Can the ego be depleted?

Attempts to replicate the ego depletion effect and integrate its explanations

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Abstract

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Key words: Self-Control; Ego Depletion; Pre-registration; Meta-Analysis; Goal Maintenance; Competition Resolution

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List of Articles

Articles included in the dissertation.

I. Dang, J. (2016). Commentary: A multilab preregistered replication of the ego-depletion effect. *Frontiers in Psychology*, *7*, 1155. doi: 10.3389/fpsyg.2016.01155

II. Dang, J. (in press). An updated meta-analysis of the ego depletion effect. *Psychological Research*. doi:10.1007/s00426-017-0862-x

III. Dang, J., Liu, Y., Liu, X., & Mao, L. (2017). The ego could be depleted, providing initial exertion is depleting: A pre-registered experiment of ego depletion. *Social Psychology*.*48*, 242-245.

IV. Dang, J., Björklund, F., & Bäckström, M. (2017). Self-control depletion impairs goal maintenance: A meta-analysis. *Scandinavian Journal of Psychology*, *58*, 284-293.

V. Dang, J., & Mao, L. (2017). Self-control depletion primarily impairs goal maintenance. *The Journal of Social Psychology*. Submitted.

Additional Publications

Articles not included in the dissertation but related to the dissertation.

I. Dang, J. (2016). Testing the role of glucose in self-control: A meta-analysis. *Appetite*, *107*, 222-230. doi:10.1016/j.appet.2016.07.021

II. Dang, J., Xiao, S., Liu, Y., Jiang, Y., & Mao, L. (2016). Individual differences in dopamine level modulate the ego depletion effect. *International Journal of Psychophysiology*, *99*, 121-124. doi:10.1016/j.ijpsycho.2015.11.013

III. Dang, J., Xiao, S., & Dewitte, S. (2015). Commentary: "Poverty impedes cognitive function" and "The poor's poor mental power". Frontiers in psychology, 6, 1037. doi: 10.3389/fpsyg.2015.01037

IV. Dang, J., Xiao, S., Shi, Y., & Mao, L. (2015). Action orientation overcomes the ego depletion effect. *Scandinavian Journal of Psychology*, *56*, 223-227. doi: 10.1111/sjop.12184

V. Dang, J., Xiao, S., & Dewitte, S. (2014). Self-control depletion is more than motivational switch from work to fun: The indispensable role of cognitive adaptation. *Frontiers in Psychology*, *5*, 933. doi: 10.3389/fpsyg.2014.00933

VI. Xiao, S., Dang, J., Mao, L., & Liljedahl, S. (2014). When more depletion offsets the ego depletion effect. *Social Psychology*, *45*, 421-425. doi: 10.1027/1864-9335/a00019

VII. Dang, J., Dewitte, S., Mao, L., Xiao, S., & Shi, Y. (2013). Adapting to an initial self-regulatory task cancels the ego depletion effect. *Consciousness and Cognition*, *22*, 816-821. doi:10.1016/j.concog.2013.05.005

Abstract

Although self-control is so important that no one from any corner of the world would dispute, it is often difficult and vulnerable. Continuous exertion is one of the most influential factors that are detrimental to self-control, which leads to a state called “ego depletion”. Before 2016, the ego depletion effect had been a hot topic for a long time. After a multi-lab replication that reported a non-significant result in 2016, however, it became highly controversial regarding whether the ego depletion effect is a true effect. In the first three articles presenting re-analyses of data from the multi-lab replication, conducting an updated meta-analysis, and implementing a pre-registered large-scale experiment, I demonstrate that the non-significant result found in the multi-lab replication may be due to the ineffectiveness of the depleting task, and there is a reliable ego depletion effect when an effective depleting task is used. Further, I introduce and compare several explanations of the ego depletion effect, by analyzing the pros and cons of each explanation. On the basis of this work, I propose a fine-grained new model (i.e., the CoMo model) that integrates various lines of research and is able to explain almost all counterintuitive findings in this area. The last two articles provide evidence in support of the new model but contradict other theories. The limitations and future directions are discussed.

1 Self-Control

Human life is filled with various conflicts, dilemmas, and struggles. We want to keep a good figure while longing for savoring palatable foods. We have to report a strenuous work before a coming deadline while being invited to an interesting party where we can enjoy music, beer, and chatting with charming guys. We are depressed and want to be alone but we have to smile in order to keep polite. We are so angry to the boss but we cannot yell. We are so excited by a new-arrival dress while worrying that this might lead to debt. The prevalence of these struggles is not only anecdotal but also supported by empirical data. For example, in an experience sampling study that obtained reports of desire at randomly chosen points during participants' daily activities, it was found that participants were experiencing desires about half the time they were awake and among 38% of these desires they were resisting (Hofmann, Baumeister, Förster, &Vohs, 2012).

In these struggles, there are always two forces that are in battle. One is the impulse or desire that needs to be satisfied immediately, whereas the other is the control or inhibition that aims for a long-term goal. That said, in order to obtain a more important goal in the long run, we need to control the strong impulse at hand. This is referred to as the capacity of self-control. To be more precise, "self-control refers to the capacity for altering one's own responses, especially to bring them into line with standards such as ideals, values, morals, and social expectations, and to support the pursuit of long-term goals" (Baumeister, Vohs, & Tice, 2007, p. 351).

