The Impact of Pain on Subsequent Effort and Cognitive Performance

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Abstract

Theoretical accounts of pain and empirical evidence indicate that pain and cognitive control share common neurocognitive processes. Numerous studies have examined the interactions between pain and cognitive performance when they occur simultaneously, typically showing analgesic effects of task performance and impaired performance due to pain. However, the sequential impact of pain on cognitive control and effort remains less clear. This study investigated the influence of a first task including painful vs. non-painful thermal stimuli on effort-related cardiac response and performance in a subsequent moderately difficult cognitive task. Drawing on the hypothesis that experiencing pain should recruit cognitive resources (such as attention and working memory) and reduce perceived ability, we predicted lower task performance and/or stronger compensatory effort in the subsequent cognitive task after the painful than after the non-painful first task. Results support our predictions regarding the effect of pain on subsequent cognitive performance, which was moderately lower after the painful task. However, such a decrease in task proficiency was not associated with a comparable decrease in perceived capacity or increase in effort-related cardiac reactivity. Nevertheless, further correlational analyses indicated that effort and perceived capacity were significantly related to pain ratings. Moderate pain was associated with stronger effort during the cognitive task whereas high pain led to disengagement, i.e., a low effort. Moreover, in line with our predictions, higher pain ratings were associated with lower self-reported capacity to perform the cognitive task. We discuss these findings regarding the relationship between effort and performance; the impact of fatigue on motivation; and interindividual variability in these after-effects.

Keywords: pain, effort, cardiovascular reactivity, sequential-task protocol, fatigue

Introduction

Physical pain, defined as “an unpleasant sensory and emotional experience associated with, or resembling that associated with, actual or potential tissue damage” (Raja et al., 2020, p. 1977), is a major public health issue associated with considerable human and economic burden (e.g., Breivik et al., 2006; Jones et al., 2018). Although most often driven by physiological mechanisms, pain engages and interacts with cognitive processes (Bushnell et al., 2013; Eccleston & Crombez, 1999; Tracey & Mantyh, 2007; Wiech, 2016). In this context, theoretical accounts of pain and empirical evidence suggest that pain and cognitive control share common and limited cognitive resources such as attention and working memory (Buhle & Wager, 2010; Legrain et al., 2009). For instance, pain typically disrupts attention and impairs performance during demanding tasks, whereas engaging cognitive exercises reduce concurrent pain (Buhle & Wager, 2010; Moore et al., 2012; Sprenger et al., 2012; Valet et al., 2004). Moreover, activation of brain areas such as the anterior mid-cingulate cortex, the lateral prefrontal cortex, and the insular cortex, have been described during both pain and cognitive control, suggesting that both phenomena might recruit overlapping neurocognitive processes (Apkarian et al., 2005; Shackman et al., 2011; Silvestrini et al., 2020).

Sequential Relationships Between Pain and Cognitive Control

Whereas the studies reviewed above support the idea of limited cognitive capacity when pain and cognitive performance occur simultaneously, much less is known about how these phenomena influence each other sequentially: i.e., how pain impacts subsequent cognitive performance and how cognitive control influences subsequent pain. Although less ecological from a clinical point of view than simultaneous settings, sequential tasks have the advantage of studying the directionality of the influence. Previous studies showed increases in pain responses elicited by noxious stimuli following demanding cognitive tasks (Silvestrini et al., 2020; Silvestrini & Rainville, 2013). This indicated that when individuals exert cognitive effort in a first demanding task, they perceive subsequent pain as stronger. In line with the

idea of shared and limited cognitive resources between pain and cognitive control, these findings were interpreted as showing less efficient pain regulatory mechanisms after cognitive exertion. However, another study indicated that manipulating the perception of available resources after cognitive performance influences pain responses as well (Silvestrini et al., 2019; see also Clarkson et al., 2010). This highlighted the impact of the mere perception of available resources following cognitive exertion on such after-effects on pain. This also suggested an alternative explanation of the underlying mechanism implicating reduced self-efficacy, or the belief we have about how well we can execute a given course of action (Bandura, 1977), including coping with painful stimuli (Bandura et al., 1987). However, the sequential relationship between pain and cognitive control in the other direction, i.e. the impact of pain on subsequent cognitive control remains open to investigate.

The Sequential Task Protocol

Numerous studies outside the domain of pain use such an experimental procedure, i.e. a sequential-task protocol, to test fatigue effects (Blain et al., 2016; Wright et al., 2019), as well as the strongly debated ego-depletion effect (Baumeister et al., 2007; Friese et al., 2019; Hagger et al., 2010; Hagger & Chatzisarantis, 2016). In the sequential-task protocol, participants perform a first task requiring self-control (or executive control) or not and then are asked to complete a second task that also requires a high level of control. The main prediction associated with this protocol is that performance should be impaired in the second task when the first task is demanding—the so-called ego-depletion effect. Importantly, a demanding task might be used equally to induce depletion on a subsequent task, or to measure the impact of a prior depleting event. Moreover, these effects are predicted to occur across domains with the idea that supramodal self-regulation rests on a common regulatory mechanism. Within this framework, previous findings on the impact of cognitive control on pain suggest that we should observe an effect in the opposite direction as well, i.e. coping with painful stimuli should impact subsequent task performance.

