta^2_p = .003$, CI_{95} [0, 0.065], respectively. On average, participants maintained the handgrip contraction during 6.66 min ($SD = 2.46$ min) whatever the cognitive task preceding the handgrip endurance task and session.

We also conducted a Bayesian repeated measure ANOVA with the same independent variables on time-to-exhaustion during the endurance handgrip task. We used a prior scale $r = 0.5$ for fixed effect and $r = 1.0$ for random effect. The results indicated a strong support in favor of the null hypothesis for the interaction between Group and Session: BF01 = 17.67, error percentage = 2.52. The main effect of Session was also in favor of the null hypothesis with a moderate support: BF01 = 5.45, error percentage = 1.60. Finally, the main effect of Group remained undetermined: BF01 = 0.72, error percentage = 1.59.

2.2.2. Maximal voluntary contraction

The MVC was measured at the beginning of each session (see Fig. 1) to ensure that participants started the session with the same force production capacity of the working muscles. We conducted an ANOVA with

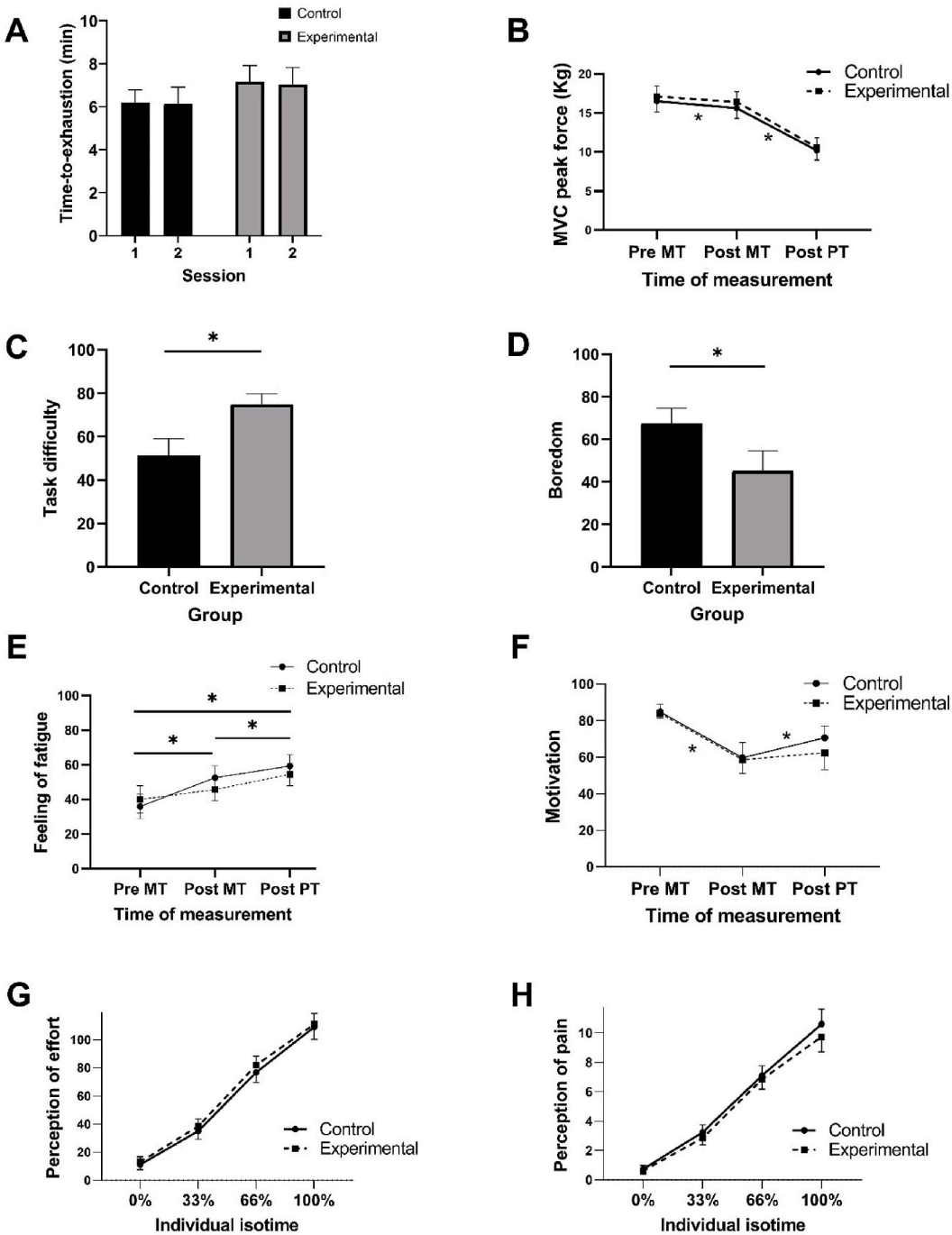

Fig. 3. Main results of experiment 1. (A) Time-to-exhaustion in the handgrip endurance task as a function of group (Control, Experimental) and session (1 or 2). (B) Mean maximal voluntary contraction (MVC) peak force as a function of group and time of measurement (Pre MT, Post MT, Post PT). (C) Task difficulty as a function of group. (D) Boredom as a function of group. (E) Feeling of fatigue as a function group and time of measurement. (F) Motivation to perform the mental task as a function of group and time of measurement. (G) Perception of effort during the handgrip endurance task as a function to individual isotime (0%, 33%, 66%, 100%) and group. (H) Perception of muscle pain during the handgrip endurance task as a function of individual isotime and group. Data are presented as mean plus or minus one 95% confidence interval, $n = 90$. Control = control group; Experimental = experimental group; Pre MT = before the mental task; Post MT = after the mental task; Post PT = after the physical task; (*) $p < .05$.

Group (depleted group vs. control group) as between-subjects factor and Session (first vs. second) as within-subjects factor on the first MVC of each session. The interaction of this ANOVA did not reach significance: F (1, 88) = 0.00, $p = .997$, $\eta^2_p = .000$, CI_{95} [0, 0]. The main effects of Group and Session also did not reach significance: F (1, 88) = 0.46, $p = .497$, $\eta^2_p = .005$, CI_{95} [0, 0.072] and F (1, 88) = 2.09, $p = .151$, $\eta^2_p = .023$, CI_{95} [0, 0.115], respectively. The mean of MCV peak force for participants was 16.7 Kg (SD = 4.16 Kg) for this first measurement.

In addition, we measured the MVC before and after the handgrip endurance task to ensure that the participants gave their best while performing the task. We conducted an ANOVA with Time (before mental task vs after mental task vs after the handgrip task) as within-subjects factor and Group (depleted group vs control group) as between-subjects factor on MVC. The interaction between Group and Time and the simple effect of Group did not reach significance: F (2, 176) = 0.47, $p = .629$, $\eta^2_p = .005$, CI_{95} [0, 0.036] and F (1, 88) = 0.49, $p = .486$, $\eta^2_p =$

.006, CI_{95} [0, 0.073], respectively. The main effect of Time remained significant after the Huynh-Feldt correction: F (1.76, 155.10) = 443.62, p < .001, η^2_p = .834, CI_{95} [0.788, 0.863]. Post-hoc comparison with Bonferroni correction indicated that participants had a lower MVC after the mental task (M = 16.0 Kg, SD = 4.33) than before (M = 16.8 Kg, SD = 4.51): t (176) = 3.42, p = .002, d_z = 0.46, CI_{95} [0.24, 0.68] (see Fig. 3B). They also had a lower MVC just after the endurance task (M = 10.4 Kg, SD = 4.07) by comparison to before and after the mental task: t (176) = 27.34, p < .001, d_z = 2.64, CI_{95} [2.20, 3.08] and t (176) = 23.91, p < .001, d_z = 2.32, CI_{95} [1.92, 2.72], respectively (see Fig. 3B).

2.2.3. Cognitive load of the depleting and control tasks

Participants reported the depleting task as more difficult (M = 74.8, SD = 16.5) than the control task (M = 51.2, SD = 25.5): t (88) = 5.25, p < .001, d_s = 1.11, CI_{95} [0.66, 1.55] (see Fig. 3C). They also reported that they used more mental resources to perform the depleting task (M = 83.5, SD = 15.4) than the control task (M = 71.7, SD = 23.9): t (88) = 2.81, p = .006, d_s = 0.59, CI_{95} [0.17, 1.01]. These two results suggest that the depleting task was experienced as more demanding than the control task.

2.2.4. Feelings of fatigue

We conducted an ANOVA with Time (before the mental task, after the mental task, and after the handgrip endurance task) as a within-subjects factor and Group (experimental group vs. control group) as a between-subjects factor on the feeling of fatigue. We observed a marginal interaction between Time and Group and a significant effect of Time after a Huynh-Feldt adjustment: F (1.81, 159.25) = 3.06, p = .055, η^2_p = .034, CI_{95} [0, 0.098] and F (1.81, 159.25) = 34.37, p < .001, η^2_p = .281, CI_{95} [0.166, 0.380], respectively (see Fig. 3E). The simple effect of Group did not reach significance: F (1, 88) = 0.38, p = .540, η^2_p = .004, CI_{95} [0, 0.068]. Post hoc comparisons with Bonferroni correction indicated that the feeling of fatigue was higher after the mental task (M = 49.0, SD = 22.7) than before (M = 38.0, SD = 24.9): t (176) = 4.90, p < .001, d_z = 0.48, CI_{95} [0.26, 0.70]. In the same way the feeling of fatigue was higher after the handgrip task (M = 56.7, SD = 21.9) by comparison to the two other assessment times: t (176) = 3.35, p = .003, d_z = 0.44, CI_{95} [0.22, 0.65] and t (176) = 8.24, p < .001, d_z = 0.76, CI95 [0.52, 0.99], respectively. Results suggested that the color-word reading task (i.e., the control task) was perceived as fatiguing as the incongruent Stroop task (i.e., the depleting task).

