A pre-registered test of competing theories to explain ego depletion effects using
psychophysiological indicators of mental effort

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Abstract

A prominent, hotly debated idea—the ‘ego depletion’ phenomenon—suggests that engaging in effortful, demanding tasks leads to poorer subsequent self-control performance. Several theories seek to explain the emergence of ego depletion effects. The two most prominent ones are the strength model of self-control (Baumeister & Vohs, 2016) and the process model of self-control (Inzlicht & Schmeichel, 2012). Predictions of these models are predominantly identical on the behavioral level. The models’ predictions differ, however, on the level of invested mental effort. The present pre-registered study ($N = 179$) contrasted these competing predictions combining an established moderator counteracting ego depletion effects (i.e., self-affirmation) and psychophysiological indicators of mental effort (i.e., systolic blood pressure and pre-ejection period). Our data provide moderate evidence for ego-depletion—decrements in self-control performance after a *high-* versus *low-*demanding task in the *non-affirmed* conditions. Self-affirmation had an unexpected effect: Contrary to previous research, *self-affirmed* participants performed similarly poorly as participants in the *high demand+non-affirmed* condition. Although this unexpected finding limited the ability to contrast competing model predictions, it points to hitherto unknown effects of self-affirmation on self-control performance. Systolic blood pressure reactivity emerged as a valid indicator of invested mental effort, but the data show no sign of disengagement after a high demanding task predicted by the process (but not the strength) model. We explore systolic blood pressure progression across the sequential task paradigm, suggest a testable account for the effects of self-affirmation on self-control performance, and discuss theoretical implications of the results for the two competing models.

Keywords: self-control, ego depletion, mental effort, pre-ejection period, blood pressure

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The literature on ego depletion is one of the most prolific and hotly debated literatures in psychology. Two prominent theoretical models—the strength model (Baumeister & Vohs, 2016) and the process model (Inzlicht & Schmeichel, 2012)—make predominantly identical predictions for self-control behavior; yet, these are based on different assumptions about *why* ego depletion effects occur. This makes it difficult to obtain empirical evidence that clearly speaks in favor of one over the other model based on behavior alone. The present study goes beyond the observation of behavior and creates a context that allows to contrast opposing predictions of the strength versus the process model for invested mental effort. To this end, we use the traditional ego depletion sequential task paradigm in combination with (a) the moderator self-affirmation intended to counteract ego depletion effects, and (b) psychophysiological indicators of mental effort (i.e., systolic blood pressure [SBP] and pre-ejection period [PEP]). The strength model assumes that compensatory mental effort has to be invested for a moderator to counteract the loss of resources due to previous mental demands. According to the process model, there is no need to compensate as not a loss of resources but motivation underlies the ego-depletion effect. Crucially, these competing model assumptions lead to competing hypotheses for psychophysiological indicators of invested mental effort.

Ego Depletion – Support and Skepticism

Self-control is commonly conceptualized as the “ability to override or change one’s inner responses, as well as to interrupt undesired behavioral tendencies (such as impulses) and refrain from acting on them” (Tangney, Baumeister, & Boone, 2004, p. 274). A prominent hypothesis suggests that the initial exertion of self-control or—more generally—high mental demand (Lin,

Saunders, Frieze, Evans, & Inzlicht, in press; Schmeichel, 2007) leads to the impairment of further self-control performance: the ‘ego depletion effect’ (Baumeister, Bratlavsky, Muraven, & Tice, 1998). Ego depletion effects have typically been examined in a sequential task paradigm, with the second task measuring self-control performance as a function of whether the preceding task was mentally demanding or not. Hundreds of studies provided support for the ego depletion idea and a first meta-analysis suggested that the effect was a robust phenomenon (Hagger, Wood, Stiff, & Chatzisarantis, 2010). However, a reanalysis and a more recent meta-analysis suggest the presence of publication bias (Carter, Kofler, Forster, & McCullough, 2015; Carter & McCullough, 2014). A registered replication report found a null effect of one specific ego depletion study in a high-powered test (Hagger et al., 2016), and further recent studies also revealed null effects (e.g., Etherton et al., 2018; Lurquin et al., 2016; Osgood, 2017). These and further criticisms question the trustworthiness of extant research and even the very existence of the ego depletion phenomenon (for a review, see Frieze, Loschelder, Gieseler, Frankenbach, & Inzlicht, 2019). At this stage, evidence in favor of ego depletion that meets current standards of transparency is rare (but see Dang, Liu, Liu, & Mao, 2017; Garrison, Finley, & Schmeichel, 2019). With respect to the theoretical foundation of ego depletion, it appears striking that—even after hundreds of seemingly supportive studies—conclusive evidence for any model is lacking (Gieseler, Loschelder, & Frieze, 2019; Inzlicht & Frieze, 2019).

Theoretical Approaches

Several theoretical models make identical predictions for *behavioral* ego depletion effects. The strength model (Baumeister & Vohs, 2016) and the process model (Inzlicht &

Schmeichel, 2012) are the two most prominent ones.¹ These models differ, however, in their assumptions *why* ego depletion effects occur.

The strength model (Baumeister & Vohs, 2016; Baumeister, Vohs, & Tice, 2007) makes two basic assumptions: (1) self-control is a domain-general phenomenon and (2) it relies on a limited (but otherwise unspecified) resource that is reduced whenever a person faces pronounced mental demand (Schmeichel, 2007). This means that meeting mental demand in one domain reduces the resource and leads to an impairment of subsequent self-control performance in other domains as well. According to the strength model, situational factors may counteract mild depletion effects by mobilizing additional effort to recruit resources.

The process model (Inzlicht & Schmeichel, 2012; Inzlicht, Schmeichel, & Macrae, 2014) assumes that facing mental demand leads to a loss of motivation to exert oneself further—people feel like doing something easier and more pleasurable. This is often described as a shift from “have-to goals” to “want-to goals”. Thus, according to the model, after meeting mental demand people are still *able* but no longer *motivated* to exert further self-control. Hence, performance is impaired after a demanding task. The process model posits that it is possible to bring performance back by reallocating motivation to self-control-demanding tasks.

In sum, both models predict the same on the level of observable behavior: The initial exertion of high mental demand leads to a decline in self-control performance. On this basis, it is difficult (if not impossible) to test the models’ diverging predictions concerning the underlying mechanisms (i.e., depleted resource versus shifts in motivation). In the present study, we

¹ Alternative models are the opportunity cost model (Kurzban, Duckworth, Kable, & Myers, 2013), the labor/leisure tradeoff concept (Kool & Botvinick, 2014), or the central governor model (Evans, Boggero, & Segerstrom, 2015).

therefore extended the traditional sequential task paradigm by a moderator and psychophysiological measures to empirically contrast the two models. We used a counting task to manipulate mental demand and a Stroop task to measure subsequent self-control performance. In addition, we included self-affirmation as a supposedly well-established moderator counteracting ego depletion, *while at the same time* assessing established psychophysiological indicators of invested mental effort. In combination, these extensions allow to differentiate between the models' theoretical assumptions.

Self-Affirmation

One fundamental human motive is to maintain a positive self-evaluation. Self-affirmation theory (Steele, 1988) suggests that in case of ego threat, affirming core aspects of the self can help to maintain a positive self-view (for a review, see Cohen & Sherman, 2014). Using self-affirmation as an intervention is beneficial in recognizing own bad habits (Harris, Mayle, Mabbott, & Napper, 2007; Harris & Napper, 2005), changing health behavior (for a meta-analysis see Epton, Harris, Kane, van Koningsbruggen, & Sheeran, 2015), or in taking others' perspectives and being less obstinate about one's own convictions (Cohen et al., 2007; Loseman & van den Bos, 2012).

Relevant for present purposes, self-affirmation has repeatedly been found to counteract ego depletion effects (Huynh, Stefanucci, & Aspinwall, 2014; Schmeichel & Vohs, 2009; Storr & Sparks, 2016). Strength and process model again differ as to why this may be the case. Neither model talks about the counteracting role of self-affirmation specifically, but from the strength model's perspective, any manipulation that counteracts ego depletion will need to mobilize additional resources. In contrast, the process model asserts that ego depletion effects result from a loss of motivation and disengagement from the task—any counteracting manipulation needs to

restore peoples' motivation to original levels for subsequent tasks. Thus, for a given counteracting effect of self-affirmation both models suggest different underlying mechanisms that cannot be disentangled based on behavior alone. This becomes possible, however, by considering predictions on exerted mental effort.