This capacity is so important that no one from any corner of the world would ever have a thought to dispute. In contrast, all cultures and religions have been having greatest esteem for self-control. In ancient China, Confucius taught in *Confucian Analects* that "The one with disciplines seldom errs" (以约失之者鲜矣). The most famous follower of Confucius, Menci, wrote that "It's a true great man whom neither riches nor honors can corrupt, neither poverty nor humbleness can swerve from principle, and neither threats nor forces can subdue" (富贵不能淫, 贫贱不能移, 威武不能屈, 此之谓大丈夫). In ancient Greece, Plato said that "Self-control is an order, a control for happiness and desire". In Buddha's teaching, there were ten vicious things out of selfishness and delusion that have to be avoided (i.e., killing, theft, sexual misconduct, lying, divisive speech, worthless chatter, harsh words, greed, malice, wrong view), otherwise we would hurt both ourselves and others. Similarly, Ten

Commandments in the Judeo-Christian Bible also specified what people might want to but "thou shalt not" do.

Likewise, modern scientists consider self-control as one of the defining features of human nature and have engaged in immense empirical exploration, as can be seen by a great number of influential and integrative books (e.g., Baumeister, Heatherton, & Tice, 1994; Boekaerts, Pintrich, & Zeidner, 2005; Hassin, Ochsner, & Trope, 2010; Vohs & Baumeister, 2016) . No matter how self-control was measured, it has been consistently associated with numerous positive outcomes. For example, a recent meta-analysis revealed that although with some variances, across different behavioral domains (e.g., school and work, eating and weight, interpersonal functioning, and well-being and adjustment), self-reported self-control capability was positively correlated with desirable behaviors such as homework hours, healthy foods eating, physical exercise, condom use, and marital satisfaction, yet was negatively correlated with undesirable behaviors such as delinquency, overeating, aggression, drug use, and marital conflict (de Ridder, Lensvelt-Mulders, Finkenauer, Stok, & Baumeister, 2012). Other-rated self-control capability showed similar results. After controlling for childhood environment and health situation, the ability to stay focused on a task and persistence in problem solving that was rated by a trained psychologist at the age of 7 predicted physical health 28 years later (Kubzansky, Martin, & Buka, 2009). Similar trends were found when self-control was measured behaviorally. In Mischel's classic "marshmallow" project, preschool children at age 4 were tested in the lab and required to wait in face of a small, immediately available reward (e.g., one marshmallow) in order to get a larger regard later (e.g., two marshmallows) (Mischel, Ebbesen, & Zeiss, 1972). One decade later, those who waited longer at age 4 became adolescents who had higher SAT scores and were rated by their parents as more rational, attentive, planful, and able to deal with frustration and stress (Mischel, Shoda, & Peake, 1988; Shoda, Mischel, & Peake, 1990). Moreover, this early delay ability can also help to buffer people with dispositional vulnerabilities (e.g., high rejection sensitivity) from diminished well-being (e.g., low self-worth and borderline personality features) (Ayduk et al., 2000; Ayduk et al., 2008).

Despite its great importance, however, self-control in general is difficult and vulnerable. Large international surveys have shown that people in general tend to cite self-control as a personal weakness (Baumeister & Tierney, 2011). Literature showed that self-control could easily be impaired by a wide range of factors, such as negative mood (Garg, Wansink, & Inman, 2007; Tice, Bratslavsky, & Baumeister, 2001), stress (Hamilton, Sinha, & Potenza,

2014; Maier, Makwana, & Hare, 2015; Oaten & Cheng, 2005), social exclusion (Baumeister, DeWall, Ciarocco, & Twenge, 2005; Stenseng, Belsky, Skalicka, & Wichstrøm, 2015), stereotype threat (Inzlicht & Kang, 2010; Major, Hunger, Bunyan, & Miller, 2014), reminding of death (Gailliot, Schmeichel, & Baumeister, 2006; Mandel & Smeesters, 2008), presence of cookie odor or erotic pictures (Ditto, Pizarro, Epstein, Jacobson, & MacDonald, 2006; Li, 2007; Van den Bergh, Dewitte, Warlop, 2008), to name only a few. Among these factors that lead to self-control failure, the most well-known factor, at least in academia, might be continuous exertion. That is to say, people's subsequent self-control performance tends to be impaired by initial exertion, which has been termed "the ego depletion effect" and will be the focus of the current dissertation.

2 Ego Depletion

2.1 Inception

The first systematic investigation of the ego depletion effect was done by Baumeister and colleagues (Baumeister, Bratslavsky, Muraven, & Tice, 1998; Muraven, Tice, & Baumeister, 1998). These authors developed the suquential-task paradigm to test ego depletion. The paradigm consists of two conditions that both require participants to complete two consecutive tasks. In the depletion condition, the first task requires self-control. In the control condition, however, the first task does not have self-control demand. In both conditions participants then move forward to a second, unrelated self-control task. Participants in the depletion condition generally perform worse than do those in the control condition.

For example, in one of the seminal studies testing the ego depletion effect, participants in the depletion condition were required to try not to show or express any emotions while watching an emotion-evoking scene from a movie for 10 minutes. They were told that they would be videotaped during watching so it was essential to try to conceal any emotional reaction. In contrast, those in the control condition were instructed to freely express their emotions during the same movie. After that, all participants completed an anagram task that comprised 13 sets of jumbled letters during a 6-minute period. Participants in the depletion condition solved significantly less puzzles than did participants in the control condition (Baumeister et al., 1998).

In their homage to Freud, Baumeister and colleagues coined the term "ego depletion" to refer to this effect. This term is apropos in the sense that the conflict between the impulse force and the control force in a typical self-control scenario seems similar to the tense relation between the id and the super-ego. Therefore, the ego that was reconciling the id and the super-ego in Freud's tripartite model traversed through time and space and got a modern outerwear.