2.2.5. Boredom during the mental task

Participants in the control group reported more boredom (M = 67.4, SD = 23.4) than participants in the experimental group (M = 45.1, SD = 32.1): t (88) = 3.72, p < .001, d_s = 0.79, CI_{95} [0.35, 1.21] (see Fig. 3D). The correlation between boredom and fatigue reached significance when including data from both groups: r = .325, p = .002. The higher level of boredom after the control task may explain the higher feeling of fatigue experienced by the participants. Furthermore, when boredom was added as a covariate in the ANOVA testing the ego-depletion effect, the interaction remained not significant: F (1, 87) = 0.53, p = .468, η^2_p = .006, CI_{95} [0, 0.075].

2.2.6. Motivation to perform the mental task

The same ANOVA design used for fatigue was applied to motivation to perform the mental task. This analysis did not show a significant interaction: F (2, 176) = 1.27, p = .282, η^2_p = .014, CI_{95} [0, 0.059]. While adjusted with the Huynh-Feldt correction, the effect of Time reached significance: F (1.91, 167.66) = 51.18, p < .001, η^2_p = .037, CI_{95} [0.253, 0.460] (see Fig. 3F). We did not observe an effect of Group: F (1, 88) = 0.59, p = .445, η^2_p = .007, CI_{95} [0, 0.076]. Post-hoc tests with Bonferroni correction showed that participants reported to be less motivated to perform the mental task again right after its completion, whatever the mental task: t (176) = 9.84, p < .001, d_z = 0.95, CI_{95} [0.70, 1.20]. This motivation significantly increased after the handgrip endurance task (t (176) = −2.90, p = .013, d_z = 0.34, CI_{95} [0.13, 0.56]) but was significantly lower than the motivation measured at the beginning of the session: t (176) = 6.94, p < .001, d_z = 0.72, CI_{95} [0.48, 0.95]. In addition, when we included the drop in motivation (composite score: motivation after mental task minus motivation before) as a covariate in the ANOVA testing the ego depletion effect, the effect of Session remained not significant: F (1, 87) = 0.08, p = .782, η^2_p = .001, CI_{95} [0, 0.048].

2.2.7. Perceptions of effort and muscle pain during the handgrip endurance task

We conducted an ANOVA with Group (experimental group vs. control group) as a between-subjects factor and Individual isotime (0% on the task, 33%, 66% and 100%) as a within-subjects factor on the perceived effort during the handgrip endurance task. The interaction did not reach significance: F (3, 255) = 0.43, p = .731, η^2_p = .005, CI_{95} [0, 0.023]. The effect of Group was also not significant: F (1, 85) = 0.82, p = .368, η^2_p = .009, CI_{95} [0, 0.086]. The effect of Individual isotime was still significant after the Huynh-Feldt adjustment: F (1.90, 161.30) = 680.65, p < .001, η^2_p = .889, CI_{95} [0.856, 0.908]. Participants reported more effort throughout the handgrip endurance task (see Fig. 3G).

The same ANOVA was conducted on the perception of muscle pain during the handgrip endurance task. The interaction did not reach significance (F (3, 255) = 1.17, p = .320, η^2_p = .014, CI_{95} [0, 0.044]) nor did the effect of Group: F (1, 85) = 0.99, p = .321, η^2_p = .012, CI_{95} [0, 0.091]. We observed an effect of Individual isotime on the perception of muscle pain in spite of the Huynh-Feldt adjustment: F (1.66, 141.41) = 542.06, p < .001, η^2_p = .864, CI_{95} [0.824, 0.889]. The perception of muscle pain increased as a function of Individual isotime throughout the handgrip endurance task (see Fig. 3H).

2.2.8. Self-control trait

Finally, at the end of the second session, participants completed the Brief Self-Control Scale. There was no effect of Group (depleted vs. control) on the self-control score: t (88) = 0.37, p = .712, d_s = 0.08, CI_{95} [-0.34, 0.49]. The mean score for the control group was 40.6 (SD = 5.92), whereas it was 40.0 (SD = 8.15) for the depleted group on a scale ranging from 13 to 65. When adding the self-control trait as covariate to the repeated measures ANOVA on the time to exhaustion in the handgrip endurance task, the interaction remained non-significant. However, an interaction effect between self-control trait and the session was obtained (F (1, 87) = 4.96, p = .029, η^2_p = .054, CI_{95} [0, 0.166]) and the effect of Session reached significance: F (1, 87) = 5.25, p = .024, η^2_p = .057, CI_{95} [0.0001, 0.170]. The lower the participants' self-control trait, the lesser they performed on squeezing the handgrip, which was even worse after the cognitive tasks (incongruent Stroop or color-word reading tasks).

2.2.9. Performance in the cognitive tasks

In this section, we compare the performances of both groups during the cognitive task to be sure that the participants followed the instructions and that the incongruent Stroop task was more demanding than the color-word reading task. We conducted a repeated measure ANOVA on mean reaction time (RT) with time-on-task (TOT) as within-subjects factor and Group as between-subjects factor. We observed an interaction between TOT and Group: F (1.89, 165.93) = 6.65, p = .002, η^2_p = .07, IC_{95} [0.010, 0.149]. When decomposing this interaction in simple effects, we observed that the effect of TOT reached significance for the control group, but not for the experimental group: F (2.14, 89.76) = 57.38, p < .001, η^2_p = .577, CI_{95} [0.435, 0.664] and F (3, 138) = 1.258, p = .291, η^2_p = .027, CI_{95} [0.00, 0.081], respectively. Post-hoc comparisons with Bonferroni correction for the control group showed that mean RT was marginally shorter in the first part of the task (M = 414.11 ms, SD = 51.07 ms) than in the second part (M = 432.29 ms, SD = 55.14 ms), t (264) = 2.95, p = .064, d = 0.94, IC_{95} [0.58, 1.30], but significantly shorter than in the third part (M = 448.04 ms, SD = 61.64 ms), t (264) = 5.50, p < .001, d = 1.16, IC_{95} [0.77, 1.55] and fourth part

($M = 457.65$ ms, $SD = 61.81$ ms), $t(264) = 7.05$, $p < .001$, $d = 1.48$, IC_{95} [1.04, 1.91]. There was also a significant difference between the mean RT of the second and the fourth part of the control task: $t(264) = 4.11$, $p < .001$, $d = 1.31$, IC_{95} [0.74, 1.51]. As expected, the effect of Group was significant: $F(1, 88) = 308.53$, $p < .001$, $\eta^2_p = .778$, IC_{95} [0.694, 0.828]. Mean reaction in the incongruent Stroop task ($M = 679.80$ ms, $SD = 73.17$ ms) were significantly longer than in the color-word reading task ($M = 437.75$ ms, $SD = 55.71$ ms).

Finally, the same analysis was conducted on mean decision error rate. The interaction between TOT and Group did not reach significance: $F(3, 264) = 2.22$, $p = .086$, $\eta^2_p = .025$, IC_{95} [0, 0.062]. In the same way, the main effect of the TOT did not reach significance: $F(3, 264) = 1.42$, $p = .295$, $\eta^2_p = .014$, IC_{95} [0, 0.048]. However, a main effect of the Group reached significance: $F(1, 88) = 82.46$, $p < .001$, $\eta^2_p = .484$, IC_{95} [0.332, 0.592]. Participants of the control group made less decision errors ($M = 0.008$, $SD = 0.023$) than participants of the experimental group ($M = 0.086$, $SD = 0.052$).

These results suggest two comments. First, the incongruent Stroop task was more demanding than the color-word reading task: performances in speed (mean RT) and accuracy (rate of decision errors) were worse in the group of participants who carried out the incongruent Stroop task than in the group of participants who performed the color-word reading task. Second, the engagement of participants in both tasks was satisfying because the rate of decision errors was relatively low in both groups (8.6% for the incongruent Stroop task and 0.8% for the color-word reading task).

2.3. Discussion

In this first experiment, we did not replicate the ego depletion effect although we used a long and effortful depleting task tapping two core executive functions (i.e., inhibitory control and cognitive flexibility). However, during the experiment, participants reported that they experienced the control task as boring. Taken together, our results suggest that the color-word reading task was a bad control task as it induced more boredom than the depleting task and led to a greater feeling of fatigue after performing the task than before, whereas the depleting task did not. This proposal is in total agreement with a prediction made in a recent theoretical article on boredom and self-control (Wolff & Martarelli, 2020) and the results of a recent study (Bieleke et al., 2021). To maintain performance in spite of this boredom, participants in the control group had likely exerted effortful control to manage the boredom induced by the reading task.

Another way to explain the lack of ego-depletion effect is that the participants did not give their best to perform the handgrip endurance task, particularly in the control group. Results did not support this hypothesis because there was a large drop in performance in the handgrip MVC task after the handgrip endurance task in both groups: MVC peak force decreased by 36% in average ($SD = 15.7$). We also observed a small decrease in MVC peak force after the mental task ($M = 3.8\%$, $SD = 12.9\%$) in both groups by comparison to the first measurement made at the beginning of the session. As prior mental exertion does not decrease force production capacity (Brown et al., 2020; Pageaux & Lepers, 2018), this small decrease in MVC is most likely due to the absence of a warm-up prior to its completion (Bishop, 2003).