Several models aimed to explain the ego-depletion effect, suggesting for instance limited (Baumeister et al., 2007) or perceived to be limited (Job et al., 2010) self-control

resources, or decreased motivation to perform the second task (Inzlicht & Schmeichel, 2012). However, currently, the ego-depletion effect is strongly debated, with concerns about publication biases and very small effect sizes in attempts to replicate this effect (e.g., Carter et al., 2015; Hagger & Chatzisarantis, 2016; Vohs et al., 2021). A seminal analysis of arguments for and against this effect suggests that the available evidence is actually inconclusive (Friese et al., 2018), although recent studies provide robust (albeit small) evidence of depletion under rigorous methodological standards (Lin et al., 2020), and a multilab replication (Dang et al., 2021). It is possible that mixed results from different studies underlie untested sources of noise, hidden moderators, or alternative explanations, which could impact individual behaviour in an unforeseen way. In this perspective, a recent model highlights the major role played by effort (Wright et al., 2007, 2019; Wright & Mlynski, 2019).

Impact of Short-Term Fatigue on Effort

In particular, one prominent account suggests that short-term fatigue due to a first demanding task decreases the perceived ability at performing a subsequent task, rather than performance itself (Wright & Mlynski, 2019). In turn, perception of reduced ability (which is close to the concept of self-efficacy, Bandura, 1977) should increase perceived difficulty of the second task and, consequently, influence the allocation of effort together with individual motivation. More specifically, drawing on motivational intensity theory (Brehm & Self, 1989), Wright and colleagues (2007, 2019) predicted and found that fatigue increases subjective task difficulty, which leads to increased effort in easy and moderately difficult tasks and disengagement (low effort allocation) in highly difficult tasks. Indeed, in easy and moderately difficult tasks, increased effort may reflect compensatory processes to preserve task performance (Hockey, 1997). However, when the required effort due to the additive effect of task demand and fatigue exceeds success importance, effort should drop, and people disengage. This model can explain mixed findings obtained in the sequential-task protocol regarding task performance (Wright & Mlynski, 2019). Additional effort may preserve performance after exertion of cognitive control, but performance should be lower when people disengage, as the task is considered to be too demanding or the required effort not

deemed to be justified. However, it is of note that the relationship between effort and performance is not completely straightforward (see Silvestrini & Gendolla, 2019).

In the studies of Wright and colleagues (2007, 2019), effort, defined as the mobilization of resources to carry out instrumental behavior (Gendolla & Wright, 2009), was quantified as sympathetic beta-adrenergic discharge on the heart (Obrist, 1981; Wright, 1996). Sympathetic activity reflects the mobilization of energy when people engage in a task, and numerous studies support the idea that sympathetic activity on the heart reflects effort during task performance (see Richter et al., 2016; Wright & Kirby, 2001, for reviews). This measure represents a more direct, and unbiased, estimate of effort than subjective reports, which are confounded by factors like individual beliefs, social-desirability biases, protection mechanisms for self-esteem, etc. (Silvestrini & Gendolla, 2019). Regarding cardiovascular parameters, pre-ejection period (PEP), the time interval between left ventricular excitation and the opening of the aortic valve (Berntson et al., 2004), is the most sensitive non-invasive parameter to assess sympathetic activity because it is mainly determined by heart contractility, which is primarily driven by sympathetic impact on the myocardium. PEP is considered a more direct measure of sympathetic activity than overall heart rate (HR), which is influenced by both sympathetic and parasympathetic components, and may reflect sympathetic activity only under the assumption that this is stronger than its parasympathetic counterpart, which is not always the case (Berntson et al., 1993).

The Present Study

In the present study, we aimed to test the impact of pain on subsequent cognitive control and to extend the investigation of such after-effects by assessing effort as cardiovascular reactivity (Wright, 1996; Wright et al., 2019). Following a sequential-task protocol, participants accomplished a first task including painful vs. non-painful thermal stimuli and then performed a demanding cognitive task during which we assessed effort-related cardiac reactivity (especially PEP) and performance, as well as estimates of ability perception. Based on the literature reviewed above, we expected that painful (vs. non-painful) temperatures should decrease performance in a subsequent task. Alternatively, we

predicted that pain should decrease perceived ability, and increase task-related cardiac response, as evidence of increased compensatory effort following beliefs of low self-efficacy.