2.2 Boom

During the first decade since the first tests of the ego depletion effect, research on this topic had been gradually increasing. In 2010, Hagger and colleagues conducted a meta-analysis of ego depletion that computed a medium-to-large effect size across 198 tests, $d = 0.62$, 95% CI [0.57, 0.67] (Hagger, Wood, Stiff, & Chatzisarantis, 2010). The conclusion from this meta-analysis that ego depletion is a robust effect provoked further explosive interest. By the end of July 2017, in Google Scholar those two seminal papers have been cited over 4000 times (Baumeister et al., 1998) and 2000 times (Muraven et al., 1998), respectively. Over 600 hundred independent experiments have tested the ego depletion effect (Carter, Kofler, Forster, & McCullough, 2015). Empirical articles on this topic were often published in leading top journals such as *PNAS* (Job, Walton, Bernecker, & Dweck, 2013), *Psychological Science* (e.g., Inzlicht & Gutsell, 2007), *Journal of Personality and Social Personality* (e.g., Schmeichel & Vohs, 2009), *Journal of Experimental Psychology: General* (e.g., Schmeichel, 2007), *and Personality and Social Psychology Bulletin* (e.g., Wan & Sternthal, 2008). Recent theoretical advances have also been published in *Trends in Cognitive Sciences* (Inzlicht, Schmeichel, & Macrae, 2014), *Behavioral and Brain Science* (Kurzban, Duckworth, Kable, & Myers, 2013), *Psychological Bulletin* (Hagger et al., 2010), *Perspectives on Psychological Science* (e.g., Inzlicht & Schmeichel, 2012), and *Personality and Social Psychology Review* (e.g., Beedie & Lane, 2012; Gailliot & Baumeister, 2007). Because there are so many studies on this single topic, researchers therefore gathered together and issued a book to specifically discuss this effect from various angles (Hirt, Clarkson, & Jia, 2016). By collaborating with science writer John Tierney, Baumeister also wrote a popular science book on the basis of findings on this topic, which became a *New York Times* bestseller (Baumeister & Tierney, 2011).

In addition to tasks used by Baumeister and colleagues, researchers also introduced various types of depleting task (i.e., the first self-control task) and outcome task (i.e., the second self-control task). Recent meta-analyses summarized the frequently used depleting

tasks and outcome tasks, each of which has been used in at least 10 independent experiments (Article II; Carter et al., 2015). The details of the frequently used depleting tasks and outcome tasks are shown in Table 1 and Table 2 respectively.

Table 1

Frequently Used Depleting Tasks

ID	Task	Description	Depletion condition requirement	Control condition requirement
1	Attention essay	Write about a topic	Cannot use a set of commonly used letters (e.g., *a* and *n*)	Free writing
2	Attention video	Watch a silent video during which stimuli occasionally appear	Give instructions to ignore the stimuli when they appear	No instruction
3	Letter crossing	Cross out specific letter(s) in a meaningless text	Complex rules	No special rules, just cross out
4	Emotion video	Watch an emotionally evocative video	Regulate emotions in some way (either suppression or exaggeration)	No special requirement
5	Food temptation	Take part in a taste test	Eat radish without eating chocolate	Eat chocolate without eating radish
6	Math	Solve math problems	Difficult math problems (e.g., 3 digit multiplication)	Simple math problems (e.g., single-digit addition)
7	Stroop	Name the ink color of color words	Most trials (if not all) are incongruent	Most trials (if not all) are congruent
8	Thought suppression	Think something	Think about anything except a white bear	Think about anything
9	Transcription	Transcribe a text on a computer	Cannot use certain keys (e.g., spacebar)	No special requirement, just transcribe
10	Working memory	Perform a working memory task	High memory load	Low memory load

Table 2

Frequently Used Outcome Tasks

ID	Task	Description
1	Food consumption	The amount of unhealthy food (e.g., ice cream) consumed
2	Hand grip	The length of time for holding a hand grip closed
3	Impossible anagram	Persistence at a set of anagrams, some of which are designed to be impossible to solve
4	Impossible puzzle	Persistence at unsolvable puzzles (e.g., tracing geometric shapes without going back over previous lines)
5	Possible anagram	Solve as many as possible solvable anagrams
6	Standardized test	Typically the graduate record exam (GRE)
7	Stroop	Accuracy and/or reaction time of the Stroop effect or incongruent trials
8	Working memory	Standard working memory tests (e.g., operation span task)

2.3 Challenge

Under the surface of the boom, a crisis brewed. Carter and McCullough (2013, 2014) argued that in Hagger et al.'s (2010) data there were very strong small-study effects (e.g., the smaller sample size, the larger effect size) that seriously biased the estimation of the true effect size and had to be corrected. They introduced a new bias-correcting method called the precision effect test (PET) and the precision effect estimate with standard error (PEESE) (Stanley & Doucouliagos, 2014). When they applied this method to Hagger et al.'s data, the overall effect size of ego depletion was indistinguishable from zero (Carter & McCullough, 2013, 2014).

These authors followed this up with a series of new meta-analyses (Carter et al., 2015). In this paper, Carter and colleagues made two important contributions. First, they included only frequently used depleting tasks and outcome tasks by assuming that researchers tend to select tasks that have valid operationalization of self-control and that provide the most interpretable results. Second, they included as many unpublished experiments as possible through an exhaustive literature search. Compared with Hagger et al. (2010), these efforts resulted in a more conservative estimate of effect size, $g = 0.43$, 95% CI [0.34, 0.52], with

signs of small-study effects. The most often used bias-correcting method, the trim and fill method (Borenstein, Hedges, Higgins, & Rothstein, 2009), yielded a lower estimate, $g = 0.24$, 95% CI [0.13, 0.34]. However, after accounting for the small-study effects by using PET-PEESE, the ego depletion effect was again indistinguishable from zero.