The drop in motivation at the end of the mental task was similar in the control and the depleting tasks, which means that the control task was perceived as effortful as the depleting task. This result could explain why we did not observe any differences in the effort that participants reported engaging in the task or the pain they felt during the handgrip endurance task. Indeed, according to the process model of self-control (Inzlicht & Schmeichel, 2012) and the working model (Wolff & Martarelli, 2020), it can be expected that a drop in motivation is observed after an effortful task inducing a lesser engagement in effort in a subsequent effortful task, particularly at the end of this task.

Results of this first experiment suggest that, the control task must be changed in order to induce a significantly lower level of effortful control demand than the depleting task. This experiment also suggests that it is crucial to control for boredom during the control task because boredom is perceived as fatiguing, may attract self-control costs and, finally, negatively affect the subsequent dependent task as well as the depleting task.

3. Experiment 2

3.1. Introduction

Results of the first experiment strongly suggest that the color-word reading task was not a good control task because it was too boring and required too much effort. Within the framework of the sequential task protocol, the hallmark of a good control task is to be the least effortful as possible. In this second experiment, a video task (watching a documentary), which has been used in a similar experiment (Pageaux et al., 2013), was compared to the reading task. The aim of this second experiment was to show that watching an emotionally neutral video is not boring and definitely less boring than performing the reading task used in experiment 1. The principal outcome of this study was the feeling of boredom during the task. Secondary outcomes included the affective state during the task (valence and arousal), the feeling of fatigue and motivation to perform the task.

3.2. Methods

3.2.1. Participants

Twenty students (six females, Mean age = 20.26 years, SD = 1.59) in sport sciences and psychology from the University of Poitiers took part in the experiment in exchange for course credit. The participants signed an informed consent form after they had received a verbal explanation about the procedure.

3.2.2. Procedure

This experiment included 2 sessions during which participants performed a mental task that lasted 30 min: the same color-word reading task as in the first experiment or watching a video (i.e., the 30 first minutes of the documentary "Earth" by Alastair Fothergill and Mark Linfield, 2007). Before and after the mental task, participants indicated their motivation to perform the task and their fatigue on a visual analog scale ranging from 0% to 100%. They also had to report their emotional state (from sad to happy) and their level of arousal (from calm to excited) using the 9-point scale, "Self-Assessment Manikin" (SAM; Bradley & Lang, 1994; Handayani et al., 2015). At the end of the video session, they finally had to answer "yes" or "no" to 10 easy questions about the content of the video documentary (e.g. "Have you seen a dog in this video?").

3.3. Results

3.3.1. Boredom

First, an ANOVA with Task (reading words in color vs. watching an emotionally neutral video documentary) as a within-subjects factor was carried out on the feeling of boredom during the task. Participants felt more bored during the color-word reading task ($M = 71.7$, $SD = 26$) than during the video task ($M = 15.9$, $SD = 16.3$): $t(19) = 9.04$, $p < .001$, $d_z = 2.02$, CI_{95} [1.24, 2.79] (see Fig. 4A).

3.3.2. Affective state, arousal, feelings of fatigue and motivation

Then, an ANOVA with Task (color-word reading task vs video task) and Time (before the task vs after the task) as repeated-measure factors was conducted on affective valence, level of arousal, the feeling of fatigue and motivation to perform the task. The interaction between Task and Time reached significance only for affective valence and motivation to perform the task: $F(1, 19) = 15.09$, $p < .001$, $\eta^2_p = .443$, CI_{95} [0.101,

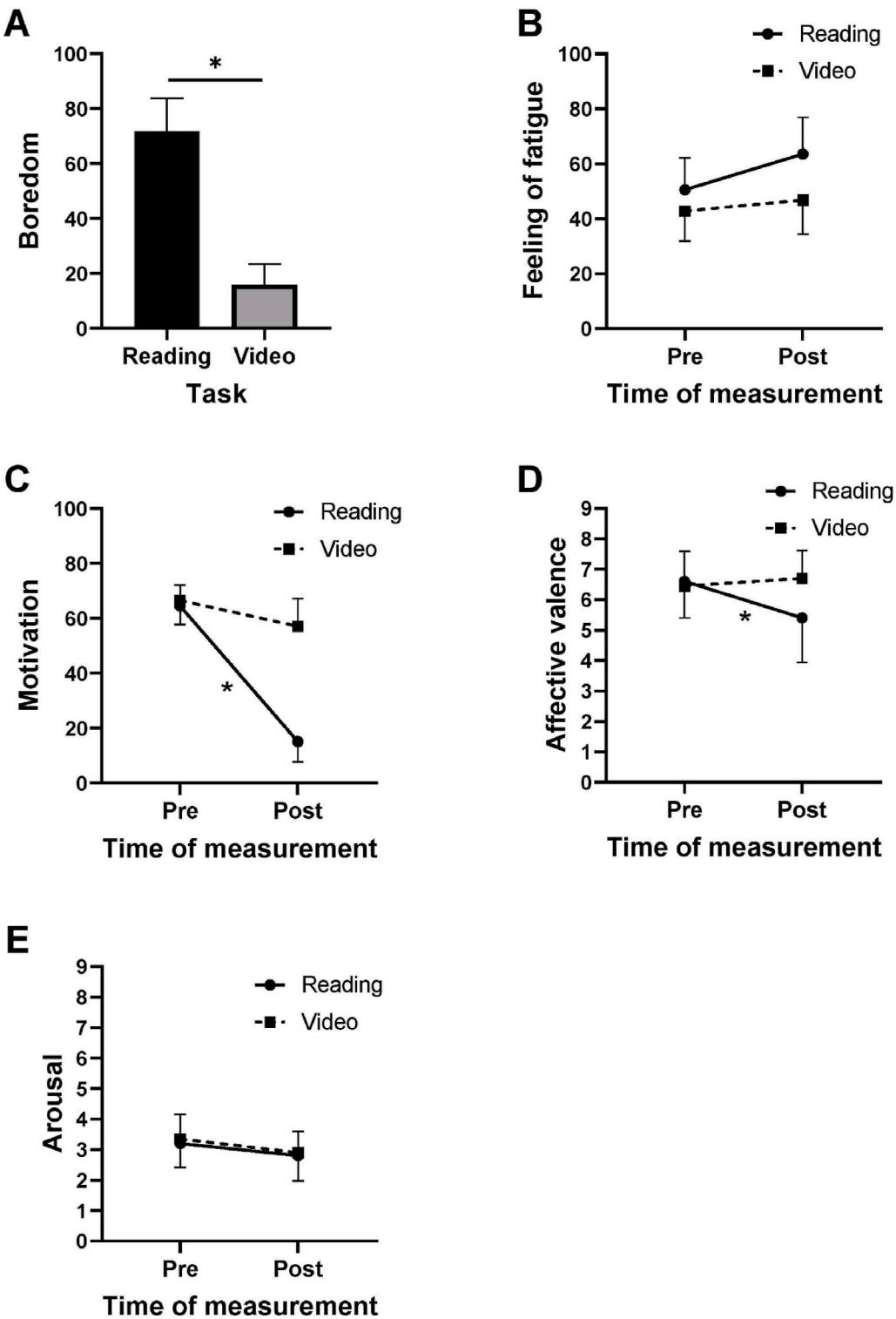

Fig. 4. Main results of experiment 2. (A) Boredom felt during the mental task as a function of the task (reading, video). (B) Feeling of fatigue as a function of mental task and time of measurement (Pre, Post). (C) Motivation to perform the mental task as a function of task and time of measurement. (D) Emotional valence of emotions felt during the mental task as a function of task and time of measurement: the lower the valence is, the more negative the emotions are. (E) Subjective level of arousal as a function of task and time of measurement. Data are presented as mean plus or minus one 95% confidence interval, $n = 20$. Reading = color-word reading task; Video = watching a documentary; Pre = before the mental task; Post = after the mental task; (*) $p < .05$.

0.644] and F (1, 19) = 50.2, $p < .001$, $\eta^2_p = .725$, CI_{95} [0.441, 0.827], respectively. Post hoc comparisons with Bonferroni correction indicated that the video task did not induce any change in affective state (t (38) = −0.95, $p = .700$, $d_z = 0.28$, CI_{95} [-0.18, 0.72]), whereas the color-word reading task induced saddest affects: t (38) = 4.55, $p < .001$, $d_z = 0.86$, CI_{95} [0.33, 1.37] (see Fig. 4D). We observed the same pattern of results with the motivation to perform the task again. The color-word reading task decreased the motivation to repeat the task (t (37.5) = 13.06, $p < .001$, $d_z = 2.82$, CI_{95} [1.82, 3.80]), whereas the video task did not induce a change in motivation: t (37.5) = 2.47, $p = .072$, $d_z = 0.57$, CI_{95} [0.09, 1.04] (see Fig. 4C). As above mentioned, the interaction between Task and Time of measurement did not reach significance for the feeling of fatigue: F (1, 19) = 2.43, $p = .136$, $\eta^2_p = .113$, CI_{95} [0, 0.376] (see Fig. 4B). However there were significant simple effects of Time and Task: F (1, 19) = 7.56, $p = .013$, $\eta^2_p = .285$, CI_{95} [0.014, 0.530] and F (1, 19) = 7.90, $p = .011$, $\eta^2_p = .294$, CI_{95} [0.017, 0.537], respectively. Participants felt more fatigue after the mental task ($M = 55.1$, $SD = 24.4$) than before ($M = 46.6$, $SD = 21.9$). In addition, they felt more fatigue during the

color-word reading session ($M = 57.0$, $SD = 24.7$) compared to the video session ($M = 44.8$,$SD = 23.6$) Finally, the level of arousal did not vary significantly as a function of the Task and Time of measurement (see Fig. 4E).