Materials and Method

Participants and Design

Thirty University students (15 women, mean age 24 years) participated voluntarily in the study and received 40 Swiss Francs (i.e., 42 USD) for their participation. Participants were volunteers free of self-reported acute or chronic pain, and cardiovascular, neurological, or psychological disease. Sample size was determined on the basis of a power analysis assuming a medium effect size ($f = .25$) with a power of .80 and an alpha of .05. The experiment was stopped once the targeted sample size was reached (30) and no additional participants were included. Moreover, we did not exclude any participants from the analyses. The study followed a 2 (first-task: painful, non-painful) within-subject design. All participants provided signed informed consent and the study protocol was approved by the ethics committee of the Department of Psychology of the University of Geneva.

Apparatus

The procedure was computerized with a script running in E-prime 2.0 (Psychology Software Tools Inc., Pittsburgh, PA). A computer controlled thermal stimulator with a 25 x 50 mm fluid-cooled Peltier probe (MSA Thermotest, Somedic, Hörby, Sweden) delivered painful and non-painful thermal stimulations. The baseline temperature was set to 36°C and each stimulation lasted 16 sec (3 sec of temperature increase, 10 sec of plateau, and 3 sec of temperature decrease).

PEP (in milliseconds) and HR (in beats per minute) were assessed using a Cardioscreen 1000 system (Medis, Ilmenau, Germany), that continuously measured ECG (electrocardiogram) and ICG (impedance cardiogram) signals. Four pairs of spot electrodes were attached on the right and the left side of the base of participants' neck and on the left and right middle axillary line at the height of the xiphoid to sample (1000 Hz) thoracic

impedance and electrocardiogram signals (Scherhag et al., 2005). Both signals were directly stored on computer disk.

Procedure

Participants were seated in a comfortable chair in front of a desktop computer. After a brief oral presentation of the study, participants read and signed the consent form. First, the probe of the thermal stimulator was installed on their right leg in the right lower part of the shinbone and the experiment started by determining individual pain threshold using a staircase procedure. To do so, we applied three series of ascending and descending thermal stimulations. After each stimulation, participants rated pain unpleasantness with a visual analog analogue scale ranging from 0 (*Not unpleasant at all*) to 100 (*The most unpleasant pain imaginable*). After an initial increase by steps of 2°C, the temperature started decreasing when participants rated pain unpleasantness as more than 70 and increased again when pain unpleasantness was lower than 50. The last series of ascending and descending stimulations included steps of 1°C. The administered temperatures and associated pain unpleasantness ratings were then displayed on a scatter plot. Based on these data, we selected one temperature that elicited a pain unpleasantness response of about 70 (painful condition) and one temperature that elicited a pain unpleasantness response of about 20 (non-painful condition). The painful and non-painful temperatures ranged between 40 and 50°C (painful: $M = 47.26$, $SD = 1.51$; non-painful: $M = 43.97$, $SD = 1.72$). Then, participants received the instruction for the cognitive control task (see below) and performed 10 practice trials.

The experiment started with the assessment of cardiac baseline values (8 min) during which participants quietly read a magazine. After that, half of the participants performed a so-called thermal perception task (11 min) including painful thermal stimulations. Ten painful and 5 non-painful stimulations were administered in a pseudo-randomized order and participants had to detect the beginning and the end of each stimulation by pressing a button on the keyboard. To keep with the cover story, participants estimated the length and the

temperature with a cursor displayed on the screen after each stimulation. Directly after this first task, participants performed the moderately difficult cognitive task, a numerical Stroop task (Bush et al., 1998). In this task, sets of one to four identical words were presented vertically on the screen and these words were the number words “one”, “two”, “three”, and “four”. Participants had to report the number of words presented on the screen using the buttons of the keyboard as quickly and accurately as possible. Only incongruent trials were presented (e.g., the word “two” written three times), which were expected to require cognitive control due to the high interference between the reading of the word and the word counting. Trials started with a fixation cross (1000ms) followed by the words to count which stayed on the screen until the participant gave his/her response but not more than 1250ms. Participants performed 65 experimental trials (5 min) always with a neutral feedback (“response entered”). The feedback appeared for 2 sec minus participants’ reaction time, assuring that the task had the same length for each participant. Inter-trial intervals varied randomly (2-5 sec).

Once the task was finished, participants rated experienced task difficulty (“How difficult was it for you to achieve the task successfully?”), subjective capacity (“Did you feel capable to achieve the task successfully?”), interest in succeeding in the task (“Were you interested to achieve the task successfully?”), and success importance (“How important was it for you to achieve the task successfully?”) on 7-point Likert scales (1 = *not at all*, 7 = *very much*). Finally, they rated with visual analogue scales the average intensity and unpleasantness of pain felt during the thermal perception task on two visual analogue scales ranging from *No pain/Not unpleasant at all* (0) to *The most intense/unpleasant pain imaginable* (100). After a pause of few minutes, they repeated the whole procedure (baseline period, thermal perception task, cognitive task) but with the thermal perception task in a non-painful condition (15 non-painful stimulations). The other half of the participants started with the thermal perception task in the non-painful condition to control the order of the conditions.