In response to Carter and colleagues' argument, Martin Hagger and Nikos Chatzisarantis organized a multi-lab pre-registered replication of the ego depletion effect (Hagger et al., 2016). The replication adopted Sripada, Kessler, and Jonides' (2014) paradigm in which participants completed an *e*-crossing task first and then a multi-source interference task, both on the computer. This project included 23 laboratories ($N = 2141$) in both English and non-English speaking countries but it failed to replicate the ego depletion effect (Hagger et al., 2016). The overall effect size was almost zero, $d = 0.04$, 95% CI [-0.07, 0.15], without using any bias-correcting method. A re-analysis of Hagger et al.'s (2016) data by collapsing all participants and using Bayesian analysis found that the result was 76.3 times more likely supporting the null hypothesis (Sripada, Kessler, & Jonides, 2016). By assuming Hagger et al.'s (2016) data were obtained under the research program-strategy, another re-analysis revealed that ego depletion could be neither a medium-sized ($d = 0.50$) nor a small-sized ($d = 0.20$) effect (Witte & Zenker, 2017), which also suggests ego depletion is unlikely to be a real effect.

2.4 Solution

2.4.1 Misleading meta-analytic conclusions

In reply to the work of Carter and colleagues, researchers counterattacked through the following arguments. First, it may not be warranted to use bias-correcting methods for the "small-study effects" (Hagger & Chatzisarantis, 2014; Inzlicht, Gervais, & Berkman, 2015). In psychology, the sample sizes are generally small and journals tend not to publish null results. Consequently the "small-study effects" occur and is often taken as a proxy for publication bias. However, the "small-study effects" can also result from other factors, such as methodological issues or true heterogeneity. Therefore, the validity of using bias-correcting methods might be questioned.

Second, even if the validity of using bias-correcting methods can be justified, the appropriateness of using PET-PEESE should be questioned. On one hand, because there are

many bias-correcting methods, there is little reason that one should only draw conclusion from PET-PEESE while ignoring other methods. For example, by using Carter et al.'s dataset, Inzlicht et al. (2015) reported a medium-sized effect (d = 0.55) for ego depletion that resulted from the *p*-curve analysis (Simonsohn, Nelson, & Simmons, 2014) and a small-sized effect (d = 0.26) that resulted from top-10 studies with the highest sample size (Stanley, Jarrell, & Doucouliagos, 2010). Blázquez, Botella, & Suero (2017) also reported a medium-sized effect (d = 0.66) by utilizing the *p*-uniform method (van Assen, van Aert, & Wicherts, 2015) based on Carter et al.'s dataset.

One the other hand, currently there is lack of consensus among statisticians regarding whether PET-PEESE can reliably account for the small-study effects (Inzlicht & Berkman, 2015). There is also evidence showing that this bias-correcting estimation sometimes perform worse than those without corrections (Reed, 2015). Very recently, Carter himself questioned the use of PET-PEESE (Carter, Schönbrodt, Gervais, & Hilgard, 2017). "The performance of PET, PEESE, and PET-PEESE is characterized by high variability, with estimates ranging from severe under-correction to severe over-correction. Given how difficult it is to determine which condition best represents one's particular situation, the safest route is to avoid using these methods with data from research on psychology." (p. 11).

Third, even if PET-PEESE itself is reliable, it requires a large number of studies in the absence of heterogeneity (Stanley & Doucouliagos, 2014). However, Carter et al.'s (2015) separate analyses for each outcome task were all based on a small number of studies (k = 13 to 21) with high heterogeneity, which is unlikely to result in accurate estimates (Article II; Cunningham & Baumeister, 2016; Inzlicht et al., 2015). Although the overall analysis was based on a large sample size (k = 116), the accuracy of its estimation has to be queried due to the high level of heterogeneity (Article II; Cunningham & Baumeister, 2016; Reed, 2015). Indeed, the developer of this method himself cited Carter et al.'s analyses as examples of the misuse of PET-PEESE (Stanley, 2017).

Fourth, if the true effect size of ego depletion is zero as revealed by PET-PEESE in Carter et al.'s (2015) dataset, effect sizes in both positive and negative directions should be observed in the literature (Cunningham & Baumeister, 2016; Hagger & Chatzisarantis, 2014). However, improvement after initial self-control exertion (i.e., reverse ego depletion) has rarely been reported, while studies showing deterioration after exertion (i.e., ego depletion) were immense. It might be argued that reverse ego depletion cannot get published because it contradicts the commonly-held view. Actually, however, the opposite is true, such that the

scant few articles reporting reverse ego depletion were all published in top journals such as *Journal of Applied Psychology* (Converse & DeShon, 2009) and *Journal Personality and Social Psychology* (Savani & Job, 2017). It might also be argued that most studies should have found null results but researchers selectively reported significant ego depletion. This does not make sense because under this assumption it would be odd that researchers do not selectively report significant reverse ego depletion. Giving the great importance of self-control, reverse ego depletion should be more attractive than ego depletion.

2.4.2 Newest evidence for ego depletion

In a reply to Hagger et al.'s (2016) replication report, Baumeister and Vohs (2016a) wrote: "In retrospect, the decision to use new, mostly untested procedure for a large replication project was foolish" (p. 574). Their main point was that the depleting task used by Hagger et al. (2016) was inappropriate. The *e*-crossing task invented by Baumeister and colleagues has three main features (Article I). First, the depletion condition includes more complex rules of crossing than does the control condition. Second, participants in the depletion condition first establish a habit of crossing out every *e* and then have to override these habitual responses given more complex rules. This switching procedure is absent in the control condition in which participants cross out every *e* throughout the task. Third, the text in the depletion condition requires closer attention because of its poor legibility. The *e*-crossing task in Hagger et al.'s replication only taps the first feature. Baumeister and Vohs (2016a) emphasized that the second feature should be critical. "Without first instilling the habit, there is nothing to override. This may be a difficult cognitive judgment task, but no impulse is overridden, contrary to the nature of self-control tasks" (p. 574).