3.3.3. Performance in the video task

Finally, to check if participants were paying attention to the video when watching it, a one-sample *t*-test was conducted to compare the percentage of their correct responses to the level of chance (i.e., 50%). The results indicated that the participants answered significantly higher than the level of chance ($M = 83\%$, $SD = 9.23\%$): $t\,(19) = 16$, $p < .001$, $d_z = 3.57$, CI_{95} [2.36, 4.78].

3.4. Discussion

As expected, participants perceived the video task as less boring than the color-word reading task. In addition, the boredom score in the video task was very low on average (16/100). Furthermore, the video task appeared to be emotionally neutral, and did not induce any change in arousal or feeling of fatigue. In contrast, the color-word reading task induced boredom as in the first experiment, the feeling of fatigue and additionally saddest affective states. For all of these reasons, watching an emotional neutral movie would appear to be a better control task to replicate the ego-depletion effect than the color-word reading task.

4. Experiment 3

4.1. Introduction

The purpose of the third experiment was to replicate the ego depletion effect with a more appropriate control task. Three methodological choices were made to improve the experimental set-up. First, we kept the long and effortful incongruent Stroop task tapping executive functions as the depleting task. Second, we used a long effortless and emotionally neutral control task (i.e., the video task used in experiment 2) rather than the reading task used in experiment 1. Third, we used a within-subjects design in order to obtain the same power with higher homogeneity but less participants (Francis et al., 2018). The principal and secondary outcomes were the same as in the first experiment.

4.2. Methods

4.2.1. Participants

Fifty-five young adult students (37 females, Mean age = 19.84 years, $SD = 2.23$) in sport sciences from the University of Poitiers or recruited from social media (Twitter and Facebook) took part in the experiment. They participated in exchange for course credit or 20 euros, respectively.

The sample size was determined using G*Power 3.1.9.2 (Faul et al., 2007) with $d = .30$, alpha = .05, and power = .90. The data from the first study allowed us to determine the correlation among the measure, $r = .80$. According to G*Power, 49 participants were sufficient to detect the effect. We used the same exclusion criteria as in the first experiment. Four participants were excluded from the analysis (100% outliers). The participants signed an informed consent form after they had received a verbal explanation about the procedure.

4.2.2. Procedure

The experiment included 4 sessions spaced by a minimum of 48 h. The first session was the familiarization session. The time course of this session was similar to that of session 1 in experiment 1 as described in Fig. 1A. The second session aimed to assess a baseline performance of the handgrip endurance task, without any mental task beforehand (i.e., baseline session). The 3rd and 4th sessions were the experimental sessions with first the depleting or control mental task and followed by the handgrip endurance task. One more time, the time course of these two sessions was similar to that of session 2 in experiment 1 as described in Fig. 1B. The mental task was the incongruent Stroop task (the same depleting task as in the first study) or the video task (the same control task as in the second study).

In this experiment, we made a deeper analysis of the Stroop task performance to check if participants followed the instructions and kept engaged throughout the task. We distinguished five categories of trials: (1) noisy trials, (2) anticipations, (3) omissions, (4) decision errors and (5) correct trials. During a noisy trial, a non-pertinent noise occurring before the response of the participant wrongly shortened the RT or prevented him/her to give a response. During anticipation trials, participants had an RT < 150 ms. An omission could be observed in three cases: (1) when the participant did not respond during the trial, (2) when the participant had an RT > 1250 ms and (3) when the response of the participant was not detected because he/she was too far from the microphone or spoke too weakly. An increase in omission rate reflects a higher difficulty to follow task instructions and self-control. In the case of a decision error, the participant gave a wrong response (e.g., RED instead of GREEN). An increase in decision error rate can reflect a failure in the decision-making process that involves executive processes. Finally, during a correct trial the participant gave a correct response with an RT ranging between 150 and 1250 ms. Omission rate, decision rate and RT were analyzed as a function of time-on-task because cognitive fatigue effects classically increase with time-on-task (e.g., Lorist, 2008). In this perspective, the data were divided into 4 intervals: from the first to the 222nd trial, from the 223rd to the 444th trial, from the 445th to the 666th trial and from the 667th to the 888th trials.

The order of the 3rd and 4th sessions was counterbalanced across participants. Before and after the tasks, participants had to complete the same questionnaires as those reported in the first study. At the end of the 4th session, the self-control trait was measured as in the first study.

4.3. Results

4.3.1. Ego-depletion

As expected, the use of an appropriate control task led to the observation of the ego-depletion effect. To highlight this effect, we conducted two planned contrasts, first by comparing the time-to-exhaustion assessed in the depleting session to the average of the baseline and control sessions. We made the hypothesis that the time-to-exhaustion should be shorter in the depleting session than in the two other sessions. This first planned comparison confirmed that participants performed worse on the handgrip endurance task after the incongruent Stroop task ($M = 5.27$ min, $SD = 2.11$) than after the video task and in the baseline session ($M = 5.67$ min, $SD = 2.14$): $t\,(100) = -2.52$, $p = .013$, $d_z = 0.41$, CI_{95} [0.12, 0.69] (see Fig. 5A). In the second planned contrast, we compared the control session to the baseline session, with the hypothesis of a null effect. As expected, the second planned comparison showed that the difference between the baseline session ($M = 5.66$ min, $SD = 2.16$ min) and the control sessions ($M = 5.69$ min, $SD = 2.37$) was far from significance: $t\,(100) = 0.18$, $p = .858$, $d_z = 0.02$, CI_{95} [-0.25, 0.30].

We also conducted a Bayesian paired sample *t*-test to test the ego-depletion effect on the time-to-exhaustion during the handgrip endurance task. For the first comparison (depleting vs. control session), we expected an effect around $d = 0.30$ (see the power analysis). Then, we chose an informed Cauchy prior with a location of 0.3 and a scale r = 0.707. The results were in favor of the alternative hypothesis (i.e., ego-depletion effect): $BF_{10} = 8.21$, error percentage < 0.001. For the second comparison, we expected no difference between the control session and the baseline session on the time-to-exhaustion. We chose an informed Cauchy prior with a location equal to zero and a scale $r = 0.707$. The results were in favor of the null hypothesis: $BF_{01} = 6.48$, error percentage = 0.05.

However, to test the robustness of our analyses, the same analyses were made using the default Cauchy prior (location at 0.0) with a width of $r = 0.707$. The first comparison remained in favor of the alternative