Mental Effort

Mental effort can be defined as “the mobilization of resources to carry out behavior” at a given point in time (Gendolla & Wright, 2009, p. 134; for a nuanced discussion on the definition of mental effort see Massin, 2017). Several parameters influence how much mental effort people mobilize in a specific situation. For instance, the lower a participant's ability, the more effort an individual has to exert to complete a task successfully. Participants' ability could, for example, be lower due to having previously faced high mental demand (Wright, Mlynski, & Carbajal, 2019). Also, participants only mobilize resources if engaging in a task is perceived worthwhile (Brehm & Self, 1989; Gendolla & Richter, 2010). Accordingly, disengagement from a task should be reflected in lowered mental effort investment. A lot of this research was conducted in the context of motivational intensity theory (Brehm & Self, 1989; Richter, Gendolla, & Wright, 2016; Wright et al., 2019). The theory makes nuanced predictions about mental effort investment as a function of various boundary factors. We will come back to this theory and its implications for the present research in the discussion.

Psychophysiological indicators of mental effort. The previous sections raise the question how researchers can measure invested mental effort—particularly given that people are often unaware of internal processes or unwilling to truthfully report them due to social desirability and self-presentational tendencies (Hofmann & Wilson, 2010; Nisbett & Wilson, 1977; van de Mortel, 2005). As a result, self-reports are limited in reliably assessing and/or

reporting participants' inner mental processes, such as (a lack of) motivation and (a lack of) mental effort invested in a given activity. To circumvent these problems associated with self-reports, we used psychophysiological measures (i.e., SBP and PEP), as established indicators of motivation and invested mental effort (Wright, 1996).

The mobilization of effort physiologically goes along with increased activation of the sympathetic nervous system. Its antagonist, the parasympathetic nervous system, is responsible for physiological deactivation. Higher mental effort is reflected by enhanced sympathetic cardiovascular activity relative to a resting baseline (Richter et al., 2016; Wright, 1996). However, the parasympathetic nervous system can mask sympathetic influences on the heart. Therefore, psychophysiological indicators of mental effort should ideally be maximally influenced by the sympathetic and minimally influenced by the parasympathetic nervous system. Two indicators are regarded as particularly suitable: systolic blood pressure and the pre-ejection period. SBP is the maximum pressure of a pulse in the vascular system (measured in mmHg). SBP increases with growing sympathetic influence due to the impact of cardiac contractility on cardiac output. In contrast, PEP reflects the contraction force of the heart: The time interval between the onset of the ventricular depolarization (i.e., the heart receives an electrical signal to contract) and the opening of the aortic valve when blood starts to flow (measured in milliseconds). PEP decreases—faster blood flow initiation after the signal to contract—with growing sympathetic influence. Both SBP and PEP are valid and reliable indicators of sympathetic influences on the heart and often used as indicators of invested mental effort (e.g., Gendolla, Wright, & Richter, 2012; Richter & Gendolla, 2009). In theory, PEP is the purest non-invasive indicator of sympathetic impact on the heart currently available, but most studies have used changes in SBP as indicator of invested mental effort (Richter, Gendolla, & Wright, 2016).

In previous research, increasing task difficulty led to a steady increase in SBP (more mental effort), but only as long as participants perceived task success as possible. If task success was perceived as too difficult, mental effort did not increase, indicating disengagement (Richter, Friedrich, & Gendolla, 2008). In a similar vein, participants showed increased SBP when working on a difficult version of a mentally demanding task compared to an easier version, indicating increased mental effort (Wright et al., 2007). A similar pattern emerged for PEP: Participants' PEP decreased when working on increasingly difficult versions of the Sternberg task (a short-term memory task), but increased when the task was unsolvable (indicating disengagement, Richter et al., 2008).

Competing predictions from the strength versus process model. Neither the strength nor the process model makes specific predictions about mental effort as a function of moderating factors. Nevertheless, it is possible to derive such predictions from the models' basic tenets.² These allow to contrast competing predictions of the two models. Proponents of the strength model assert that the "crucial prediction that exerting self-control reduces motivation to perform well on the second task has not been supported" (Baumeister & Vohs, 2016, p. 104). They emphasize that "[...] explaining all depletion phenomena based on motivation [...] seems untenable" (Baumeister & Vohs, 2016, p. 105). Thus, although the model allows for exceptions, it predicts no difference in exerted mental effort as a function of previous self-control exertion, provided that no counteracting factor (such as self-affirmation) is present. After an exertion of

² Please note that it may be possible to derive different predictions from the strength and the process models when considering research based on motivational intensity theory (Brehm & Self, 1989; see discussion section).

self-control, participants should be less *able* to exert further control—this should, however, not be reflected in reduced levels of exerted mental effort.

Predictions of the process model are different: “initial acts of control lead people to become less motivated to engage in further deliberative control” (Inzlicht & Schmeichel, 2012, p. 451). Thus, mental effort should decline in the second task indicating disengagement relative to a group that faced *low demand* in the initial task (see Figure 1: Mental effort).

Adding self-affirmation to the experimental design reveals another difference in predictions between the two models: According to the strength model, any intervention counteracting ego depletion effects needs to overcome the partial loss of resources to allow for non-impaired performance. This makes performing well on subsequent tasks particularly strenuous. Thus, the strength model predicts that self-affirmation causes people who have previously faced high demand to invest *more* mental effort compared to those who have faced low demand to show similar levels of self-control performance in the second task.

By contrast, the process model assumes that after facing high demand, no resource but peoples’ motivation to invest effort is reduced. Any intervention counteracting ego depletion needs to re-establish motivation. No additional effort is needed above-and-beyond the effort exerted by participants who faced low demand in the first task. Thus, the process model predicts no difference as a function of prior demand in the self-affirmed condition (see Figure 1: Mental effort).

Figure 1. Predictions based on the strength model and the process model for Stroop interference (left panel) and invested mental effort (right panel). Experimental design: Mental demand (*high* vs. *low*) $\times$ self-affirmation (*yes* vs. *no*). Pre-registered contrast weights are shown for both the behavioral measure (Stroop interference)—for which both models predict the same outcome—and the psychophysiological indicators of mental effort (Furr & Rosenthal, 2003).

The Present Research

The field of ego depletion research is highly contested, and particularly mistrusted claims need particularly trustworthy evidence. To regain trust, researchers called for theory-oriented research and transparent empirical work that follows open science principles (Friesen et al., 2019; Lurquin & Miyake, 2017). In the present research, we sought to conduct a study that would make a contribution—irrespective of the specific empirical results—due to its theory-driven model comparison approach and its adherence to open science principles. Specifically, we created a context that allowed to contrast competing predictions of the strength and the process model. To this end, we added the moderator self-affirmation and assessed invested mental effort during the sequential task paradigm. This design allowed us to directly compare the suitability of both models to explain the empirical pattern of results—a crucial quality for the advancement of the

field. In addition, the present study provides the first pre-registered conceptual replication attempt of the (presumably) established moderator self-affirmation counteracting ego depletion effects.

Methods

Pre-Registration

The pre-registration to this study can be found at osf.io/my5x2. Deviations from the pre-registration are explicitly noted in the manuscript.

Materials, Data, and Code

All materials, data, and code can be found in the OSF project associated with this study at osf.io/kxb2c/. All analyses were conducted in *R* (R Core Team, 2019); for specific packages, please see the analysis script.

Reporting

We report all focal measures, how we determined our sample size, all data exclusions (if any), and all manipulations in the study. All non-focal measures and analyses and some of the pre-registered exploratory analyses are reported in the supplementary material.

Ethical Approval

The study was approved by the local ethics committee.

Participants and Design

We tested 179 participants ($M_{\text{age}} = 22.79$, $SD = 3.27$; 128 females; no psychology students) in a 2 (mental demand: high vs. low) $\times$ 2 (self-affirmation: no vs. yes) design with both factors varied between persons. Our main dependent variables were (1) Stroop interference (based on error rates) and (2) mental effort assessed via SBP and PEP. We restricted the sample to right-handed participants as the psychophysiological measurement was done on the left arm.