Hagger and colleagues did not agree. "While we have some sympathy with this claim, we do not think it provides sufficient basis to dismiss the task as failing to tax self-control. As we pointed out, participants must suppress the time-pressured urge to respond to any "*e*" in presented words in favor of the rules--they must stop themselves from making an impulsive judgment as time dictates when they sight an "*e*" in order to apply the rule. On this basis, we reckon the letter "*e*" task requires self-control and is consistent with the use of "*e*-crossing" tasks without the habit-forming period used previously (e.g., Wan and Sternthal, 2008)" (Hagger & Chatzisarantis, 2016, p. 2). Inzlicht (2016) expressed similar idea on his blog.

2.4.2.1 Article I

My opinion is not totally in line with Baumeister and Vohs (2016a). Rather, consistent with Hagger and Chatzisarantis' (2016) argument, an unpublished study conducted by our team (Fredrik, Martin, and I) did find significant ego depletion by using an *e*-crossing task that tapped the first and the third features. In Carter et al.'s (2015) dataset, when focusing on studies using the *e*-crossing as the depleting task, I failed to find difference in weight average effect size between studies using the *e*-crossing that tapped all three features and studies that did not tap the second feature.

However, I do think the *e*-crossing task in Hagger et al.'s (2016) replication might not be strong enough. In Article I, I collapsed datasets from different labs into one single dataset and found the effect sizes were similar to those calculated from Hagger et al.'s (2016) meta-analyses. An interesting finding was that the depletion condition and the control condition did not differ with each other in one of the four manipulation check items (i.e., fatigue). Although they differed in the other three items, scores on only one item (i.e., effort) were above the midpoint the scale (i.e., "4"). That is to say, even in the depletion condition, the *e*-crossing task was generally considered not "depleting". Therefore, the effectiveness of the depleting task was questioned.

This led me to think that although the *e*-crossing task in the multi-lab replication in general was ineffective, for a subsample of individuals it might be "depleting". Those who experienced depletion during the *e*-crossing task should have performed worse on the subsequent task, thus manifesting the typical ego depletion effect. As a result, I found a significant interaction between condition and effort. In the control condition, self-reported effort that was exerted in the *e*-crossing task did not predict subsequent self-control performance. However, in the depletion condition, increased effort in the *e*-crossing task predicted deteriorated performance in the subsequent task. That is to say, participants generally did not consider the *e*-crossing task as "depleting". However, for those who considered it as effortful, there was an ego depletion effect.

This re-analysis induced some interesting responses. For example, on Twitter, Michael Kane sent a message "Is ego depletion *unfucked*?". I especially appreciate the open-mindedness of the first author and the second author of the multi-lab replication. Actually, this article was reviewed by the second author of the multi-lab replication, Nikos Chatzisarantis. And, the first author of the multi-lab replication, Martin Hagger, commented

the online version of this article pertinently (http://journal.frontiersin.org/article/10.3389/fpsyg.2016.01155/full): "Many thanks for your contribution. An interesting set of findings, and an intriguing adjunct to our analysis. I have a few of comments, just for clarity. First, in the interest of balance, it would be worthwhile noting the effect size for your interaction effects. The t-values from the simple slopes did not include degrees of freedom, so I was unsure what sample size to use. However, assuming the df's for these interactions were from the main sample, I computed effect sizes of d = .15 and d = .12, for the reaction time variability (RTV) and reaction time (RT) dependent variables, respectively, for the slopes for the depletion condition. While these may be significantly different from zero (it would have been nice to see the 95% CIs on the betas), they still represent quite small effects. This is backed up by the betas from the initial regression analysis (0.08 and 0.10), which I assume were standardized regression coefficients and, as a consequence, indicate small effects. I suppose these effect sizes may be revised if you present the actual dfs, so please update if that is the case. But I am guessing they will be small. These effect sizes appear to be closest to those found by Carter and McCullough in their corrected effects before correcting using PET-PEESE, but below their uncorrected estimate that includes the unpublished data and well below our original meta-analytic finding in our 2010 meta-analysis. Second, in the interest of balance, the 'habit-forming' period for the e-canceling task is not described as being used in Baumeister et al.'s original 1998 article nor has it been used in some other studies using the task, including Sripada et al.'s orginal study, and these studies found depletion effects. We have reiterated these points on numerous occasions (Hagger, M. S., & Chatzisarantis, N. L. D. (2016). Commentary: "Misguided effort with elusive implications" and "sifting signal from noise with replication science". Frontiers in Psychology, 7, 621. doi: 10.3389/fpsyg.2016.00621). Third, the fact that some participants found the task more depleting than others is of great interest to me. Why is that? Individual differences? Variations in levels of fatigue that participants 'bring with them' when they visit the lab? It is certainly something that needs to be considered if the field is to identify tasks that are consistently successful in evoking a depleted state on a consistent basis and for the majority of people. Food for thought."

Later, Drummond and Philipp (2017) argued that effort should be a mediator rather than a moderator. I cannot completely agree with them because many studies reported significant ego depletion by using difficult and effortful tasks as the control condition (i.e., no effort difference in two conditions) (Hagger et al., 2010). Certainly, effort is also not necessarily a

moderator. Drummond and Philipp (2017) also argued that my results might not be accurate because in Hagger et al.'s (2016) dataset there was significant collinearity between effort rating and the depletion manipulation because participants reported higher effort in the depletion condition than in the control condition. This is correct. Article I is a re-analysis and is constrained by various factors (e.g., collinearity and small effect size). Therefore, I personally do not expect too much from it. It sheds some light on the problem we face and the direction we might go forward, which is enough.