Data Analyses

First, we preprocessed ECG and ICG signals to determine PEP and HR values. R-peaks, defined by the maximum peak amplitude of QRS-complexes in the ECG signal, were identified using a threshold peak-detection algorithm and visually confirmed. Only artifact-free cardiac cycles were included. ICG analysis software (Richter, 2010) computed the change in thoracic impedance (first derivate). The resulting dZ/dt signal was ensemble averaged (1 min periods) using the detected R-peaks (Kelsey et al., 1998). B-point location was estimated based on the RZ interval (Lozano et al., 2007) visually inspected and corrected if necessary as recommended (Sherwood et al., 1990). PEP was determined as the time interval between R-onset in the ECG signal and B-point in the ICG signal (Berntson et al., 2004). Shorter PEP indicates a stronger beta-adrenergic impact on the heart—i.e., a stronger effort.

Statistical analysis of the data was performed using SPSS software (Version 26.0, IBM Corp., Armonk, NY). First, we ran preliminary analyses to establish how to compute the mean baseline scores of the cardiac measures. Preliminary repeated measures ANOVAs on PEP baseline measurements associated with painful and non-painful conditions indicated main effects of time ($ps < .005$). Additional paired-sample t -tests indicated that for the baseline preceding the painful condition, PEP scores decreased from the first to the second minute, $t(29) = 2.81$, $p = .009$, from the sixth to the seventh minute, $t(29) = 2.19$, $p = .037$, and then remained stable ($p > .47$). For the PEP baseline preceding the non-painful condition, only the first minute differed from the second minute, $t(29) = 3.23$, $p = .003$, and then remained stable ($ps > .21$). To remain consistent, PEP and HR baseline scores were calculated for the two conditions as the arithmetic mean of the last two minutes of the baseline period ($as > .97$). Means of the baseline scores preceding the painful condition were: PEP ($M = 100.83$, $SE = 1.95$) and HR ($M = 71.80$, $SE = 1.57$). Means of the baseline scores preceding the non-painful condition were: PEP ($M = 100.47$, $SE = 1.95$) and HR ($M = 71.87$, $SE = 1.60$). Paired-sample t -tests indicated no difference between the two baselines scores for PEP and HR ($ps > .63$), which were then averaged as overall scores for PEP ($M = 100.65$, $SE = 1.91$) and HR ($M = 71.83$, $SE = 1.55$), respectively. Then, cardiovascular

changes (deltas) were calculated for each participant and for each cardiac measure by subtracting their respective baseline scores from the 1-min values obtained during each experimental condition of interest (Llabre et al., 1991).

To reduce the influence of extreme values, we applied a robust outlier detection and recoding approach (median absolute deviation) to these change deltas as well as to all our dependent variables (Leys et al., 2019). This was achieved by recoding values exceeding the median ± 2.5 times the median absolute deviation with the closest values within these limits.

Subsequently, we ran preliminary analyses to determine whether time affected PEP and HR reactivity scores during the task phases. Preliminary analyses on PEP deltas during the thermal perception task and during the Stroop task indicated time main effects ($ps < .001$) due to stronger PEP reactivity during the first minute compared to the subsequent minutes. HR change scores also showed time main effects ($ps < .02$). Therefore, the subsequent analyses tested our hypotheses using the average mean of each phase as well as only the first minute of each phase.

Then, we tested whether PEP and HR baseline scores influenced their respective reactivity scores. Preliminary 2 (phase: thermal perception task, Stroop task) $\times$ 2 (first-task: painful, non-painful) ANCOVAs with PEP mean baseline scores as covariate revealed a significant three-way interaction between baseline scores, phase, and first task on PEP mean reactivity scores, $F(1,28) = 5.27$, $p = .029$, $\eta_p^2 = .16$. As this study was designed to test the Phase $\times$ First-Task two-way interaction, it becomes here clear that this effect is in turn modulated by the baseline values. Hence, PEP reactivity scores were analyzed with 2 (phase) $\times$ 2 (first-task) ANCOVAs by including PEP mean baseline scores as nuisance covariate. Preliminary 2 (phase) $\times$ 2 (first-task) ANCOVAs with HR mean baseline scores as covariate did not reveal any main effect or interaction of the covariate on HR reactivity scores ($ps > .38$). Hence, HR reactivity scores were analyzed under the simple 2 (phase) $\times$ 2 (first-task) factorial design, without any nuisance covariate.

Preliminary ANOVAs did not reveal any main effect or interaction associated with gender ($ps > .13$) and condition order ($ps > .09$), with the exception of significant interactions

with order for HR and subjective task difficulty ($ps < .03$). However, including order as a between-subject effect in the analyses of HR reactivity scores and subjective task difficulty did not change the main findings. Therefore, gender and condition order were not further considered.