Sample size rationale and sequential stopping. We based our sample size calculation on the mean empirical effect of $f = 0.21$ for the interaction effect between mental demand and self-affirmation found by Schmeichel and Vohs (2009; Studies 1 and 4). We pre-registered an $\alpha = .05$ and a minimum statistical power of $1 - \beta = .80$. Using these values in an a-priori power analysis with G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) resulted in a minimum sample size of $N = 180$ participants. To save resources, we employed Bayes Factor Design Analysis (BFDA, Schönbrodt, Wagenmakers, Zehetleitner, & Perugini, 2017). This sequential procedure allows to examine the data at predefined points in the data collection process using Bayes Factors. If, at one of these points, a predefined threshold is met, data collection is stopped. Otherwise, data collection continues in pre-determined increments. We used $BF_{10} = 6$ as evidential threshold in favor of the alternative hypothesis and $BF_{10} = 1/10$ as evidential threshold in favor of the null hypothesis for the interaction effect of Stroop performance (checking for the expected pattern of the interaction). As pre-registered, we started this process at $N = 80$ and continued data collection until we reached the full sample (neither of the thresholds was met before).³

Procedure

Participants were recruited via notices and approached directly on campus. Data collection took place in individual laboratory sessions. Upon arrival, the participant filled out an informed consent describing, among others, the electrode placement and blood pressure cuff procedures. The experimenter then attached ten pre-gelled disposable electrodes to participants' neck and torso for impedance cardiography measurement (PEP) and a blood pressure cuff on

³ Due to a mistake in the documentation, only 179 participants were tested.

their left upper arm (SBP). The sex of experimenter and participant were matched to make participants feel more comfortable. When all electrodes were successfully connected to the MP160 BIOPAC System (*Biopac Systems Inc.*, 2019), the recording was started and the experimenter launched the computerized tasks using the software Inquisit (*Inquisit 5*, 2016). To ensure that the experimenter was blind to the experimental conditions, the participant entered her/his ID themselves, which s/he drew randomly from an envelope containing all IDs for the current sequential-stopping phase (1-80; 81-100; 101-120; 121-140; 141-160; 161-180).

During the first ten minutes, a baseline measure for SBP and PEP was assessed. Participants were instructed to move sparsely and to put their feet in a box under their desk, designed to restrict excessive movement of their feet. After the baseline, participants practiced the Stroop task (the future dependent variable, 20 trials with feedback after every trial), followed by the manipulation of *mental demand* (*high* vs. *low*) using a counting task (*difficult* vs. *easy*). Participants then underwent the self-affirmation manipulation (detailed below). Subsequently, they worked on the Stroop task practiced before (dependent measure) and answered several questions. Finally, participants were debriefed, thanked, and paid for their participation.

Manipulated variables

Manipulation of mental demand. A counting task was used to manipulate mental demand (Kirschbaum, Pirke, & Hellhammer, 1993). In the *low demand* condition, participants counted upwards from zero in steps of two. Each number was entered in a new response field via the keyboard. The counting pace was comfortable, as each trial lasted 3,000ms before the next response field appeared. In case of blunder, participants were asked to continue as if nothing had happened. In the *high demand* condition, participants were asked to count backwards in steps of 13 as fast as possible starting from a random number between 4,020 and 4,820. There was no

time limit to account for individual differences in mathematical aptitude. In case of blunder, participants had to restart from a new random number. The counting task lasted 8 minutes.

Self-affirmation manipulation. Participants in the self-affirmation condition read a list of eleven values and were asked to rank them by personal importance. Participants then wrote an essay explaining why their highest ranked value is important to them and described a time in their lives when this value had been particularly important (Cohen, Aronson, & Steele, 2000). This manipulation is one of the most frequently used self-affirmation manipulations (McQueen & Klein, 2006) and has repeatedly been used successfully as a manipulation to counteract ego depletion (Schmeichel & Vohs, 2009; Storr & Sparks, 2016). In the control condition, participants were instructed to write an essay describing an ordinary, grey hole puncher placed on the desk in front of them in as much detail as possible (Miketta & Frieese, 2019). Describing neutral objects instead of writing about personally less important values has the benefit that it constitutes a similar kind of activity as in the self-affirmation condition, but is not concerned with values in any ways that could have unwanted downstream effects on the following task. Both essay tasks lasted 6 minutes.

Measured variables

Manipulation check mental demand. After the counting task, participants were asked, “How hard did you have to concentrate during the counting task?” and “How exhausting was it to work on the just finished counting task?” compared to a math exam of 30 minutes. Answers were given on 7-point-scales (1 = *much less than in an exam* to 7 = *just like in a math exam*; mean of 2 items; $\rho = .83^4$).

⁴ Spearman-Brown reliability coefficient, recommended for two item scales (Eisinga, Grotenhuis, & Pelzer, 2013).

Stroop task. A color Stroop task served as the behavioral dependent variable (Luethi et al., 2016). The words “red”, “yellow”, and “blue” were presented in three different font colors. Participants had to indicate the font color of the word as quickly as possible, while ignoring the literal meaning. The font color either matched (congruent trial) or did not match (incongruent trial) the literal meaning of the word. Each trial consisted of the presentation of a word for 1,500ms on a black screen followed by an inter-stimulus interval of 500ms. If a participant did not press a key during these 2,000ms a warning message appeared asking for a quicker reaction.

We created a modified version of the Stroop task. The word “yellow” served as an exception: Whenever “yellow” appeared, participants had to indicate the literal meaning of the word instead of its font color. This made sure that participants had to actually read each stimulus instead of looking at the periphery to detect the color of the stimuli without reading them, thereby circumventing the self-control demand of the task. Each participant completed 4 blocks of 45 trials each (56% congruent, 28% incongruent, 16% “yellow” exception rule) with no breaks between the blocks. The order of trials was pseudorandomized and fixed. The Stroop task lasted approximately 6 minutes.

Psychophysiological measures. Each psychophysiological indicator was measured during four experimental periods: Baseline, manipulation of demand, self-affirmation manipulation, and Stroop task.

Systolic blood pressure. We used a *GE Carescape Dinamap V100* to measure participants’ SBP every 60sec during the relevant experimental periods. For the baseline, we calculated the mean of all measures (only last 7 minutes). For the remaining tasks, we calculated the change in mean SBP during the respective task relative to the baseline.

Pre-ejection period. We used an *ECG100C* module to obtain the ECG signal and a *NICO100C* module to obtain the cardiac impedance signal dZ/dt both wired to a *MP150* polygraph (Biopac Systems Inc., Goleta, CA, USA). The sampling rate was 1 kHz. We equipped each participant with 10 spot electrodes. First, participants' skin was abraded for optimal contact and additional gel was applied to the electrodes. Next, the upper two voltage electrodes were placed on the left and right side of the base of the neck, the lower two on the right and left side of the torso at the level of the lower end of the sternum. The current electrodes were placed at a distance of 3cm from the respective voltage electrodes. The remaining two electrodes for the ECG signal were placed below the right collarbone and on the lowest left rib. Finally, we connected the leads, put them in loops and fastened them with adhesive tape for optimal signal quality (see supplementary material for an illustration).

We used the software *AcqKnowledge 4.3* (Biopac Systems Inc., Galeta, CA) to record and process the psychophysiological signal. The PEP for each of the relevant periods was determined and calculated using partially automated scripts. To detect the B point, we used the third derivative classification with the local maximum found within 300ms to the C point. As there are several possible algorithms to detect the B point, we used the method suggested as superior by research examining the efficacy of different detection algorithms (Árbol et al., 2017). The penultimate entire cycle of the baseline served as representative cycle for the automated analysis. For all tasks, we use PEP change relative to the baseline level.

Results

Manipulation Check (Pre-Registered, Confirmatory)

As expected, participants in the *high demand* conditions felt that the counting task required more concentration and was more exhausting than participants in the *low demand*

conditions ($t_{\text{one-sided}}[176.55] = -11.32, p < .001, d = -1.69, 95\%CI [-\infty, -1.41], M_{\text{high demand}} = 4.90, SD_{\text{high demand}} = 1.35, M_{\text{low demand}} = 2.64, SD_{\text{low demand}} = 1.33$).

Behavioral Self-Control Performance based on Stroop Interference

We pre-registered two different outlier-cutoffs for the Stroop interference. The primary, confirmative criterion— ± 2.5 SDs from the respective mean—is one that we have used in previous research (e.g., osf.io/t6v4a/). The secondary, exploratory criterion was ± 3 median absolute deviations (MAD, Leys, Delacre, Mora, Lakens, & Ley, 2019; Leys, Ley, Klein, Bernard, & Licata, 2013). MAD is sometimes preferred because it is based on a measure of central tendency—the median—not influenced by the very outliers it shall detect. We report results for both criteria.