2.4.2.2 Article II

Because Article I implied the importance of the depleting task's effectiveness, a following question would be which depleting task is effective. This important issue was not tapped by Carter et al. (2015) but was addressed by Article II. Meanwhile, ten experiments in Carter et al.'s (2015) analysis employed more than one depleting task before the outcome task, which makes them incomparable to the remaining experiments. Rather than simply removing these studies, in Article II a separate meta-analysis was done to estimate the downstream effect of multiple depletion.

Article II revealed that attention video and working memory seem ineffective to induce ego depletion. In contrast, attention essay, emotion video, and Stroop should be considered as reliable depleting tasks considering the medium-sized effect as well as low heterogeneity. At the same time, letter crossing, food temptation, and thought suppression also showed significant effects. However, the heterogeneity was also high, which indicates they may not be as reliable as attention essay, emotion video, and Stroop. Interestingly, multiple depletion (i.e., more than one depleting task) yielded a non-significant result, which I would return in the section discussing the strength model.

2.4.3.2 Article III

Article II showed attention essay, emotion video, and Stroop should be considered as reliable depleting tasks. To verify this, pre-registered experiments might be the best practice, as suggested by several reviewers of my papers. Article III aimed to do this. One important reason that Hagger et al.'s (2016) replication adopted Sripada et al.'s (2016) paradigm was that it seemed to be the only one that was fully computerized and could be easily replicated by other labs. Therefore, we focused on the Stroop task because it is easy to standardize. We also

chose another computerized task as the dependent measure (i.e., the antisaccade task). The sample size, procedure, and analysis plan have been specified in advance in the pre-registration (https://osf.io/ydc7z/).

Article II showed a medium-sized effect for ego depletion by using the Stroop task as the depleting task. We used G*Power to determine the required sample size, which showed that a sample with 160 participants (80 in each of the two conditions) would be able to detect a comparable effect size with a power of .80 (two tails). In Hagger's commentary on Article I, he was thinking about why some people were more vulnerable to the depletion manipulation. Thus, in Article III we investigated whether individual difference variables would moderate the ego depletion effect. We included three individual difference variables that have been examined at least twice: trait self-control (Imhoff, Schmidt, & Gerstenberg, 2014; Wang et al., 2015), action orientation (Dang, Xiao, Shi, & Mao, 2015; Gröpel, Baumeister, & Beckmann, 2014), and lay theories about willpower (Job, Bernecker, Miketta, & Friese, 2015; Job, Dweck, & Walton, 2010).

The dependent measure (i.e., the accuracy of the antisaccade task) showed a statistically significant result. Participants in the depletion condition performed worse than did those in the control condition, Hedge's $g = 0.48$. 95%CI = [0.18, 0.78]. None of the three individual difference variables was found to moderate the ego depletion effect. Therefore, this pre-registered experiment demonstrated a significant ego depletion effect in a large sample when the Stroop task was employed as the depleting task. The effect size is comparable to that found in the meta-analysis reported in Article II. This highlights the importance of the depleting task's effectiveness. That is to say, the "ego" could be "depleted", but only when initial exertion is "depleting".

Michael Inzlicht signed as one of the reviewers of this article. He wrote: "the attempts made here are better than 99.99% of the published literature and should be commended. This would be only the 3rd pre-registered ego depletion study to be published."

3 Explanations

So far I have shown the ego depletion is a real effect, and presented evidence that it could be a medium-sized effect. The following question would concern why it happens. Actually, Baumeister and colleagues developed the ego depletion paradigm in order to support an "energy" or "strength" model of self-control (Baumeister et al., 1998; Baumeister & Heatherton, 1996; Muraven & Baumeister, 2000; Muraven et al., 1998). Later on, several alternative models have also been proposed such as the opportunity cost model (Kurzban et al., 2013), the process model (Inzlicht & Schmeichel, 2012, 2016; Inzlicht et al., 2014), and the cognitive control account (Dang, Xiao, & Dewitte, 2014; Dewitte, Bruyneel, & Geyskens, 2009). I will introduce these explanations one by one and analyze the pros and cons for each of them.

3.1 Strength Model

The main idea of this model is that self-control operates like a muscle or a kind of "strength". Below I will briefly introduce the development and variants of this model.

3.1.1 Original version

According to the cybernetic theory of self-regulation, effective self-control depends on three major ingredients: goal/standard, monitoring, and operation (Carver & Scheier, 1982). Goal/standard is the desired state; monitoring compares the actual state and the goal to detect whether there is a mismatch between them; when a mismatch is found, operation take over to make corrections and adjustments to reduce such mismatch. Drawing from the theory, the strength model was initialized to conceptualize the operation phase in terms of a limited resource upon which one internal process overrides another (Baumeister & Heatherton, 1996). Later, the formal theory was proposed (Muraven & Baumeister, 2000).

The formal theory comprises five core assumptions. First, acts of self-control require a resource or strength. Second, this resource or strength is limited. Third, all kinds of self-control acts draw on the same resource. Fourth, exertion of self-control expends the resource. Fifth, the success of self-control depends on the available level of resource. Therefore, in the ego depletion paradigm, the two consecutive tasks were generally different, which was designed to demonstrate all self-control draws on the same resource. The decline of

performance on the second task was taken as the evidence for that initial exertion expends or depletes self-control resource, leaving less for the subsequent self-control and thus leading to reduced performance.