Then, we analyzed Stroop performance (percentage of correct responses and response times), perceived difficulty, perceived capacity, interest, task importance, pain intensity, and pain unpleasantness using paired-sample t -tests.

Finally, we ran correlational analyses to investigate the relationship between pain ratings, PEP reactivity, task performance, and task ratings. To do so, we calculated difference scores for these dependent variables between the values obtained after the painful vs. the non-painful condition and ran Spearman's correlations on these difference scores. Moreover, we computed bootstrapped 95% confidence intervals for significant correlations (5000 iterations).

Results

Cardiac Reactivity

Preejection Period. The 2 (phase) x 2 (first-task) ANCOVA on mean PEP reactivity including mean baseline scores as covariate revealed a significant Phase x First Task interaction, $F(1,28) = 4.87$, $p = .036$, $\eta^2 = .15$, and a significant three-way interaction with baseline scores as presented above, in absence of other effects ($ps > .14$). To decompose the two-way interaction, we ran further 2 (first task) ANCOVAs for each phase. PEP reactivity scores did not differ during the thermal perception ($ps > .54$). However, PEP reactivity scores did not differ during the Stroop task either ($ps > .25$). As presented in Table 1, PEP reactivity during the Stroop was slightly lower after the painful than after the non-painful first task but this difference was not reliable. Moreover, the 2 (phase) x 2 (first task) ANCOVA on the first minute of PEP reactivity did not reveal any effect ($ps > .18$). Means and standard errors are presented in Table 1.

Heart Rate. The 2 (phase) x 2 (first-task) ANOVA on mean HR reactivity did not reveal any effect ($ps > .29$). Moreover, the 2 (phase) x 2 (first-task) ANOVA on the first minutes of HR reactivity only revealed a marginal main effect of period, $F(1,28) = 3.60$, $p = .068$, $\eta^2 = .11$, in absence of other effects ($ps > .41$). This effect emerged because HR reactivity was slightly lower during the thermal perception task ($M = 0.84$, $SE = 0.49$) than during the Stroop task ($M = 1.82$, $SE = 0.66$). Means and standard errors are presented in Table 2.

Performance during the Stroop Task

As predicted, participants were less accurate in the Stroop task after the painful ($M = 95.37\%$, $SE = 0.53$) than after the non-painful condition ($M = 96.41\%$, $SE = 0.44$), $t(29) = 2.09$, $p = .023$, $\eta^2 = .13$ (see Figure 1). However, we found no difference on reaction times ($p > .31$) between the painful ($M = 647.86$, $SE = 14.47$) and the non-painful condition ($M = 641.23$, $SE = 12.71$).

Task Ratings

We found no difference on subjective task difficulty, perceived capacity, and perceived importance between the painful and the non-painful condition ($ps > .42$). Means and standard errors are presented in Table 2. However, participants reported less interest toward the Stroop task after the painful ($M = 6.10$, $SE = 0.13$) than after the non-painful condition ($M = 6.30$, $SE = 0.12$), $t(29) = 1.99$, $p = .028$, $\eta^2 = .12$.

Thermal Perception Task

Participants estimated temperature as higher in the painful ($M = 45.47$, $SE = 0.29$) than in the non-painful condition ($M = 41.13$, $SE = 0.32$) during the thermal perception task, $t(27) = 11.53$, $p < .001$, $\eta^2 = .83$. Moreover, participants estimated the stimulations as longer in the painful ($M = 8.63$, $SE = 0.26$) than in the non-painful condition ($M = 7.31$, $SE = 0.20$) during the thermal perception task, $t(27) = 5.47$, $p < .001$, $\eta^2 = .53$.

In line with a successful pain induction, participants rated pain associated with the thermal stimulations as more intense in the painful ($M = 63.85$, $SE = 2.97$) than in the non-

painful condition ($M = 22.19$, $SE = 4.05$), $t(29) = 8.94$, $p < .001$, $\eta^2 = .73$. Similarly, the stimulations were rated as more unpleasant in the painful ($M = 68.80$, $SE = 2.38$) than in the non-painful condition ($M = 19.16$, $SE = 3.39$), $t(29) = 10.94$, $p < .001$, $\eta^2 = .80$.