As pre-registered, we excluded Stroop trials with reaction times $< 200\text{ms}$ ($N_{\text{trials excluded}} = 1$), Stroop trials with reaction time $> |2.5 \text{ SD}|$ from an individual's overall reaction time ($N_{\text{trials excluded}} = 756$), individuals whose total number of errors on congruent trials deviated more than the respective outlier-cutoff from the overall mean ($N_{\text{excluded}} = 5$), and individuals whose Stroop interference deviated more than the outlier-cutoff from the condition mean ($N_{\text{excluded}} = 4$).

Outlier-cutoff 2.5 SDs (pre-registered, confirmatory). In line with the predictions of both the strength and the process model (see Figure 1: Behavior), participants in the *non-affirmed* conditions performed worse in the Stroop task after high compared to low mental demand (Figure 3). However, this difference was not significant ($t_{\text{one-sided}}[80.49] = -1.59, p = .058, d = -0.35, 95\%CI [-0.79, 0.09]$; for descriptive statistics, see Table 1).

Contrary to predictions of both models, the self-affirmation manipulation did not counteract the effect of the ego depletion manipulation (pre-registered contrast: *high demand+non-affirmed* = +3; remaining three conditions = -1; Furr & Rosenthal, 2003; see

Figure 1: Behavior). In contrast, participants in the *self-affirmed* conditions showed similarly poor Stroop performance as participants in the *high demand+non-affirmed* condition. The pre-registered contrast thus did not fit the data ($F[1, 168] = 0.39, p = .536, f = 0.05$; see Figure 3; for descriptive statistics see Table 1).

Table 1

Stroop interference on errors (outlier cutoff 2.5 SDs from condition means).

		Self-affirmation		Overall
		No	Yes	
Mental demand	High	10.38 (6.70) $N = 41$	10.09 (7.47) $N = 45$	10.23 (7.07)
	Low	8.15 (6.13) $N = 43$	10.61 (7.11) $N = 41$	9.37 (6.71)
	Overall	9.24 (6.47)	10.34 (7.26)	

Note. M (SD). Stroop interference: % errors on incongruent trials minus % errors on congruent trials.

Figure 2. Stroop task: Raincloud plots (from left to right: jittered raw data for all participants, barplots [M and $\pm 1 SEM$], and probability density of the data) showing interference on errors (% errors on incongruent trials - % errors on congruent trials) as a function of mental demand in the first task and the self-affirmation condition.

Bayesian model comparisons (exploratory)⁵. Comparing our pre-registered model (*high demand+non-affirmed > remaining three conditions equal*) against a model with no differences in Stroop performance (“all-equal”) resulted in a $BF = 4.18$ in favor of the “all-equal” model. The best fit was provided by the model specified as *low demand+non-affirmed < remaining three conditions equal* compared to the pre-registered model ($BF = 5.57$). Thus, the data most supported the model stating that participants in the *low demand+non-affirmed* condition performed better than participants in the remaining three conditions who all showed similar performance.

Outlier-cutoff 3 MADs (pre-registered, exploratory). As predicted by both the strength and the process model, participants in the *non-affirmed* conditions performed significantly worse in the *high demand* condition than in the *low demand* condition ($t[79.63] = -1.76, p = .041, d = -0.39, 95\%CI[-\infty, -0.02]$).

Consistent with analyses relying on the SD outlier-cutoff, self-affirmation did not counteract the detrimental effects of high mental demand. Participants in both *self-affirmed* conditions showed similar performance as participants in the *high demand+non-affirmed* condition. Again, the pre-registered contrast did not fit the data ($F[1, 168] = 0.77, p = .381, f = 0.07$; for descriptive statistics see Table 2).

Bayesian model comparisons (exploratory). Again, the best fit was provided by the model specified as *low demand+non-affirmed < remaining three conditions equal* compared to the pre-registered contrast ($BF = 4.76$). The “all-equal” model fitted the data similarly well as

⁵ A Bayes Factor of $BF = X$ indicates that the hypothesis is X-times more likely than the hypothesis compared to given the observed data (for an introduction, see Hoijtink, Mulder, van Lissa, & Gu, 2019). All Bayes Factors were obtained using informative hypothesis testing with the *bain* package in R using default settings (Hoijtink et al., 2019).

our pre-registered contrast ($BF = 1.53$). Again, our data provide most support for the model assuming that participants in the *low demand+non-affirmed* condition performed better than participants in the remaining three conditions.

Table 2

Stroop interference based on errors (outlier cutoff ± 3 MADs)

		Self-affirmation		Overall
		No	Yes	
Mental demand	High	10.79 (6.95) <i>N</i> = 41	10.79 (7.96) <i>N</i> = 45	10.79 (7.45)
	Low	8.26 (6.13) <i>N</i> = 43	10.03 (6.10) <i>N</i> = 41	9.12 (6.15)
	Overall	9.49 (6.63)	10.43 (7.11)	

Note. *M* (*SD*). Stroop interference: % errors on incongruent trials - % errors on congruent trials.

Interim summary. As expected, participants in the *non-affirmed* conditions showed impaired performance in the *high demand* compared to the *low demand* condition (although this effect fell just short of significance using one of the two outlier criteria). In contrast to our expectations and to previous research (Huynh et al., 2014; Schmeichel & Vohs, 2009), self-affirmation did not counteract the detrimental effect of a demanding first task. Instead, self-affirmed participants performed similarly poorly as non-affirmed participants after high demand.

Mental Effort

The predictions of the strength and the process model differ concerning participants' investment of mental effort. Therefore, we had planned to contrast the predictions of both models on mental effort as indicated by SBP and PEP. As pre-registered, we excluded participants deviating more than 2.5 *SDs* from the respective condition mean. Using our exploratory outlier cutoff of 3 *MADs* did not meaningfully change the results (see supplementary material).

Systolic blood pressure (pre-registered, confirmatory). As expected, participants in the *high* compared to the *low-demand* conditions exerted more mental effort during the manipulation of mental demand as indicated by higher SBP relative to the baseline ($t[165.38] = -4.65, p < .001, d = -0.71, 95\%CI [-\infty, -0.45]$). This speaks to the strength of our manipulation in terms of required mental effort and suggests that the SBP measurement was successful in picking up participants' increased effort in the *high* versus the *low demand* conditions.

Testing the different predictions derived from the strength model and the process model was technically possible, but not theoretically meaningful after learning that the behavioral performance pattern did not match the models' predictions. Accordingly, the pre-registered contrasts for invested mental effort during the Stroop task did not fit the data (strength model predictions: $F[3, 174] = 0.53, p = .661, f = 0.10$; process model predictions: $F[3, 174] = 0.53, p = .661, f = 0.16$; see Figure 4; for descriptive statistics see Table 3).

Bayesian model comparisons (exploratory). We used Bayesian informed hypothesis testing to examine if the strength model, the process model or an alternative fit the data best. The best fit was indicated for the “all-equal” model (all BFs > 10). The models derived from the predictions of the strength and the process model provided no better fit to the data than the “*low demand+non-affirmed < remaining three conditions equal*” model (BF = 1.12 and BF = 1.34; see Table 3).

When comparing the *no affirmation* groups only, the best fit was indicated for the “both-equal” model (represents the predictions of the strength model) over the predictions of the process model (less mental effort in the *high demand* condition, BF = 4.58).

Figure 3. Raincloud plots (from left to right: jittered raw data for all participants, barplots [M and ± 1 SEM], and probability density of the data) show systolic blood pressure reactivity (change scores) during the Stroop task relative to the baseline as a function of *mental demand* and *self-affirmation*. Higher values indicate increased invested mental effort.