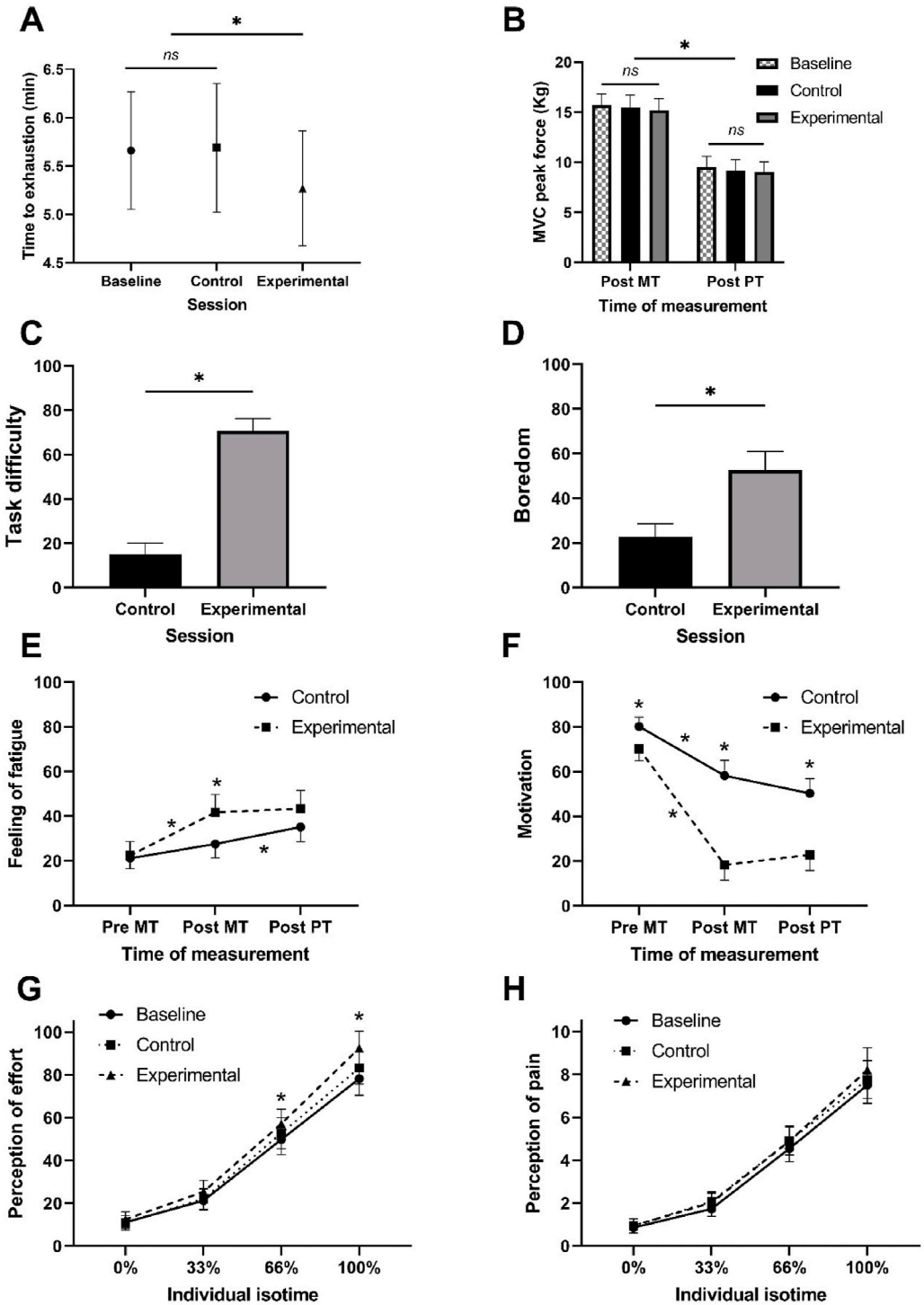

Fig. 5. Main results of experiment 3. (A) Time-to-exhaustion in the handgrip endurance task as a function of session (Baseline, Control, Experimental). (B) Mean maximal voluntary contraction (MVC) peak force as a function of session and time of measurement (Post MT, Post PT). (C) Task difficulty as a function of session. (D) Boredom as a function of session. (E) Feeling of fatigue as a function session and time of measurement (pre MT, post MT, post PT). (F) Motivation to perform the mental task as a function of session and time of measurement. (G) Perception of effort during the handgrip endurance task as a function to individual isotime (0%, 33%, 66%, 100%) and session. (H) Perception of muscle pain during the handgrip endurance task as a function of individual isotime and session. Data are presented as mean plus or minus one 95% confidence interval, $n = 51$. Baseline = baseline session; Control = control session, Experimental = experimental session; Pre MT = before the mental task; Post MT = after the mental task; Post PT = after the physical task; (*) $p < .05$.

hypothesis under this prior, $BF_{10} = 6.50$, error percentage <0.001 or under an ultrawide prior $BF_{10} = 3.99$. The second comparison remained in favor of the null hypothesis, $BF_{01} = 6.48$, error percentage <0.001 or under an ultrawide prior, $BF_{01} = 12.62$.

4.3.2. Maximal voluntary contraction

As in experiment 1, the MVC was measured at the beginning of each session (see Fig. 1) to ensure that participants started the session with the same force production capacity of the working muscles. We conducted an ANOVA with Session (baseline vs. control task vs. depleting task) as repeated-measures factor on the first MVC of each session. The F-test for the effect of Session reached significance: $F(2, 100) = 5.99$, $p = .003$, $\eta^2_p = .107$, CI_{95} [0.013, 0.218]. Post hoc comparison with Bonferroni correction indicated that participants had lower MVC peak force at the beginning of the baseline session ($M = 15.7$ Kg, $SD = 3.99$) by comparison to the control session ($M = 16.4$ Kg, $SD = 4.45$): $t(100) = 3.46$, $p = .002$, $d_z = 0.44$, CI_{95} [0.15, 0.73]. The MVC peak force at the beginning of the depleting task session ($M = 16.0$, $SD = 4.22$) did not differ from control session and baseline session: $t(100) = 1.86$, $p = .197$, $d_z = 0.27$, CI_{95} [-0.01, 0.55] and $t(100) = 1.60$, $p = .341$, $d_z = 0.24$, CI_{95} [-0.04, 0.52], respectively. This improvement of performance from the baseline session to the second session could be interpreted as a practice

effect.

In addition, we compared the MVC of participants before and after the handgrip endurance task to ensure that they gave their best while performing the task. We conducted an ANOVA with Time (before vs. after the handgrip task) and Session (baseline, depleting and control) as within-subjects factors on MVC. The F-test was calculated for this interaction did not reach significance: F (2, 100) = 0.15, p = .859, η^2_p = .003, CI_{95} [0, 0.035]. The F-test for this simple effect reached significance: F (2, 100) = 3.29, p = .041, η^2_p = .062, CI_{95} [0, 0.158]. A post-hoc test with the Bonferroni correction showed that the average of two MVCs recorded during the baseline session was significantly lower than that recorded during the depleting session: t (100) = 2.56, p = .036, d_z = 0.38, CI_{95} [0.09, 0.66]. The main effect of Time also reached significance: F (1, 50) = 377.13, p < .001, η^2_p = .883, CI_{95} [0.815, 0.915]. Post-hoc comparison with Bonferroni correction indicated that participants had a lower MVC after the handgrip endurance task than before whatever the session: t (93.4) = 16.09, p < .001, d_z = 2.70, CI_{95} [2.10, 3.29] for the baseline session; t (93.4) = 16.55, p < .001, d_z = 1.88, CI95 [1.41, 2.33] for the control session; and t (93.4) = 16.11, p < .001, d_z = 2.56, CI_{95} [1.99, 3.13] for the depleting session (see Fig. 5B).

4.3.3. Task difficulty

Participants perceived the incongruent Stroop task (M = 70.7, SD = 19.8) more difficult than the video task (M = 14.9, SD = 18.5): t (50) = −15.40, p < .001, d_z = 2.16, CI_{95} [1.65, 2.66] (see Fig. 5C).

4.3.4. Feelings of fatigue

An ANOVA with Session (control session vs. depleting session) and Time (before the mental task vs. after the mental task vs. after the handgrip endurance task) as within-subjects factors was then carried out on the feeling of fatigue. The interaction between Session and Time reached significance: F (2, 100) = 7.96, p < .001, η^2_p = .137, CI_{95} [0.029, 0.254] (see Fig. 5E). Post hoc comparisons with Bonferroni correction indicated no difference in the feeling of fatigue before performing any task (depleting task, M = 22.4, SD = 22.1; control task, M = 21.1, SD = 16.6): t (114) = −0.44, p = 1, d_z = 0.10, CI_{95} [-0.18, 0.37]. During the control session, the video task did not increase the feeling of fatigue (M = 27.5, SD = 22.2), whereas the handgrip endurance task (M = 35.1, SD = 23.2) did it marginally: t (184) = −2.32, p = .189, d_z = 0.47, CI_{95} [0.17, 0.75] and t (184) = −2.77, p = .067, d_z = 0.43, CI_{95} [0.15, 0.72], respectively. During the depleting session, the incongruent Stroop task (M = 41.7, SD = 28.5) increased the feeling of fatigue: t (184) = −7.66, p < .001, d_z = 0.81, CI_{95} [0.49, 1.12]. In contrast, the handgrip endurance task did not increase the feeling of fatigue (M = 43.4, SD = 28.9): t (184) = −0.17, p = 1, d_z = 0.10, CI_{95} [-0.17, 0.38]. Furthermore, and more importantly, participants felt more fatigued after the incongruent Stroop task than after the video task: t (114) = −4.81, p < .001, d_z = 0.59, CI_{95} [0.29, 0.89].

4.3.5. Motivation

The same repeated-measures ANOVA was conducted on motivation to perform the mental task. The interaction between Session and Time with Huynh-Feldt correction reached significance: F (1.84, 92.06) = 24.4, p < .001, η^2_p = .328, CI_{95} [0.171, 0.450] (see Fig. 5F). According to post hoc comparison with Bonferroni correction, the difference between both sessions before the mental task reached significance (depleting task, M = 70.2, SD = 18.6; control task, M = 80.2, SD = 14.9): t (140) = 2.97, p = .040, d_z = 0.61, CI_{95} [0.31, 0.91]. Participants were more motivated to perform the video task than the incongruent Stroop task. In addition, during the control session, participants were less motivated to repeat the video task (M = 58.2, SD = 24.7) than to perform it for the first time (M = 80.2, SD = 14.9): t (190) = 6.37, p < .001, d_z = 0.88, CI_{95} [0.56, 1.20]. No differences were found when comparing the motivation score after the video task and after the handgrip endurance task (M = 50.3, SD = 23.1): t (190) = 2.28, p = .207, d_z = 0.36, CI_{95} [0.07, 0.64]. During the depleting session, participants were considerably less motivated to repeat the incongruent Stroop task (M = 18.3, SD = 24.4) than to perform it for the first time (M = 70.2, SD = 18.6): t (190) = 14.98, p < .001, d_z = 1.97, CI_{95} [1.49, 2.44]. There was no difference when comparing motivation after the handgrip endurance task (M = 22.8, SD = 24.8) and after the incongruent Stroop task (M = 18.3, SD = 24.4): t (190) = −1.30, p = 1, d_z = 0.29, CI_{95} [0.01, 0.57] (i.e., motivation did not decrease more after a second effortful task).

Even though the motivation was lower after both mental tasks than before, the drop was larger after the incongruent Stroop task: t (140) = 11.81, p < .001, d_z = 1.55, CI_{95} [1.13, 1.95]. This result indicates that the incongruent Stroop task induced a greater drop in motivation than the video task. Moreover, when we added the drop in motivation (composite score: motivation after mental task minus motivation before) as a covariate, the effect of the session on ego-depletion disappeared (F (2, 98) = 0.67, p = .513, η^2_p = .013, CI_{95} [0, 0.074]), suggesting that the change in motivation may explain the ego-depletion effect.