Correlational Analyses

We ran Spearman's correlations between the difference scores (painful – non-painful) of pain ratings (intensity and unpleasantness), PEP reactivity during the first minute of the thermal perception task and the Stroop task (due to time main effects), performance during the Stroop task (accuracy and response times), and self-reports (subjective difficulty, capacity, interest, importance). Differences in pain intensity and pain unpleasantness ratings were highly correlated, $r(30) = .82$, 95% CI [.57, .95], $p < .001$. More importantly, we found significant positive correlations between difference scores of PEP reactivity during the Stroop task and difference scores of pain intensity, $r(30) = .47$, 95% CI [.17, .69], $p = .009$, and pain unpleasantness, $r(30) = .47$, 95% CI [.18, .68], $p = .009$. As presented in Figure 2 (Pannel A), participants with larger differences in pain unpleasantness showed lower PEP reactivity during the Stroop task. Such correlation was not visible regarding difference scores of PEP reactivity during the thermal perception task ($ps > .57$). Moreover, we found significant negative correlations between difference scores of perceived capacity and pain intensity, $r(30) = -.45$, 95% CI [-.75, -.06], $p = .012$, and pain unpleasantness, $r(30) = -.56$, 95% CI [-.78, -.25], $p = .001$. As depicted in Figure 2 (Panel B), participants who showed larger differences in pain unpleasantness reported lower capacity to execute the Stroop task. The correlation matrix is presented in Table 3. To further investigate these relationships, we tested a mediation model with pain ratings as predictors, PEP reactivity during the Stroop task as the outcome, and capacity ratings as the mediator. However, this analysis did not support such mediation (total effect, $p = .014$, direct effect, $p = .073$, indirect effect, $p = .654$).

Discussion

This study aimed to investigate the impact of pain on performance and effort during a subsequent cognitive task. Drawing on the hypothesis that experiencing pain should recruit cognitive resources such as attention or working memory and reduce perceived ability in a subsequent cognitive task, we predicted that painful temperatures should either lower subsequent task performance, and/or lead to stronger compensatory effort as a consequence of diminished perceived capacity. Results partially confirmed our predictions.

After-Effect of Pain on Effort

First, we did not find support for the prediction that painful (vs. non-painful) stimulations lead to increased effort-related cardiac reactivity in the subsequent task, neither when considering the average PEP/HR signal during the whole task, nor just for the first minute. Although we found a reliable interaction between phase and first-task on mean PEP reactivity, such an effect could not be explained in terms of the effect of first-task in the Stroop-related signal. We also found a main effect of time on both PEP and HR reactivity during task performance, which suggests that participants engaged more effort during the first minute of the task and then disengaged—a common finding in studies assessing effort (e.g., Framorando & Gendolla, 2018; Silvestrini & Gendolla, 2011).

After-Effect of Pain on Performance

Second, we confirmed the prediction of reduced performance (lower accuracy) during the Stroop task after the painful thermal perception task relative to its non-painful counterpart. Although the difference between the conditions seems relatively small (1.04%), this difference was significant with a medium to large effect size ($\eta_p^2 = .13$). The effect was not found in reaction times, which is explainable by the fact that the time response window was fixed and rather short (1250 ms). Consequently, responses slower than the allocated response window were categorized as incorrect. This finding on accuracy supports our reasoning that coping with a painful procedure taxes cognitive processes and leads to impaired performance in a subsequent cognitive task—in line with typical fatigue or ego-depletion effects (Baumeister et al., 2007; Dang et al., 2021; Hagger et al., 2010).

We may interpret our findings as showing that overall participants did not engage more effort to compensate for a potential reduction in (perceived) available cognitive resources such as attention or working memory, but consequently their performance was lower after the painful than it was following the non-painful condition. Recent analysis on the impact of fatigue on effort and performance suggests that reduced performance might only occur if individuals disengage from the task (Wright et al., 2019; Wright & Mlynski, 2019), which might be the case in the present study. Therefore, mixed findings on performance in the ego-depletion literature might be related to the compensatory role of effort, which should be more systematically investigated in this context. However, the relationship between effort and performance is not straightforward (see Silvestrini & Gendolla, 2019). Correlational analyses did not indicate a direct association between effort-related cardiac reactivity and performance. Moreover, accuracy was overall very high (more than 95%) despite relatively low effort, which may reflect the engagement of automatic processes during task performance. Future research should more closely investigate such a relationship between effort and performance in the sequential-task protocol.

Impact on Task and Pain Self-Reports

Third, the analysis of self-reports did not provide evidence for our hypothesis that a painful procedure should reduce perceived capacity and increase subjective difficulty of the subsequent cognitive task. However, whereas the effect on task importance was not significant, we found that participants reported less interest in performing the Stroop task after the painful task. This suggests an alternative or parallel mechanism by which the painful procedure might have impacted task performance. As proposed for instance by the process model (Inzlicht & Schmeichel, 2012) and other motivational accounts of the ego-depletion effect (Giacomantonio et al., 2014; Muraven et al., 2006), engaging cognitive effort in a first task might reduce the motivation to perform a second demanding task, presumably because individuals are motivated to conserve their (limited) resources. Interestingly, according to motivational intensity theory (Brehm & Self, 1989), reduced motivation should lead to

disengagement in difficult tasks when the required effort is not justified by success importance. Therefore, reduced motivation, as reflected in lower scores of self-reported interest in the present study, might contribute to disengagement due to fatigue in addition to reduced perceived ability, as noted in previous research (Wright et al., 2019; Wright & Mlynski, 2019).