Table 3

Systolic blood pressure (SBP) and SBP reactivity (change scores)

1) Systolic blood pressure (SBP) in mmHg. A): Absolute values, B) – D): Reactivity (change score) relative to the resting baseline

A) Mean SBP during baseline (absolute values in mmHg).				
		Self-affirmation		Overall
		No	Yes	
Mental demand	High	113.14 (9.21) N = 42	110.74 (7.56) N = 45	111.90 (8.43)
	Low	110.28 (7.94) N = 45	111.96 (10.27) N = 45	111.12 (9.17)
	Overall	111.66 (8.64)	111.35 (8.99)	
B) SBP reactivity: Change score Manipulation of mental demand (counting task) minus Baseline.				
Mental demand	High	6.54 (5.27) N = 86		
	Low	3.13 (4.39) N = 89		
C) SBP reactivity: Change score Self-affirmation manipulation minus Baseline.				
		Self-affirmation		Overall
		No	Yes	
Mental demand	High	6.50 (6.95) N = 43	6.09 (3.90) N = 44	6.29 (5.59)
	Low	4.28 (6.06) N = 45	6.24 (4.88) N = 43	5.24 (5.57)
	Overall	5.36 (6.57)	6.16 (4.39)	
D) SBP reactivity: Change score Stroop task minus Baseline.				
		Self-affirmation		Overall
		No	Yes	
Mental demand	High	6.92 (6.00) N = 43	5.61 (5.88) N = 44	6.25 (5.94)
	Low	5.76 (7.00) N = 46	6.22 (4.90) N = 45	5.99 (6.03)
	Overall	6.31 (6.35)	5.92 (5.39)	
2) Bayesian model comparisons for invested mental effort as indicated by SBP (reactivity)				
	Process model over ...	low demand+non-affirmed < remaining 3 conditions equal over ...		All equal over ...
Strength model	BF = 0.83	BF = 1.12		BF = 12.19
Process model		BF = 1.34		BF = 14.06
low demand+non-affirmed < remaining 3 conditions equal				BF = 10.88

Note. M (SD). Number of participants excluded: 1A): N = 2, 1B): N = 4, 1C): N = 1, 1D): N = 4.

Pre-ejection period (pre-registered, confirmatory). We did not find the expected difference in invested mental effort between conditions during the manipulation of mental demand ($d = -0.11$, 95%CI [-0.44, 0.22], $M_{\text{high demand}} = -0.78$, $SD_{\text{high demand}} = 6.80$, $M_{\text{low demand}} = -1.54$, $SD_{\text{low demand}} = 7.18$). Thus, the PEP measurement did not reveal the increased mental effort that was necessary to work on the counting task in the *high* compared to the *low demand* condition contrary to the questionnaire-based manipulation check and SBP reactivity. We therefore stopped the analysis of PEP at this point as there was no evidence that it picked up the differential levels of mental effort exerted by participants in the *high* versus *low demand* conditions.

Table 4

Pre-ejection period (PEP) in milliseconds

<i>A) Mean PEP during baseline (absolute scores in ms).</i>				
		Self-affirmation		<i>Overall</i>
		No	Yes	
Mental demand	High	109.88 (13.22) <i>N</i> = 38	111.76 (14.37) <i>N</i> = 41	<i>110.86 (13.77)</i>
	Low	113.17 (17.14) <i>N</i> = 42	111.32 (15.22) <i>N</i> = 36	<i>112.31 (16.21)</i>
	<i>Overall</i>	<i>111.61 (15.40)</i>	<i>111.55 (14.68)</i>	
<i>B) PEP reactivity: Change score Manipulation of mental demand minus Baseline.</i>				
Mental demand	High	-0.78 (6.80) <i>N</i> = 75		
	Low	-1.54 (7.18) <i>N</i> = 72		

Note. *M* (*SD*). Number of participants excluded: A): 22, B): 32.

SBP progression over the course of the study (exploratory). All pre-registered analyses relating to mental effort referred to reactivity (i.e., change) relative to the baseline measurement. On an exploratory basis, we examined SBP progression over the course of the study, that is, relative to the previous task in the experimental procedure (see Figure 4; for descriptive statistics see Table 5).

Mental demand manipulation. Figure 4 illustrates the ongoing SBP progression; it first shows that—relative to baseline levels of SBP—high demands led to a starker increase of SBP reactivity (black line) than low demands (grey line). There are only two conditions here because the manipulation of self-affirmation only followed thereafter.

Self-affirmation manipulation. Relative to the previous task (mental demand manipulation), participants showed a stronger increase in mental effort while affirming core personal values compared to describing the hole puncher (see upward progression for dotted

lines in Figure 4; main effect self-affirmation: $F[1, 175] = 12.08, p = .001, \eta_p^2 = 0.07$; for descriptive statistics see Table 5A). This increase in SBP was particularly pronounced for participants who completed the *low demand* counting task beforehand (main effect mental demand: $F[1, 175] = 19.38, p < .001, \eta_p^2 = 0.09$). This latter finding may reflect that it was easier for participants in the low demand condition, who initially exerted less effort to mobilize additional mental effort (potential ceiling effect for *high demand*). The interaction between *mental demand* and *self-affirmation* was not significant ($F[1, 175] = 0.15, p = .699, \eta_p^2 < 0.01$).

Stroop task. During the Stroop task and relative to the self-affirmation manipulation, participants in the *self-affirmed* conditions showed a decrease in invested mental effort—contrary to participants in the *non-affirmed* conditions (see decline for dotted lines in Figure 4; main effect self-affirmation: $F[1, 175] = 4.97, p = .027, \eta_p^2 = 0.03$; for descriptive statistics see Table 5B). Only participants in the *low demand+non-affirmed* condition showed a pronounced increase in invested mental effort during the Stroop task relative to the previous task (i.e., incline for continuous grey line). As only these participants showed superior performance during the Stroop task, these findings provide a possible explanation for the unexpected (lack of) behavioral effect of the presumed moderator self-affirmation: Participants in the *self-affirmed* conditions showed a stronger increase in invested mental effort during the self-affirmation manipulation relative to the previous task than those in the *non-affirmed* conditions. We did not expect the self-affirmation manipulation to evoke a more pronounced investment in mental effort relative to the control task. However, the additionally invested mental effort relative to the previous task might explain why participants subsequently invested relatively less effort during the Stroop task—and therefore why they did not perform better than participants in the *high demand+non-affirmed* condition. Alternatively, a parsimonious explanation for decreased mental effort in the

non-affirmed conditions may be a natural decrease due to the time elapsed. Obviously, this reasoning is post hoc and therefore exploratory.

Figure 4. SBP progression relative to the previous task_{X-1} over the course of the experiment. The more pronounced increase from Baseline to the mental demand manipulation for the two *high demand* conditions (black) versus the *low demand* conditions (grey) reflects the expected change in SBP relative to the Baseline. SBP progression from thereon indicates a markedly more pronounced reaction in the *self-affirmed* conditions (dotted lines) compared to the *non-affirmed* conditions (continuous lines). During the Stroop task, only participants in the *low demand+non-affirmed* condition (continuous grey line) invested more mental effort relative to the previous task.

Table 5

SBP progression over the course of the study

<i>A) SBP progression: Self-affirmation manipulation relative to mental demand manipulation</i>				
<i>Descriptive statistics</i>		Self-affirmation		<i>Overall</i>
		No	Yes	
Mental demand	High	-1.84 (4.18) <i>N</i> = 43	0.72 (4.11) <i>N</i> = 45	-0.53 (4.32)
	Low	1.27 (3.19) <i>N</i> = 46	3.33 (5.59) <i>N</i> = 45	2.29 (4.63)
	<i>Overall</i>	-0.23 (4.00)	2.03 (5.05)	
<i>B) SBP progression: Stroop relative to self-affirmation manipulation</i>				
<i>Descriptive statistics</i>		Self-affirmation		<i>Overall</i>
		No	Yes	
Mental demand	High	0.29 (3.39) <i>N</i> = 43	-0.70 (4.80) <i>N</i> = 45	-0.22 (4.18)
	Low	1.07 (3.78) <i>N</i> = 46	-0.92 (5.69) <i>N</i> = 45	0.08 (4.89)
	<i>Overall</i>	0.69 (3.60)	-0.81 (5.24)	

Note. *M* (*SD*). No outliers excluded.

Discussion

The main aim of this study was to contrast competing predictions from two theoretical accounts that explain ego depletion effects in psychologically different ways: the strength model (Baumeister & Vohs, 2016) and the process model (Inzlicht & Schmeichel, 2012). Both models predict poorer self-control performance after facing high demand, but they provide markedly different explanations for the same behavioral phenomenon. To contrast these competing predictions, we combined the traditional sequential task paradigm with a moderator approach and psychophysiological indicators of mental effort.

Disentangling Two Theoretical Approaches

The prerequisite to contrast the predictions of the two models concerning underlying mechanisms was that we would replicate a presumably established moderator effect: self-affirmation should counteract ego depletion on the behavioral level. Despite evidence suggesting otherwise (Huynh et al., 2014; Schmeichel & Vohs, 2009; Storr & Sparks, 2016), the affirmation of core personal values seemed not to have a counteracting effect. Although we found moderate evidence supporting the traditional ego depletion effect in the *non-affirmed* conditions, *self-affirmed* participants who had previously worked on a demanding counting task did not show improved self-control performance during the Stroop task. To the contrary, performance in the two self-affirmed conditions was similarly poor as performance of participants who had engaged in a demanding task without subsequent self-affirmation.