4.3.6. Boredom

As in study 1, a t-test was carried out to compare perceived boredom during the depleting and control tasks. Participants were significantly more bored during the incongruent Stroop task (M = 52.6, SD = 29.8) than during the video task (M = 22.9, SD = 20.5): t (50) = −7.38, p < .001, d_z = 1.03, CI_{95} [0.69, 1.37] (see Fig. 5D). The feeling of fatigue after each mental task was correlated with the boredom felt during the task (r = .29 and p = .038 for the video task; r = .38 and p = .006 for the incongruent Stroop task). The drop in motivation (composite score: motivation after the mental task minus motivation before) in each task was also correlated with the boredom felt during these tasks (r = −.43 and p = .002 for the video task; r = -.31 and p = .028 for the incongruent Stroop task). Furthermore, when boredom was added as a covariate to the ego-depletion effect, the effect of Session disappeared: F (2, 96) = 0.16, p = .857, η^2_p = .003, CI_{95} [0, 0.037]. Thus, the ego-depletion effect can be explained by the boredom induced by the first task.

4.3.7. Perception of effort in the handgrip endurance task

An ANOVA with Session (baseline, control and depleting sessions) and Individual isotime (0%, 33%, 66% and 100%) as within-subjects factors was carried out on the perception of effort during the handgrip endurance task. The interaction between Session and Individual isotime reached significance in spite of the Huynh-Feldt correction: F (3.84, 176.61) = 3.68, p = .007, η^2_p = .074, CI_{95} [0.006, 0.140] (see Fig. 5G). According to post hoc comparison with Bonferroni correction, there was no difference between the three sessions at the start of the handgrip endurance task (0%) and at 33% of the individual isotime. At 66% of the individual isotime, participants perceived the handgrip endurance task as more effortful in the depleting session than in the baseline session: t (255) = 3.40, p < .001, d_z = 0.46, CI_{95} [0.17, 0.75]. Finally, at 100% of the individual isotime, participants perceived more effort to perform the handgrip endurance task after the incongruent Stroop task than after the video task (t (255) = 3.74, p < .001, d_z = 0.42, CI_{95} [0.12, 0.71]) or than in the baseline session: t (255) = 5.55, p < .001, d_z = 0.56, CI_{95} [0.25, 0.86]. In addition, there was a significant effect of Individual isotime on the perception of effort with the Huynh-Feldt correction: F (1.78, 82.00) = 331.26, p < .001, η^2_p = .878, CI_{95} [0.826, 0.905]. The perception of effort increased throughout the handgrip endurance task whatever the session (see Fig. 5G).

4.3.8. Perception of muscle pain in the handgrip endurance task

The same repeated-measures ANOVA as for perception of effort was conducted on the perception of muscle pain. The interaction between Session and Individual isotime with the Huynh-Feldt correction did not reach significance: F (3.80, 174.78) = 1.86, p = .123, η^2_p = .039, CI_{95} [0, 0.090] (see Fig. 5H). In contrast, the effect of Individual isotime with the Huynh-Feldt correction reached significance: F (1.41, 64.95) = 229.04, p < .001, η^2_p = .833, CI_{95} [0.752, 0.874]. The perception of muscle pain increased throughout the handgrip endurance task whatever the session

(see Fig. 5H).

4.3.9. Self-control trait

At the end of the 4th session, participants answered the Brief Self-Control Scale. When used as a covariate on the time to exhaustion in the handgrip endurance task after the mental tasks, the main effect of the self-control trait was marginal: $F(1, 49) = 3.67$, $p = .061$, $\eta^2_p = .070$, CI_{95} [0, 0.230]. Participants with higher self-control had a tendency to perform better at squeezing the handgrip. However, the interaction between session and self-control trait did not reach significance: $F(2, 98) = 1.11$, $p = .333$, $\eta^2_p = .022$, CI_{95} [0, 0.093]. Furthermore, the main effect of Session (no mental task vs. control task vs. depleting task) on time-to-exhaustion disappeared when self-control trait was controlled, $F(2, 98) = 1.03$, $p = .362$, $\eta^2_p = .021$, CI_{95} [0, 0.090], indicating that self-control trait was a moderator of the handgrip performance. Consequently, the self-control trait needs to be controlled when studying the ego-depletion effect, especially with a between-subjects design when groups may be different. The average self-control score for the whole group was 42.9 ($SD = 7.62$) on a scale ranging from 13 to 65.

4.3.10. Performance in the incongruent stroop task

The mean rate of noisy trials was in average relatively low: $M = 0.0326$, $SD = 0.043$. The mean rate of anticipations was even lower: $M = 0.0004$, $SD = 0.001$. Concerning the omissions, we conducted a repeated-measure ANOVA with time-on-task (TOT) as within-subjects factor. We observed a significant effect of TOT: $F(2.28, 123.06) = 6.09$, $p = .002$, $\eta^2_p = .101$, IC_{95} [0.016, 0.199]. Post-hoc comparisons with Bonferroni correction showed that the omission rate was significantly lower in the first part of the task ($M = 0.056$, $SD = 0.053$) by comparison to the second part ($M = 0.076$, $SD = 0.070$): $t(162) = 2.88$, $p = .035$, $d = 0.39$, IC_{95} [0.11, 0.66], third part ($M = 0.094$, $SD = 0.109$), $t(162) = 3.24$, $p = .0.30$, $d = 0.40$, IC_{95} [0.12, 0.69], and fourth part ($M = 0.102$, $SD = 0.103$), $t(162) = 3.92$, $p = .010$, $d = 0.45$, IC_{95} [0.17, 0.72]. No other comparisons were significant.

Then, we conducted a repeated-measure ANOVA on mean reaction time with the same design and observed a significant effect of TOT: $F(2.40, 129.50) = 12.54$, $p < .001$, $\eta^2_p = .188$, IC_{95} [0.073, 0.294]. Post-hoc comparisons with Bonferroni correction showed that mean reaction time was significantly quicker in the first part of the task ($M = 658.20$ ms, $SD = 81.18$ ms) by comparison to the second part ($M = 676.29$ ms, $SD = 82.07$ ms), $t(162) = 3.29$, $p = .011$, $d = 0.44$, IC_{95} [0.16, 0.72], third part ($M = 688.11$ ms, $SD = 89.37$ ms), $t(162) = 4.61$, $p < .001$, $d = 0.62$, IC_{95} [0.33, 0.91], and fourth part ($M = 688.62$ ms, $SD = 89.06$ ms), $t(162) = 4.14$, $p < .001$, $d = 0.56$, IC_{95} [0.27, 0.84]. There was also a significant difference between the second and the third part of the task: $t(162) = 2.92$, $p = .030$, $d = 0.39$, IC_{95} [0.12, 0.67]. No other comparisons were significant.

Finally, the same analysis was conducted on mean decision error rate. The effect of TOT did not reach significance: $F(3, 162) = 0.96$, $p = .413$, $\eta^2_p = .017$, IC_{95} [0, 0.059]. In average, the decision error rate remained around 6%: $M = 0.059$, $SD = 0.050$.

These results indicate that participants followed the instructions of the incongruent Stroop task with a low rate of decision errors (6%) and anticipations (0.04%). Furthermore, it is interesting to note that two indexes of performance (i.e., rate of omissions and mean RT) deteriorated as time on task increased indicating that the incongruent Stroop task induced a cognitive fatigue.

4.3.11. Performance in the video task

Finally, we conducted a one-sample *t*-test to compare the percentage of correct responses related to the video content to the level of chance (50%). The results showed that the participants paid attention to the video and answered with a significantly higher percentage of correct responses than to the level of chance ($M = 81.4\%$, $SD = 11.5\%$): $t(50) = 19.5$, $p < .001$, $d_z = 2.73$, CI_{95} [2.13, 3.33].

4.4. Discussion

In this experiment, we replicated the ego-depletion effect with the incongruent Stroop task as the depleting task, and an emotionally neutral and effortless video task as the control task. The incongruent Stroop task induced boredom and the feeling of fatigue, whereas the video task did not. Moreover, the motivation to watch the movie again right after watching it the first time was lower than before. This result suggests that it seems not to be interesting to perform this effortless and not boring task a second time. Nevertheless, the motivation to perform the mental task decreased much more after the incongruent Stroop task than after the video task. When used as a covariate, the drop in motivation may explain, at least in part, the ego-depletion effect. Furthermore, the boredom felt during the mental task was correlated with the feeling of fatigue and with the motivation. It is not possible in our experiment to determine if boredom generated the feeling of fatigue and the negative change in motivation or vice versa. Eastwood et al. (2012) listed numerous studies showing that boredom is associated with negative affect, such as displeasure, sadness or anger. In addition, Milyavskaya et al. (2019) showed that participants confronted to a 20-min boredom condition reported more fatigue than those that had to cope with a 20-min effortful cognitive task. Furthermore, the MAC model of boredom (Westgate & Wilson, 2018) presents evidence that bored people are not motivated to continue the boring task but to switch toward a more enjoyable activity. All these arguments support the view that, in our experiment, boredom caused an increase in the feeling of fatigue and a decrease in motivation. In the future, it would be interesting to conduct path analysis studies examining the causal link between all of these variables. Taken together, our results suggest that the ego-depletion effect is multifactorial and can be explained by several factors: decrease in self-control capacities, drop in motivation, increase in boredom and the feeling of fatigue.