Drawing further on the muscle metaphor, the strength model suggests that having a rest can replenish the resource. Right after initial exertion, the resource is depleted and insufficient for following control. However, after a period of rest, the resource would be replenished to the normal level. "It is important to note that this depletion of regulatory strength is a short-term effect only; after a period of rest it should return to its previous level" (Muraven et al., 1998, p. 775). There is also empirical evidence showing that a 10-minute period of rest eliminates the typical ego depletion effect (Tyler & Burns, 2008).

Out of the same metaphor, the strength model also suggests self-control can be improved by regular exercise interspersed with rest. "Indeed, much like muscular strength, it is possible that after repeated exertions the overall capacity for self-regulation may increase. This means that self-control in all domains may get easier after repeated attempts at self-control in one specific domain" (Muraven et al., 1998, p. 775). Subsequently, Muraven, Baumeister, and Tice (1999) found practicing self-control on a specific task (i.e., monitoring and improving posture, regulating mood, or maintaining a diary of eating) for 2 weeks could improve self-control in general, as measured by persistence on a hand-grip task following a thought-suppression task (i.e., reduced ego depletion).

3.1.2 Updated version

Later on, as ego depletion and the strength model attracted more and more attention, researchers started to explore the boundary conditions of ego depletion. The first research in this line was done by Muraven and Slessareva (2003). They found that providing extra motivation, such as raising the importance of the task or giving monetary incentives, could eliminate ego depletion, which was also replicated by many other labs (e.g., Gröpel & Kehr, 2014; Kazén, Kuhl, & Leicht, 2015; Luethi et al., 2016). Moreover, researchers showed ego depletion could be counteracted by manipulating perceptions and beliefs. For example, Job, Dweck, and Walton (2010) found people who believed self-control resource is unlimited could be prevented from ego depletion. Clarkson, Hirt, Jia, and Alexander (2010) showed it was the perception of resource depletion, rather than actual depletion, that caused performance decline in subsequent self-control.

These findings forced the proponents of the strength model to revise the original version in order to reconcile the additional findings. As Baumeister (2014) wrote: "Subsequent findings have added important aspects to the strength model. First, ego depletion does not mean that the brain has run out of fuel, as was first proposed. (Indeed, the word depletion has two meanings, referring to partial and total reduction in a resource, and this ambiguity has confused some.) Instead, it appears that most ego depletion findings represent an effort to conserve a resource that is only somewhat diminished (Muraven, Shmueli, & Burkley, 2006). The analogy of a muscle is apt: As muscles get tired, the body naturally seeks to conserve energy, long before the point of exhaustion is reached. Hence people in the state of ego depletion can still self-regulate effectively if an important situation arises and they are accordingly motivated to do so" (p. 314).

However, the concept of self-control resource is kept in the revised version of strength model and is still the core of this model. It argues self-control relies on resource but a short exertion in the lab does not deplete the resource fully and thus lead to a complete "refractory period". "If the tank were truly and thoroughly empty, it is unlikely that increasing incentives would counteract depletion" (Baumeister & Vohs, 2007, p. 125). Rather, depletion makes people value the limited resource more and thus unwilling to exertion further unless being fully motivated. It should be noted that, because the muscle metaphor is kept in the updated version, the recovering effect of rest and improving effect of practice are still key adjunct hypotheses.

Importantly, the proponents of the strength model are very ambiguous regarding whether the resource could be fully drained. On one hand, they seem to imply it could be the case, such that when depletion becomes more severe, which implies even less resource is left, motivation and perception manipulations cease to work (Baumeister, 2014; Baumeister & Vohs, 2016b; Baumeister et al., 2007). For example, they cited Vohs, Baumeister, and Schmeichel's (2012) work that found although belief of unlimited self-control resource and motivation to perform well could help to counteract ego depletion, as demonstrated by previous research (e.g., Job et al., 2010; Muraven & Slessareva, 2003), those effects were limited to the typical paradigm consisting of two consecutive tasks. When participants were asked to engage in two or more self-control tasks before the final task that served as the dependent measure, the effects of belief and motivation diminished. That is to say, participants in this severe depletion condition performed worst compared with those who did zero (control condition) and one initial self-control task (mild depletion, the usual depletion

condition), regardless of their belief about self-control resource and motivational level. It might be called updated version A.

One other hand, these authors also seem to imply no resource limit but only the increased tendency to conserve energy and thus reduced willingness to exert. "The energy available for self-regulation does not get entirely used up, and indeed even ego depleted people possess *ample energy* available to enable unimpaired performance. Thus, decrements in self-regulatory performance may represent an inclination to conserve the self's diminished resources rather than an inability to wield further self-control" (Baumeister & Vohs, 2016b, p. 81). It might be called updated version B.

3.1.3 Pros and cons

The strength model gained attention due to the appeal of its simplicity and excellent match with people's intuition. However, the appeal does not necessarily entail reasonableness and soundness. Although the updated version has solved some queries, there are actually greater challenges it cannot reconcile, which will be discussed below.

3.1.3.1 Is ego depletion caused by failure of operation?

The strength model might have been problematic from the very beginning when it was proposed to explain the operation phase of the cybernetic theory (Carver & Scheier, 1982). According to the cybernetic theory, self-control can be undermined if any of the three ingredients fail. Therefore, it is very likely that the reduced performance on the second task in the suquential-task paradigm results also from failures of the goal/standard ingredient and the monitoring ingredient. Surprisingly, this possibility has never been directly examined in the past two decades. The biggest obstacle may be due to the difficulty of disentangling these three ingredients in a self-control task. Because basic executive functions are assumed to underpin successful self-control (Hofmann, Schmeichel, & Baddeley, 2012; Vohs & Baumeister, 2016), drawing on research in executive control would help to address this issue.