Even if—due to the unexpected effect of the self-affirmation manipulation—we could not test the competing patterns for all four experimental conditions, our results for invested mental effort provide preliminary evidence as to the fit of the two models, particularly for the *non-affirmed* conditions. First of all, the robust effect of the mental demand manipulation on SBP reactivity as well as on self-reports suggests that SBP was a suitable measure of mental effort. PEP reactivity, by contrast, did not capture the more pronounced mental effort investment for participants in the *high* versus *low demand* conditions. We therefore refrained from interpreting PEP measures any further.

Concerning the emerging pattern in the Stroop task for participants in the *non-affirmed* conditions, the data on invested mental effort as indicated by SBP reactivity provided less support for the process model than for the strength model: Participants in the *high demand+non-affirmed* condition did not invest less mental effort than participants in the *low demand+non-*

affirmed condition (see exploratory Bayesian model comparisons). This is in line with the predictions we derived from the strength model but not with those we derived from the process model that predicts a *decrease* in invested mental effort due to decreased motivation after the highly demanding task without self-affirmation. Although preliminary, this finding is one of the first pieces of evidence for one model over the other in a systematic attempt to pit predictions of the models against each other. However, please note that these were predictions that we derived from the models. The models do not explicitly talk about how moderators influence mental effort.

Unexpected Effect of the Self-Affirmation Manipulation

We expected self-affirmation to counteract a behavioral ego depletion effect and to lead to similar performance as for participants who initially engaged in a hardly demanding task. However, after self-affirmation, participants performed poorly on the Stroop task. Although the reasons for this unexpected finding must remain speculative, there are possible explanations. First, a concrete versus abstract mindset induced by the self-affirmation may have played a role: Participants not affirming core values focused on a specific object (hole puncher) for several minutes with a narrow focus of attention (for an overview of global versus local processing, see Förster & Dannenberg, 2010). This narrow focus might have been beneficial for the Stroop task that requires a focused, narrow mindset instead of a global, abstract mindset. By contrast, affirming core personal values may have induced a more global mindset. In previous studies on the counteracting role of self-affirmation on the ego depletion effect, affirming core personal values benefited tasks as the cold pressor challenge and delay of gratification (Schmeichel & Vohs, 2009). Potentially, value affirmation may be beneficial in these cases as pain tolerance and short-term sacrifice in favor of future gains might profit more from the “big picture” that the self-

affirmation manipulation may have evoked rather than the focus on details (e.g. how much it hurts and how long it takes). This is in line with previous research suggesting higher construal level as a mechanism potentially underlying the counteracting effect of self-affirmation on ego depletion phenomena (see Schmeichel & Vohs, 2009). Conversely, an abstract mindset may have impaired participants performance in the Stroop task that may benefit from a concrete mindset. Corroborating our reasoning, recent research argues that people are able to distinguish between tasks that profit from *low-level* versus *high-level* construal and to prepare themselves accordingly to promote performance (Nguyen, Carnevale, Scholer, Miele, & Fujita, 2019). Most relevant to present purposes, this work suggests that people understand that a concrete mindset is beneficial for performance on a Stroop task.

To test the idea that the self-affirmation manipulation may have induced different mindsets, we coded the essays that participants wrote for their abstractness on an exploratory basis (verbal abstractness scores based on ratings of 40 thousand words by Brysbaert, Warriner, & Kuperman, 2014). In line with our speculation, essays written while confirming one's core values were more abstract opposed to while describing the hole puncher ($t(57.16) = 4.53, p < .001, d = 1.16$), see supplementary material for details).

Second, compared to their most important values in life as family and friends, participants may have felt that the task was hardly worth the effort. Thus, disengagement due to perceived low success importance could explain their performance. If this were the case, the results could be interpreted in favor of the process model: As participants were no longer motivated, they showed worse performance in the Stroop task.

In sum, these exploratory speculations pave the way for a new and testable hypothesis concerning the counteracting effect of self-affirmation on ego depletion effects: Self-affirmation

may be beneficial for performance on subsequent self-control tasks that profit from an abstract mindset (such as making decisions about the future in a delay-of-gratification task). It may be detrimental, however, for tasks that profit from a narrow focus of attention—such as the Stroop task. Future research might investigate this hypothesis by experimentally varying the dependent variable. Such work would also contribute to the discussion about the suitability of various self-control-related dependent variables in ego depletion research and their often low correspondence (Duckworth & Kern, 2011; Friese et al., 2019; Wennerhold & Friese, 2020).

Furthermore, our exploratory results on invested mental effort as indicated by SBP progression over the course of the study suggest that participants invested more mental effort during the affirmation of core personal values and less in the following Stroop task. Thus, as the value affirmation might have been more mentally demanding than the control task and as *self-affirmed* participants invested less mental effort during the Stroop task, it may not be surprising that their performance was impaired and comparable to those of participants in the *high demand+non-affirmed* condition. This speculation is hinted at by the data and post hoc analyses of SBP progression. Future research may systematically investigate this possibility.

Insights Offered by the Motivational Intensity Theory

Motivational intensity theory is concerned with determinants of effort mobilization in goal pursuit (Richter et al., 2016). According to this theory, effort mobilization depends on subjective difficulty and success importance. As the present study was intended to test competing predictions of two other theoretical models from the ego depletion literature, we did not systematically test the effects of the determinants specified by motivational intensity theory. However, we nonetheless discuss some considerations based on this nuanced theoretical framework:

First, effort should rise with difficulty if task difficulty is known—but only as long as success is possible and worthwhile. As participants practiced the Stroop task and received error feedback at the beginning of the study, the task may be assumed to be of known difficulty. Second, from the perspective of motivational intensity theory, subjective difficulty may have decreased after high demand in the first task (provided demand was high enough). According to the theory, decreased subjective difficulty should lead to increased mental effort in the subsequent task as long as subjective difficulty is not too high and success worthwhile (see Wright et al., 2019). Thus, if we assume that task difficulty was known but not too high, that subjective difficulty increased after facing high demand and that only for affirmed participants the task was worthwhile, motivational intensity theory may have predicted for invested mental effort that participants in the *non-affirmed* conditions would have disengaged, and that participants in the *high demand+affirmed* condition would have invested more mental effort than those in the *low demand+affirmed* condition due to lower ability but equally high success importance. This reasoning is made in hindsight and alternative predictions are possible depending on the assumptions for the various determinants of mental effort specified by motivational intensity theory.

Recently, scholars from motivational intensity theory provided an intriguing “outsider’s perspective” on ego depletion research. Particularly relevant for present purposes, they proposed that ego depletion effects may only emerge in a behavioral-restraint “sweet spot” (Wright et al., 2019). Specifically, the sweet spot—“a multidimensional motivational space wherein rested study participants view restraint as possible and worthwhile and fatigued study participants do not” (Wright et al., 2019, p. 6)—provides an explanation similar to our interpretation of the present findings. Participants in the *self-affirmed* conditions may not have seen restraint in the

Stroop task as worthwhile. Thus, even if they may have been able (i.e., sufficiently rested) to master the Stroop task's difficulty, a lack of success importance may have reduced the amount of effort invested and ultimately impaired task performance.

Limitations

Several limitations of our study deserve attention. First, the behavioral ego depletion effect was not significant based on the outlier cutoff of $2.5SDs$, although descriptively as expected and of small-to-moderate effect size ($p = .058$, $d = -0.35$). However, the effect did emerge significant as predicted when excluding outliers based on the pre-registered exploratory outlier criterion using median absolute deviations. This criterion is less influenced by extreme values and is therefore recommended by some researchers over outlier criteria based on standard deviations from the mean (Leys et al., 2019, 2013). In addition, it is important to keep in mind that our pre-registered power analysis focused on the predicted interaction of mental demand and self-affirmation. For the simple two-group comparison we had 80% statistical power to detect and effect of $d \geq 0.55$.