Results concerning the handgrip MVC task showed that, as in experiment 1, participants consistently gave their best at performing the handgrip endurance task in the three sessions. The decrease in MVC peak force was very similar in the three sessions when comparing the performance before and after the handgrip endurance task: $M = 40.5\%$ ($SD = 15.1$) in the baseline session, M = 41.4% (SD = 16.8) in the control session, and $M = 41.5\%$ ($SD = 15.0$) in the depleting session. As in experiment 1, we also observed that there was a little drop in MVC peak force after the mental task whatever the session: $M = 5.1\%$ ($SD = 6.8$) in the control session and $M = 5.3\%$ ($SD = 6.9$) in the depleting session. As proposed in the discussion of study 1, this small decrease in MVC peak force is likely due to the absence of warm-up before performing the MVC after a 30 s period of rest.

Concerning the perception of effort, according to the motivational intensity theory (Richter et al., 2016) and the prediction of Wright (2014), when the participants are mentally fatigued, they should invest more effort to perform the same task. In the third experiment, compared to the video task, participants reported feeling more fatigued after the incongruent Stroop task. In the same way, they had a greater perception of effort at the end of the handgrip endurance task after the incongruent Stroop task in comparison to the video task. This result supports the idea that performing the handgrip endurance task after an effortful depleting task incurs more costs than after an effortless control task. This result is also in line with the literature on cognitive fatigue consistently observing an increased perception of effort following prolonged mental exertion (for review see Pageaux & Lepers, 2018).

Concerning the perception of muscle pain, our results did not reveal any effect on muscle pain induced by the completion of the handgrip endurance task. This difference between our result and the literature is likely due to the different nature of the pain investigated. In our task, we investigated naturally occurring muscle pain during a physical task (O'Connor & Cook, 2001), why others investigated thermal pain in a resting state (Silvestrini & Rainville, 2013) or pain induced by cold water immersion (Vohs et al., 2008). Further studies are needed to better

appraise the effect of ego-depletion on pain perception.

5. General discussion

5.1. Replication

The aim of this series of studies was to replicate the ego-depletion effect in favorable conditions of replication in order to avoid possible bias met by unsuccessful replication studies (e.g., Etherton et al., 2018; Hagger et al., 2016; Lurquin et al., 2016; Osgood, 2017; Xu et al., 2014). Two parameters of the depleting task have been calibrated to facilitate the observation of an ego-depletion effect: a long duration (close to 30 min) and a high cognitive load (a task requiring both inhibitory control and cognitive flexibility). In addition, the boring and effortful control task used in experiment 1 was replaced with a strongly less effortful and not boring control task in experiment 3. Finally, we used a classic dependent task: the handgrip endurance task, which requires task persistence, a trait closely related to effortful control (e.g., Mägi et al., 2018).

In the first experiment, we failed to replicate the ego-depletion effect, but the results suggest that this null effect was obtained because of an inappropriate control task. We chose this control task in order to put the participants in exactly the same experimental conditions in depleting and control conditions, except for the load of the executive and effortful control that the participants have to exert in each condition. In the depleting condition, they had to inhibit either the automatic response to read the word presented on the screen or the response corresponding to the color of the ink. In addition, they also had to switch from reading the word to naming the color of the ink at the beginning of a trial each time there was a change of preparatory signal. These two instructions made the depleting condition very effortful and attention demanding. In contrast, in the control condition, the participants had simply to read the word at each trial throughout the task. This condition required little attention and was not supposed to tap executive control. Thus, we expected to have created a good contrast between the two experimental conditions. Unexpectedly, the results showed that the control task was evaluated as more boring than the depleting task. Furthermore, boredom was significantly correlated with subjective fatigue. Milyavskaya et al. (2019) observed very similar results in a number manipulation or viewing task: participants reported more fatigue in the boredom condition (passive number viewing) than those in the cognitive effort condition (adding 3 to the presented digit), despite reporting exerting less effort. It is possible that the management of boredom requires effortful control, for instance to counteract the desire to stop the boring activity when the individual is constrained to continue the task until the end. The self-control costs required by the management of boredom during task performance should be more carefully examined in the future (see section 5.4).

Nevertheless, only two studies (MacMahon et al., 2019; Pageaux et al., 2014) have already found the ego-depletion effect using the same depleting and control tasks as in our first study. To our knowledge, these two studies are the only ones to use an incongruent Stroop task with a minimum duration of 30 min as depleting task and a congruent Stroop task (i.e., color-word reading task) of the same duration as control task. First, both studies had low sample size (13 and 12 participants, respectively) and consequently lower statistical power. A false positive is more possible than with a larger sample size. Second, the tasks they used were similar to ours except for what concerns the response instructions of the Stroop task. In our first study, participants answered orally to the depleting and control tasks, while in the two other studies, they answered by pressing a key on a keyboard. The oral answer is an automatic response that does not need learning and then can create boredom quickly. In contrast, pressing the key located on a keyboard, in response to a word in color, is not a natural stimulus-response mapping established since childhood. In this case, there is no dimensional overlap between the stimuli and the responses (Kornblum et al., 1990). Participants need to practice extensively the task to strengthen the link between stimuli and responses. Consequently, the manual version of the reading Stroop task is presumably more attention demanding and less boring than its vocal version. This hypothesis needs to be tested.

Our second experiment confirmed that a long, color-word reading task generates a high level of boredom and induces negative affective states. The video-watching task, was frequently used as a control task in experiments examining the effect of cognitive fatigue on physical performance or motor skills (e.g., Badin et al., 2016; Brown & Bray, 2019; Head et al., 2017). In contrast to the color-word reading task, the video task was evaluated as emotionally neutral and did not induce boredom. Consequently, we decided to use this task as the control task in the third experiment.

The third experiment showed that with some methodological precautions, we replicated the ego-depletion effect. The participants gave up the handgrip endurance task earlier after the long and effortful incongruent Stroop task than after watching a neutral video of the same duration or when no mental task preceded the handgrip endurance task. In addition, the feelings of fatigue and boredom were higher after the incongruent Stroop task than after the documentary. These results are coherent with those of six other comparable within-subjects design studies showing that performing a long and effortful cognitive task has a detrimental effect on a subsequent physical performance (Brown & Bray, 2019; Head et al., 2017; Marcora et al., 2009; Pageaux et al., 2013; Penna et al., 2018; Smith et al., 2015). All these studies used a cognitive task tapping executive functions with a duration greater than 30 min as the depleting task and a neutral documentary of the same duration as the control task. In contrast, each of these studies used a different physical outcome in the dependent task: time to exhaustion in a cycling task at 80% peak workload (Marcora et al., 2009); 20% knee extensors MVC time-to-exhaustion (Pageaux et al., 2013); velocity during a self-paced intermittent running task (Smith et al., 2015); decision-accuracy errors in a marksmanship task (Head et al., 2017); total work in a self-paced cycling task (Brown & Bray, 2019); and completion time in a 1500 m swimming task (Penna et al., 2018). In all these studies, the performance in the physical task was worse when it was carried out after the effortful cognitive task in comparison to the effortless video task. The sample size of our study was notably larger than that of these studies, 51 participants in our third experiment against a sample ranging between 10 and 25 participants in the other studies, but the other studies led to a moderate effect size ($M = 0.39$, $SD = 0.26$) as well as our study ($d_z = 0.41$).

5.2. Role of motivation in the ego depletion effect

Three main different theoretical approaches explain the disengagement of effort and the drop in performance observed after carrying out an effortful task: the depletion of an internal resource (Baumeister et al., 1998, 2018), a shift of motivation and attention toward more pleasant activities (Inzlicht et al., 2014) and an imbalance between effort costs and effort benefits (Boksem & Tops, 2008; Shenhav et al., 2017). Our experiment did not allow determining which mechanisms explain best the drop in performance. However, it was possible to check if our data fit well with the predictions of one of these models.

Concerning the motivation to perform an effortful task, the process model of self-control (Inzlicht & Schmeichel, 2012) makes clear predictions: it must be lower after the depleting task by comparison to before. This pattern of results was observed in experiment 3 with a large effect size. In addition, when we added the decrease in motivation as a covariate in the ANOVA testing the session effect (depleting task vs control task) the ego-depletion effect disappeared. These results strongly support the process model of self-control but are in contradiction with the results of a recent study published by Stocker et al. (2020) in which the ego depletion effect was not mediated by motivation. Furthermore, the hypothesis of a decrease in motivation to exert effortful control after the performance of a first effortful task does not exclude that a decrease

in internal resource precedes or accompanies the shift in motivation toward less effortful activities. This resource depletion hypothesis requires psychophysiological, electrophysiological or brain imaging measurements to be appropriately tested, such as the assessment of effort deployment with pre-ejection period (Kelsey, 2012) or prefrontal theta waves (Umemoto et al., 2019) when effort is viewed as a mental resource. However, to stay more neutral about the mechanisms underpinning the ego-depletion effect, it would be more appropriate in the future to use other terms while designating the "depleting task" and the "control task". For instance, the terms "high control task" or "high-effort demanding task" could be used instead of "depleting task" and "low control task" or "low-effort demanding task" instead of "control task".

If we further challenge the process model of self-control, it predicts that the motivation to perform the depleting task should decrease again after the second effortful task (i.e., handgrip endurance task) because people are generally aversive to perform a second costly task while they already performed a first costly task. We did not observe this additional decrease of motivation after the second effortful task (see section 4.3.5). This result can be due to a ceiling effect: the motivation score being very low after the depleting task with an average of 18/100. Then, after the handgrip endurance task, participants could not report a lower motivation to perform the depleting task again. This possible evolution of motivation until reaching a ceiling limit needs further investigations.