Pain ratings supported an effective calibration of painful and non-painful thermal stimulations and a successful pain induction during the thermal perception task. Participants rated pain associated with the thermal stimulations as much more intense and unpleasant during the painful than during the non-painful procedure. However, whereas the average effect on pain ratings was large, we found substantial individual differences as well (see correlational analyses below). Moreover, in line with this effective manipulation, participants estimated temperatures as higher and stimulations as longer in the painful than in the non-painful condition during the thermal perception task.

Relationships Between Pain and Effort

Finally, and importantly, correlational analyses provided an indirect support to our hypotheses. Participants with larger differences in pain intensity and pain unpleasantness between the experimental conditions showed lower differences in PEP reactivity during the Stroop task. Such a correlation was not visible in difference scores of PEP reactivity during the thermal perception task. Participants who were moderately sensitive to the implemented pain (between 20-50 on a scale from 1-100) had stronger PEP reactivity during the Stroop task following the painful (vs. painless) temperature. Therefore, moderate pain led to increased effort during the subsequent Stroop task. In contrast, participants most sensitive to the implemented pain (between 60-90) had lower PEP reactivity during the Stroop task following the painful (vs. painless) temperature. This suggests that experiencing a strong pain recruited a high amount of cognitive resources such as attention or working memory, which led to reduced effort during the subsequent Stroop task.

In further support of our predictions, correlational analyses also indicated that participants with larger differences in pain intensity and pain unpleasantness between experimental conditions reported a lower capacity to execute the Stroop task. Therefore, stronger pain not only decreased effort-related cardiac reactivity, but also led to lower perceived capacity. Ideally, it would be reasonable to assume that perceived capacity mediated the relationship between pain ratings and effort-related PEP reactivity. However, this conjecture was not supported by a formal mediation analysis.

Implications for Pain Processes

Regarding pain, the present findings are in line with previous studies suggesting that pain interacts with cognitive control and is related to cognitive control capacity (Silvestrini et al., 2019, 2020; Silvestrini & Rainville, 2013). However, whereas these previous studies revealed an impact of cognitive control on subsequent pain, the present study is the first one to show the impact of a painful procedure on a subsequent cognitive task. From a clinical perspective, these findings are in line with observations that chronic pain patients very often report recurrent feelings of fatigue and difficulty to plan and perform demanding tasks (Solberg Nes et al., 2009).

Perspectives for Future Studies

Overall, these findings offer several avenues in the context of the ego-depletion literature and the current debate on this effect. First, they are consistent with research suggesting that such after-effects may benefit from an explanation in terms of effort (Wright et al., 2019; Wright & Mlynski, 2019). Accordingly, executing a first demanding task should not automatically lead to decreased performance in the second task, but this should depend on factors determining the allocation of effort. Fatigue effects may lead to stronger compensatory effort in the second task to prevent performance impairment, but only if such an investment is justified by success importance. If this is not the case, individuals might disengage from the task and performance should decline, as visible in the present study. Future research might focus on the role of effort in the sequential-task protocol by

systematically assessing effort in the second task. In this context, effort-related cardiovascular reactivity represents a valid and objective indicator of effort (Richter et al., 2016; Wright & Kirby, 2001).

Second, the present findings indicate that exerting control in a first task may also impact the motivation to perform the second task, as indicated here by reduced interest reports. In the context of effort, this suggests that fatigue not only reduces perceived ability but (potential) motivation as well, i.e. the maximally justified effort. Accordingly, one may consider that both effects may contribute to task disengagement. This assertion would be in line with research suggesting reduced motivation after a first demanding task (Giacomantonio et al., 2014; Inzlicht & Schmeichel, 2012). Therefore, it might be of interest to further investigate the impact of the first task on motivation and determine how far this should influence effort in addition to perceived ability.

Finally, the present findings offer an interesting insight into interindividual variability that might be related to mixed evidence when analyzing average effects. In the present study, the impact of the experimental manipulation related to the first task was not reliable on the means of effort-related cardiovascular reactivity. However, further correlational analyses revealed interindividual variability related to the impact of pain induction on pain ratings, the impact of the first task on perceived capacity, and to the impact of the first task on effort. Most important, these differences were related to each other indicating that participants with higher pain ratings showed lower perceived ability and lower effort. Wenzel et al. (2019) used a similar approach to test the ego-depletion effect in a sequential-task protocol with a highly powered within-subject design. They did not find evidence that manipulation check responses covary with subsequent self-control performance or that manipulation check responses moderated or mediated the ego depletion effect. However, these authors suggest that research could exploit the within-subject crossover design to investigate other possible state moderators to explain within-subject variability in ego depletion effects. Moreover, Lin et al. (2020) applied similar analyses as well and found that participants who reported

increased fatigue, demand, or effort after the first task had reduced boundary parameters on a subsequent Stroop task. Accordingly, it is plausible that such interindividual differences and within-subject variability contribute to mixed findings at the mean level. Therefore, future studies may use within-subject designs to assess interindividual differences in such fatigue effects, which could offer insights into the mixed findings obtained when averaging the findings.