Second, our psychophysiological indicators of invested mental effort showed mixed results in terms of convergent validity. During the manipulation of mental demand, only SBP indicated that, as expected, participants in the *high demand* conditions invested more mental effort than participants in the *low demand* conditions. By contrast, for PEP there were no differences between conditions. As the SBP findings and the self-reports strongly speak to the strength of the mental demand manipulation, we would have expected differences in PEP as well. We therefore did not analyze PEP change any further. Please note that we did not visually inspect B-points as is usually recommended. This is due to the large number of heart contractions per person (27 minutes of psychophysiological recording) and the substantial sample size which

would have required to visually inspect more than 300,000 B-points. This was clearly unfeasible, but might have contributed to the lack of sensitivity of this measure.

Conclusion

We sought to contrast competing predictions of the strength and the process model regarding underlying mechanisms that cause ego depletion effects. The study also provides a pre-registered replication attempt of the hypothesis that self-affirmation counteracts ego depletion effects. Unexpectedly, the self-affirmation manipulation had a negative effect on self-control performance. This limited our ability to contrast the models' competing predictions. At the same time, the effects of the self-affirmation manipulation led to a testable follow-up hypothesis for future research about when self-affirmation may help versus hinder subsequent self-control performance, thus contributing not only to the literature on ego depletion, but also on self-affirmation.

The lack of counteracting influence of self-affirmation prevented us from testing the pre-registered competing moderation patterns. Nonetheless, the non-affirmed control conditions—in terms of invested mental effort—favored the strength model. In line with the model, a Bayesian analysis provided moderate evidence for no differences between the two groups as a function of mental demands. In addition, exploratory analyses of the progression of invested mental effort over the course of the study suggested that such in-depths examinations may be a new and promising analysis for future research. More generally, psychophysiological measures as indicators of mental effort allow for a deeper understanding of the psychological processes involved. They further open new directions for ego depletion research to test theoretical assumptions that cannot be tested based on behavioral data alone.

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Supplement

Non-Focal Measures

We assessed self-reported mental fatigue at the beginning of the study and after the manipulation of mental demand. Final questions assessed morningness/eveningness, demographic information, self-rated data quality, strategies used during the Stroop task, experience with the Stroop task, presumed study purpose, visual impairment, and subjective perceptions of the psychophysiological measurement. The full list of items and their English translations can be found in the associated OSF project (<https://osf.io/kxb2c/>).

Electrode Placement

Figure 5. Spot electrode placement with voltage electrodes located at the base of the neck and at the level of the lower end of the sternum. Current electrodes were placed at a distance of 3cm from the respective voltage electrodes. ECG electrodes were placed below the right collarbone and on the lowest left rib. For optimal quality, the leads were put in loops and fastened with adhesive tape.

Pre-Registered Exploratory Analyses

Lay theories about willpower. The effect of mental demand on Stroop interference (errors) was not moderated by participants' lay theories about willpower ($\alpha = 0.86$; see Table 1).

Table 1

Lay theories about willpower: Moderation of the effect of mental demand on Stroop interference (errors)

	<i>b</i>	<i>SE B</i>	<i>t</i>	<i>p</i>
Mental demand	0.50	1.17	0.43	.667
Lay theories about willpower (exhaustion)	0.54	0.78	0.70	.487
Mental demand $\times$ Lay theories	0.39	1.18	0.33	.744

Note. $N = 174$. $R^2 = .01$. Continuous predictors are mean-centered and scaled by 1 *SD*.

Trait self-control. The effect of mental demand on Stroop interference (errors) was not moderated by participants' trait self-control ($\alpha = 0.85$; see Table 2).

Table 2

Trait self-control: Moderation of the effect of mental demand on Stroop interference (errors)

	<i>b</i>	<i>SE B</i>	<i>t</i>	<i>p</i>
Mental demand	0.50	1.15	0.43	.667
Trait self-control	-0.94	0.88	-1.07	.286
Mental demand $\times$ Trait self-control	-0.72	1.17	-0.62	.535

Note. $N = 174$. $R^2 = .03$. Continuous predictors are mean-centered and scaled by 1 *SD*.

SBP reactivity: Outlier-cutoff 3 MADs. As expected, participants showed no difference in SBP during the baseline (2×2 ANOVA with mental demand $\times$ self-affirmation: all $ps > .130$). Also, as expected, participants in the high compared to the low demands conditions exerted more mental effort during the manipulation of mental demand—difficult versus easy counting task—as indicated by higher SBP relative to the baseline ($t[160.03] = -4.78$, $p < .001$, $d = -0.73$, 95%CI $[-\infty, -0.47]$). This speaks to the strength of our manipulation in terms of required mental effort and suggests that the SBP measurement was successful in picking up participants' increased effort in the high as compared to the low demand conditions.

During the self-affirmation manipulation, the four experimental conditions did not differ in invested mental effort (*mental demand* $\times$ *self-affirmation* ANOVA: all $ps > .118$). Also, there were no differences between conditions as indicated by SBP reactivity during the Stroop task—neither as a function of mental demand, nor as a function of self-affirmation or their interaction (all $ps > .259$; for descriptive statistics see Table 4).

Table 4

*Systolic blood pressure with outlier cutoff 3.0 MADs**1) Systolic blood pressure (SBP) in mmHg*

		Self-affirmation		<i>Overall</i>
		No	Yes	
Mental demand	High	113.82 (10.13) <i>N</i> = 43	110.74 (7.56) <i>N</i> = 45	112.25 (8.99)
	Low	110.84 (8.74) <i>N</i> = 46	111.96 (10.27) <i>N</i> = 45	111.40 (9.49)
	<i>Overall</i>	112.28 (9.50)	111.35 (8.99)	
<i>B) SBP Reactivity: Manipulation of mental demand.</i>				
Mental demand	High	6.54 (5.27) <i>N</i> = 86		
	Low	3.13 (4.07) <i>N</i> = 88		
<i>C) SPB Reactivity: Self-affirmation manipulation.</i>				
		Self-affirmation		<i>Overall</i>
		No	Yes	
Mental demand	High	6.50 (6.95) <i>N</i> = 43	6.35 (4.23) <i>N</i> = 45	6.42 (5.69)
	Low	3.96 (5.76) <i>N</i> = 44	6.24 (4.88) <i>N</i> = 43	5.09 (5.44)
	<i>Overall</i>	5.21 (6.47)	6.29 (4.53)	
<i>D) SBP Reactivity: Stroop task.</i>				
		Self-affirmation		<i>Overall</i>
		No	Yes	
Mental demand	High	6.78 (5.99) <i>N</i> = 43	5.27 (5.32) <i>N</i> = 44	6.02 (5.68)
	Low	5.74 (7.01) <i>N</i> = 46	6.22 (4.91) <i>N</i> = 45	5.98 (6.04)
	<i>Overall</i>	6.24 (6.52)	5.75 (5.11)	

Note. M (SD).

Additional Exploratory Analyses

Self-reported mental fatigue. Current mental fatigue was assessed with three items of the German version of the State Self-Control Capacity Scale (SSCCS; items 1, 12, & 15; Bertrams & Dickhäuser, 2009) and two additional items (“I feel mentally drained”, “I feel mentally efficient”) rated on a 7-point-scale (1 = *strongly disagree* to 7 = *strongly agree*). Current mental fatigue was assessed both at the beginning of the study and after the manipulation of mental demand (mean of 5 items; $\alpha = .89, .87$).

There were no significant differences concerning self-reported mental fatigue between the conditions neither at the beginning of the study (as a function of mental demand and/or self-affirmation, for inference statistics see Table 6) nor after the manipulation of mental demand (as a function of mental demand: $t[175.78] = 0.16, p = .876, d = 0.02, 95\%CI [-\infty, 0.32]$). For descriptive statistics see Table 6.

Fatigue baseline and Stroop performance / SBP reactivity Stroop task. Only for the condition *high demand+non-affirmed*, there was a significant correlation of fatigue at the beginning with Stroop performance (see Figure 6). There was no other significant correlation, neither for the other conditions (see Figure 6) nor for fatigue after the mental demand manipulation and Stroop performance (see Figure 7).

Including self-reported mental fatigue at the beginning of the study for the *non-affirmed* conditions did not change the conclusions for the Stroop task or for SBP reactivity during the Stroop task (see Table 2).

Table 6

Self-reported mental fatigue (mean of 5 items)

<i>A) At the beginning of the study.</i>			
<i>A.1) Descriptive statistics</i>			
		Self-affirmation	
		No	Yes
Mental demand	Low	3.38 (1.29)	3.06 (1.15)
	High	3.24 (1.21)	3.26 (1.12)
<i>A.2) Inference statistics</i>			
	$F(1,175)$	p	η_p^2
Mental demand	0.51	.559	.002
Self-affirmation	0.09	.802	<.001
MD $\times$ S-A	0.39	.611	.001
<i>B) After the manipulation of mental demand.</i>			
Mental demand	Low	3.25 (1.16)	
	High	3.22 (1.22)	

Note. M (SD).