5.3. Role of boredom in the ego depletion effect

According to Wolff and Martarelli (2020), the boredom associated with the depleting task can increase the effort cost of this task and thus contribute to the ego-depletion effect. In this perspective, the depleting task can be viewed as more self-control demanding than the control task for two main reasons: (1) a higher demand in effortful control because the involvement of executive functions, (2) a higher demand in effortful control because the occurrence of boredom with time-on-task. In our last experiment, the ego-depletion effect is then the consequence of the contrast in control demand and/or boredom between the Stroop task and the video-watching task. Our results clearly showed that when boredom was controlled, the ego depletion was no more significant. In the future, it would be important to disentangle the respective role of the boredom and the cognitive load induced by the depleting task in the ego depletion effect. For instance, it would be interesting to use two conditions with the same cognitive load (e.g., same executive function and same level of difficulty) but with two levels of boredom (e.g., continuous and monotonous boring task vs. a variety of sequential short tasks tapping the same executive function) in addition to a non-effortful control task.

5.4. Limits

We identify five main limits in our study. The first limit is related to the use of a between-subjects design in the first experiment while we used a within-subjects design in the third experiment. We decided to change the design for two main reasons: to have sufficient statistical power as in the first experiment with less participants, because we knew the correlation among repeated measures of the principal outcome thanks to the first study (May & Hittner, 2012); and to reduce inter-individual differences (e.g., self-control trait), which may lead to between group differences. However, a recent meta-analysis about the effect of mental fatigue on physical performance (Brown et al., 2020) showed that between-subjects designs lead to larger effect sizes than within-subjects designs. Consequently, we can conclude that we found the ego-depletion effect in the worst case, suggesting that our results are robust.

The second limit concerns the fact that we measured the affective valence of the control tasks during the second experiment, while we never assessed the affective valence of the depleting task. Thus, the depleting effect could be due to the negative affective change associated with the unpleasant experience of performing the depleting task in comparison to the video task that did not elicit negative affective states. However, the negative valence associated with the depleting task could just be a product of the depletion of resources or increase in boredom and not a causal factor that participates in the occurrence of the ego-depletion effect. More research should be done to clarify this point.

The third limit concerns the fact that many participants were excluded from the first experiment (23%), mainly because they were exposed to unpredictable stressful events before the scheduled experimental session or did not respect the handgrip task instructions. The rate of exclusions considerably decreased during the third experiment (7%). This decrease of exclusions from experiment 1 to experiment 3 can be explained by better preparation of the participants before the beginning of the experimental sessions. For instance, concerning the handgrip endurance task, the experimenter controlled more frequently the position of the pointer within the target zone and told the participants to go back above the 12% line each time they passed below this line. In addition, experiment 3 started earlier in the academic semester to allow the experimenter to make a new appointment with a participant as soon as an unpredictable event changed his/her psychological and physiological states just before a session (e.g., a lack of sleep). With these methodological precautions, only participants whose performance was considered an outlier were excluded from experiment 3. However, to check the influence of the excluded participants on the results, we performed ANOVA with all the participants (excluded + included) in experiments 1 and 3. Results of both experiments remained the same.

The fourth limit concerns the problem of dissimilarity between the depleting task and the control task in the third experiment. The best control task would have been a task very similar to the depleting task but without any effortful component, ceteris paribus. The control task used in experiment 1 was conceived to play this role. However, a simple difference in the rule of responding between the two tasks increased boredom over time in the control task in comparison to the depleting task. The choice of an emotionally neutral documentary as the control task could also have had some methodological implications that affected the state of the subject. The video task and the incongruent Stroop tasks differed in at least two main aspects: (1) participants were active in the depleting task (saying a word every 2 s), while they were passive in the control task (watching a documentary); (2) there was a limited number of visual stimuli in the depleting task, whereas the stimuli constantly changed throughout the documentary. Even though these dissimilarities question the pertinence of the documentary as a good reference task, this task met two important criteria: it is not boring and requires little effort.

A fifth and final limit to our studies concerns the time between the mental task and the handgrip endurance task. In our experiments 1 and 3, participants answered to some questions about their feelings between the mental task and the handgrip task. However, the duration to complete this short list of questions was not fully standardized. Then some participants took more time to answer, whereas others were shorter (approximately the range was between 4 and 7 min). In their meta-analysis, Hagger et al. (2010) indicated that when participants have an intermediate period between the two tasks of the sequential protocol, used to complete questionnaires, perform a filler task or rest, the effect size of the ego depletion effect is greater ($d = 0.71$) than when participants do not have such period ($d = 0.47$). Then, it is possible that the duration of this period could have a moderating effect on the size of the ego-depletion effect. However, we think this limit did not weakened our results. In the first experiment, we had enough participants to randomize fast and slow answerers to both groups. In the third experiment, the comparison of the performance was made in the framework of a within-subjects design, and participants who took more time to answer during one session took more time to answer during the other. However, to be sure that the duration of the intermediate period between the depleting and the independent task does not influence the results, future experiments should standardized it by imposing a deadline for each response, when questions are used during this period.

5.5. Recommendations and perspectives for future research

In the current paper, we saw that the self-control trait predicts how participants will perform at the dependent task: the higher the self-control trait was, the better their performance at squeezing the handgrip was. This result suggests that in the case of between-subjects design, it should be appropriate to measure and to control this trait to be sure that groups are homogeneous; otherwise, it could increase the type 1 or 2 error. For instance, if the depleting group had higher self-control trait, the size of the ego-depletion effect could decrease drastically and even become non-significant. A solution to deal with this issue would be to use a within-subjects design. Even if the effect size of the ego-depletion effect is larger in between-subjects designs when the dependent task requires physical performance, it is still significant in within-subjects designs with the same type of dependent task (Brown et al., 2020). Furthermore, the use of a within-subjects design with different sessions (and not just one) increases the statistical power and reduces the error variance of the statistical analysis aiming to challenge the ego-depletion effect (Francis et al., 2018).

In this article, the ego-depletion effect was replicated while using a 30-min effortful depleting task tapping two executive functions. Only few studies have paid attention to the duration and the executive control cost of the depleting task. Concerning the duration of the depleting task, Brown and Bray (2017) identified a threshold below which the ego-depletion effect is not observed: a duration of 6 min at exerting an effortful control. However, these authors showed that there is no dose-response effect and the amplitude of the ego depletion effect did not increase over time. In addition, the meta-analysis of Brown and collaborators showed that cognitive tasks lasting less than 30-min and more than 30-min have a similar moderate and significant negative effect on subsequent physical performance (Brown et al., 2020). However, very long tasks (more than 2 h) are rarely used and a study conducted by Blain et al. (2016) suggests that more than 6 h of effective and continuous work at performing tasks tapping executive functions without a break is necessary to obtain a significant effect of cognitive fatigue. It would be interesting to explore this other side of the time axis with very long work sessions lasting an entire day such as is the case in many labor situations.

To our knowledge, no study manipulated the cognitive load of the depleting task in a sequential task protocol. The sole manipulation consists of comparing the effortless control task to the effortful depleting task. However, several studies manipulated cognitive load and studied the effect of cognitive fatigue on performance as a function of time-on-task (e.g., Hopstaken et al., 2015). Future research should gradate more finely the amount of executive control required by the depleting task while controlling the boredom induced by each level of difficulty.

Another point that needs to be addressed in the future is the determination of the respective contribution of each explanatory mechanism in the ego-depletion effect. As mentioned earlier, the strength model of self-control (Baumeister et al., 1998, 2018) proposed that an internal resource is progressively depleted throughout the task. The hypothesis of blood glucose as a possible depletable resource, which comes from this model (Gailliot et al., 2007), has been challenged and severely criticized (e.g., Kurzban et al., 2013; Vadillo et al., 2016), and a more plausible internal resource needs to be identified. A recent model proposed by André et al. (2019) posits the connectivity of large-scale neuronal networks involved in effortful control and executive control, such as the salience network and the central executive network, as a possible resource that can be weakened through an intensive and long use of processing units involved in the exertion of control. In this framework, cognitive fatigue is viewed as an intrinsic cost that influences effort-based decision-making. Challenging this new model with the help of brain imaging and psychophysiology and examining how motivation varies with a weakening of these networks to exert control offers a heuristic direction for future studies.

Concerning the influence of self-control on sport performance and exercise adherence, two main issues needs to be addressed in the next decade. First, considering that cognitive fatigue is viewed as a serious determinant of physical performance, it becomes urgent to examine the compensation or recovery processes allowing an athlete to overcome or decrease cognitive fatigue during a long sport event and to propose effective techniques allowing a maintenance of or a rapid return to the optimal level of performance. Second, considering that the capacity to exert self-control can be decreased by the exertion of a first effortful task, it would be interesting to examine how to increase this capacity with training to decrease or delay cognitive fatigue effects and to increase adherence to exercise. Several studies showed that the self-control capacity can be trained through several modalities (for a review, Audiffren et al., 2021), but few studies identified the most effective training programs and the most relevant characteristics of these programs.

Open practices

The materials and the data of the three experiments can be found online at: https://osf.io/tuay5/?view_only=c4e9cff8a76a4eeca4d2aeb303280ff5.

Funding source

This work was supported by the Regional Council of New-Aquitaine (AAPR2020F-2020-8595710).

Declaration of competing interest

The authors declare no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.psychsport.2021.102033.

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