Limitations

We acknowledge that the present study presents several limitations, which should lead to a cautious interpretation of the results. First, the study is not as highly powered as recent ones (Lin et al., 2020; Wenzel et al., 2019). However, we calculated our sample size based on an a priori power analysis. Moreover, we did not recruit additional participants once the target sample was attained and we did not exclude participants for data analyses. Therefore, we still consider that our sample was at least large enough to test our hypotheses. Second, we assessed pain ratings after the second task and after other self-reports. It might have been more appropriate to assess pain during or directly at the end of the thermal perception task, before the second task. It is possible that pain ratings were influenced by task performance or the other self-reports. This is especially crucial in the context of correlational analyses, which are anyway not interpretable in terms of causal relationships. However, we found an association between pain ratings and perceived capacity and not with other self-reports. Therefore, one may exclude an interpretation in terms of systematic response bias in self-reports.

Conclusion

To conclude, despite these limitations, the present findings offer interesting insights into potential avenues that increase our understanding of fatigue and depletion effects. Given the ongoing debate on these effects, it is crucial to develop new approaches, such as investigating effort during the second task or taking into account interindividual differences

and within-subject variability with within-subject designs, to try to understand the mixed findings related to one of the most criticized effects in psychology.

Conflict of Interest

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

Author Contributions

N.S. and C.C.D.A conceived the study; N.S. analyzed the data with contributions from C.C.D.A.; N.S. wrote the first draft of the paper and C.C.D.A. contributed to the final manuscript.

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Table 1

Cell Means and Standard Errors (in Parentheses) of Pre-ejection Period and Heart Rate Reactivity

	Thermal Perception Task		Stroop Task	
	Painful	Non-painful	Painful	Non-painful
PEP (average)	- 0.52 (0.42)	- 0.19 (0.41)	- 1.46 (0.60)	- 0.77 (0.65)
PEP (first minute)	- 2.23 (0.57)	- 1.77 (0.46)	- 2.53 (0.73)	- 1.73 (0.64)
HR (average)	0.40 (0.54)	0.34 (0.67)	0.95 (0.62)	0.79 (0.66)
HR (first minute)	0.48 (0.59)	1.19 (0.59)	1.76 (0.70)	1.88 (0.72)

Note: PEP: pre-ejection period; HR: heart rate. Units of measure are milliseconds for PEP and beats per minute for HR. Reactivity scores were obtained by subtracting individual baseline means from the respective task-related values.

Table 2

Cell Means and Standard Errors (in Parentheses) of Subjective Task Difficulty, Perceived Capacity, and Perceived Importance

	Painful	Non-painful
Task Difficulty	2.67 (0.33)	2.67 (0.27)
Capacity	5.53 (0.29)	5.50 (0.27)
Importance	6.20 (0.13)	6.27 (0.12)

Note: $N = 30$

Table 3

Correlations (Spearman's rho) Between Difference Scores (Painful – Non-Painful) of Pain Ratings, Pre-ejection Period Reactivity, and Self-Reports

	Pain Intensity	Pain Unpleasant- ness	PEP Thermal Task	PEP Stroop Task	Accuracy Stroop	RT Stroop	Difficulty	Capacity	Interest
Pain Intensity	-								
Pain Unpleasantness	.82 ***	-							
PEP Thermal Task	-.11	-.13	-						
PEP Stroop Task	.47 **	.47 **	.28	-					
Accuracy Stroop	.12	-.04	.19	-.14	-				
RT Stroop	.35	.22	.11	.21	-.09	-			
Difficulty	-.14	-.14	-.34	-.18	-.22	-.36	-		
Capacity	-.45 **	-.56 **	-.08	-.31	.24	-.16	-.08	-	
Interest	-.14	-.12	.06	-.21	-.12	-.14	-.23	.14	-
Importance	.00	-.21	-.08	-.01	.01	-.09	-.32	.16	.12

Note: N = 30; PEP: Pre-ejection Period; RT: Response times. PEP reactivity scores during the first minutes of the tasks.

** $p < .01$, *** $p < .001$

Figure 1

Figure 2

Figure captions

Figure 1. Means and standard errors (black lines), individual observations (grey dots and lines), and density violin plots of accuracy during the Stroop task after the painful and the non-painful condition.

Figure 2. Associations between difference scores (painful – non-painful) of pain unpleasantness and pre-ejection period reactivity during the first minute of the Stroop task (Pannel A), and between difference scores of pain unpleasantness and perceived capacity (Pannel B).