Figure 6. Correlations for Stroop performance and self-reported fatigue at the beginning of the study.

Figure 7. Correlations for Stroop performance and self-reported fatigue after the manipulation of mental demand.

Table 7

Linear regressions including self-reported mental fatigue baseline as covariate

<i>A) Stroop performance</i>				
	<i>Estimate</i>	<i>SE</i>	<i>t</i>	<i>p</i>
Mental demand	-2.26	1.40	-1.16	.111
Self-affirmation	0.60	0.60	1.01	.317
<i>B) SBP reactivity Stroop task</i>				
	<i>Estimate</i>	<i>SE</i>	<i>t</i>	<i>p</i>
Mental demand	-1.03	1.37	-0.75	.454
Self-affirmation	-1.02	0.58	-1.77	.080

Morningness/eveningness. We exploratorily assessed morningness versus eveningness using the last item of the D-MEQ (D-MEQ; item 19; Griefahn, Künemund, Bröde, & Mehnert, 2001). Higher values stand for “eveningness”, lower values for “morningness” (see Table 8). There was no significant relationship between morningness/eveningness ratings and Stroop performance (see Figure 8).

Table 8

Morningness/Eveningness

		Self-affirmation	
		No	Yes
Mental demand	Low	2.59 (0.93) <i>N</i> = 46	2.93 (0.84) <i>N</i> = 45
	High	2.74 (0.82) <i>N</i> = 43	2.73 (0.94) <i>N</i> = 45

Note. M (SD).

Figure 8. Correlations for morningness/eveningness and Stroop performance.

Relationship SBP reactivity and Stroop interference. There was no significant correlation for SBP reactivity (during the Stroop task, relative to the baseline) and Stroop performance (see Figure 9).

Figure 9. Correlations for SBP reactivity (during the Stroop task, relative to the baseline) and Stroop performance.

Bayesian model comparisons SBP reactivity Stroop task (non-affirmed conditions).

The strength model assuming no difference in invested mental effort for the non-affirmed conditions as a function of mental demand was superior to both the process model (low demand < high demand) and a third alternative (low demand > high demand, see Table 4).

Table 9

Bayesian model comparisons for SBP reactivity in the Stroop task (non-affirmed conditions)

	Strength model (low demand = high demand) over ...	Process model (low demand > high demand) over ...
Process model (low demand > high demand)	BF = 4.58	
Alternative (low demand < high demand)	BF = 15.73	BF = 3.43

Stroop interference based on reaction times. Participants in *the non-affirmed* conditions did not perform worse after exerting self-control than after not exerting self-control ($t_{\text{one-sided}}[75.16] = -1.12, p = .133, d = -0.25, 95\% \text{ CI } [-0.68, 0.19]$; for descriptive statistics, see Table 3). Self-affirmation did not counteract the detrimental effect of the ego depletion manipulation (pre-registered contrast: *high demands/non-affirmed* = +3, remaining three conditions = -1). The pre-registered contrast thus did not fit the data ($F[1, 166] = 0.17, p = .682, f = 0.03$).

Table 10

Stroop interference on reaction times (outlier cutoff 2.5 SDs from condition means; reaction time [ms] on incongruent trials minus reaction time [ms] on congruent trials)

		Self-affirmation		Overall
		No	Yes	
Mental demand	High	194.15 (62.62) <i>N</i> = 41	220.16 (65.43) <i>N</i> = 42	207.31 (65.00)
	Low	180.46 (48.25) <i>N</i> = 43	195.77 (61.33) <i>N</i> = 42	188.02 (55.31)
	Overall	187.14 (55.81)	207.96 (64.21)	

Note. *M* (*SD*).

Wordcount of essays. We exploratorily counted the number of words written during the self-affirmation manipulation. Participants in the *self-affirmed* conditions wrote more words (*M*

= 101.08, $SD = 24.98$) than participants in the *non-affirmed* conditions ($M = 90.15$, $SD = 21.78$; $t[174.28] = 3.12$, $p = .002$, $d = 0.47$, 95%CI [0.17, 0.77]). SBP reactivity did not relate to the number of written words (see Figure 10).

Figure 10. Correlations for SBP reactivity (during the self-affirmation manipulation, relative to the baseline) and wordcount.

Abstractness of essays. We exploratorily calculated abstractness scores for the most used words in the essays written during the self-affirmation manipulation based on a data base of 40,000 words by Brysbaert, Warriner, and Kuperman (2014). German stopwords were excluded. Participants in the *self-affirmed* conditions used more abstract words ($M = 3.36$, $SD = 0.97$) than participants in the *non-affirmed* conditions ($M = 2.29$, $SD = 0.86$; $t[57.16] = 4.53$, $p < .001$, $d = 1.17$, 95%CI [0.61, 1.73]; see Figure 11). The results were similar for the 20 ($t[57.16] = 4.53$, $p < .001$, $d = 1.17$, 95%CI [0.61, 1.73]) or 10 ($t[57.16] = 4.53$, $p < .001$, $d = 1.17$, 95%CI [0.61, 1.73]) most used words, respectively.

Figure 11. Abstractness scores of 30 most used words by self-affirmation condition written during the self-affirmation manipulation. Abstractness scores based on a database by Brysbaert et al. (2014).

Stroop questions. We asked five questions after the Stroop task. There were no significant differences between the groups for any of the questions (see Table 11).

Table 11

Stroop questions

<i>1) How motivated were you to work on the color task according to the instructions?</i>			
<i>1.1) Descriptive statistics</i>			
		Self-affirmation	
		No	Yes
Mental demand	Low	6.48 (0.72)	6.53 (0.69)
	High	6.49 (1.01)	6.73 (0.54)
<i>1.2) Inference statistics</i>			
	$F(1,175)$	p	η_p^2
Mental demand	0.87	.352	.005
Self-affirmation	1.76	.186	.010
MD $\times$ S-A	0.70	.403	.004
<i>2) How much effort did you put into working on the color task according to the instructions?</i>			
<i>2.1) Descriptive statistics</i>			
		Self-affirmation	
		No	Yes
Mental demand	Low	6.62 (0.57)	6.67 (0.56)
	High	6.58 (0.73)	6.84 (0.37)
<i>2.2) Inference statistics</i>			
	$F(1,175)$	p	η_p^2
Mental demand	0.58	.447	.003
Self-affirmation	3.04	.083	.017
MD $\times$ S-A	1.76	.186	.010

3) How difficult was it for you to work on the color task according to the instructions?

3.1) Descriptive statistics

		Self-affirmation	
		No	Yes
Mental demand	Low	4.02 (1.56)	4.11 (1.35)
	High	3.77 (1.77)	3.80 (1.77)

3.2) Inference statistics

	$F(1,175)$	p	η_p^2
Mental demand	1.37	.244	.008
Self-affirmation	0.06	.815	< .001
MD $\times$ S-A	0.01	.907	< .001

4) How much did you want to work on the color task according to the instructions?

4.1) Descriptive statistics

		Self-affirmation	
		No	Yes
Mental demand	Low	5.35 (1.45)	5.38 (1.61)
	High	5.53 (1.58)	5.67 (1.54)

4.2) Inference statistics

	$F(1,175)$	p	η_p^2
Mental demand	1.06	.304	.006
Self-affirmation	0.13	.716	.001
MD $\times$ S-A	0.05	.826	<.001

5) *How exhausting did you find it to work on the color task according to the instructions?*

5.1) *Descriptive statistics*

		Self-affirmation	
		No	Yes
Mental demand	Low	4.59 (1.56)	4.69 (1.56)
	High	4.28 (1.61)	4.11 (1.63)

5.2) *Inference statistics*

	$F(1,175)$	p	η_p^2
Mental demand	3.49	.064	.020
Self-affirmation	0.03	.872	< .001
MD $\times$ S-A	0.32	.571	.002

Note. M (SD).

Bayesian model comparisons SBP baseline. We explored if participants already differed during the SBP baseline as a function of mental demand condition. The model assuming no differences between the group provided a better fit than the model assuming higher / lower SBP during the baseline for the high demand conditions (BF = 4.38 / BF = 11.86).