According to the dual-process theory of executive control (Kane & Engle, 2003; Engle & Kane, 2004), effective executive control is determined by two processes. The first process is the maintenance of the task goal in active memory whereas the second is the resolution of response competition. For instance, in the Stroop task, participants are required to name the

color of a word while ignoring the meaning of the word. In incongruent trials, the color and the meaning of the word are in conflict (e.g., *RED* in blue). Participants have to maintain the goal of naming the color (goal maintenance) and then overcome the prepotent response of saying the word (competition resolution). Goal maintenance maps onto the first two ingredients of self-control (i.e., goal/standard and monitoring) because effective goal maintenance requires keeping the self-control goal active in working memory (e.g., naming the color) and monitoring whether the actual behavior would go astray (Hofmann, Friese, Schmeichel, & Baddeley, 2011). Competition resolution maps onto the operation ingredient because competition resolution means overcoming the prepotent response (e.g., naming the word) after the conflict (e.g., between naming the color and naming the word) has been detected, which is exactly the process the operation ingredient refers to (Hofmann et al., 2011). If initial depletion only impairs goal maintenance but spares competition resolution, the strength model would be challenged. In contrast, if self-control depletion impairs competition resolution but spares goal maintenance, strength model would be supported. There is also another possibility that both goal maintenance and competition resolution are negatively affected. If so, the strength model would be partially supported but a revision is needed. Article IV and Article V were designed to address this issue.

3.1.3.1.1 Article IV

Although goal maintenance and competition resolution jointly result in the Stroop effect, their respective impacts can be dissociated by manipulating the task set (Kane & Engle, 2003). In a task context dominated by congruent trials, participants might tend to slip into reading the word rather than naming the color because they can respond both quickly and accurately on most trials even if they fail to act in accordance with the goal. Thus, the infrequent incongruent stimuli place especially high demand on goal maintenance. Participants should be more likely to make errors if the color-naming goal is temporarily lost, and/or to respond very slowly to a subset of incongruent trials if the goal is lost but then recovered from memory before committing an overt error. In contrast, in a task context in which all trials are incongruent, the need for goal maintenance is greatly reduced since all stimuli repeatedly reinforce the color-naming goal. Instead, such a task context should be more sensitive to individuals' capabilities of resolving response competition, as reflected in a consistent slowing on all incongruent trials (Kane & Engle, 2003). That is to say, in this task context, the color-naming goal should not be difficult to keep, so participants would make fewer errors.

However, they still need to overcome the prepotent response of saying the word, which would lead to longer response time on every trial.

Because the Stroop task is a widely used outcome task in the ego depletion literature and researchers have adopted different versions that differed in congruency proportion, a systematic survey in the form of meta-analysis would be very useful for examining ego depletion in different contexts. This was what we did in Article IV. Results showed that initial exertion led to increased errors on the subsequent Stroop task when the congruency was higher than 0%, which indicates that goal maintenance is impaired. These results were not contaminated by publication bias. Although depletion also led to increased reaction time (RT) on the subsequent Stroop task when the congruency was 0%, which indicates competition resolution is impaired, Begg and Mazumdar's rank correlation (Begg & Mazumdar, 1994) and Egger's regression intercept (β_0) (Egger, Smith, Schneider, & Minder, 1997) showed that there were small-study effects.

Therefore, it was concluded that self-control depletion affects goal-maintenance but its effect on competition resolution is in need of further investigation.

3.1.3.1.2 Article V

In addition to the Stroop task, the antisaccade task has also been used to disentangle goal maintenance and competition resolution (Unsworth, Spillers, Brewer, & McMillan, 2011). At the same time, the dual-process theory also makes predictions regarding the RT distribution, which can not be tested in Article IV because almost no study included in the meta-analysis reported the RT distribution. Therefore, in Article V the antisaccade task was employed as the outcome task and the RT distribution was also examined besides RT and error.

In the antisaccade task, participants are required to look at a central fixation. After a variable amount of time, a cue flashes on the screen either to the left or the right of the fixation. Participants are instructed to immediately attend to the opposite side of the screen. In this task, the goal of shifting attention has to be actively maintained (goal maintenance) in the first place. Any lapse in attention would lead to a reflexive prosaccade to the flicking cue and thus an error. Further, even if the task goal could be maintained, there is still a need to overcome the prepotent response of looking toward the flicking cue in order to initiate the antisaccade according to the goal (competition resolution), which would result in longer response time. If the goal is fully maintained during the task, there would be a consistent

slowing across all trials because of competition resolution. Very often, however, the goal is only partially maintained. That is to say, in certain trials, the goal is temporarily lost but then recovered from memory before committing an overt error. Although such failure of goal maintenance cannot be revealed by error rates, it could be reflected in a small subset of very slow responses (Unsworth et al., 2011). Therefore, failure of goal maintenance will lead to errors and a long right tail in the RT distribution, whereas failure of competition resolution will lead to a shift of the entire RT distribution (Unsworth et al., 2011).

By utilizing the antisaccade as the second task in the ego depletion paradigm and ex-Gaussian function fitting to examine the RT distribution, results showed self-control depletion impaired goal maintenance but spared competition resolution, thus contradicting the strength model.

3.1.3.1.3 Summary of Article IV and Article V

Taken together, Article IV and Article V suggest failures of goal/standard and monitoring play crucial roles in ego depletion. The role of the operation ingredient, which is emphasized by the strength model, is in need of investigation. Therefore, the strength model might have been problematic from the very beginning and at least need a major revision.

3.1.3.2 What is the resource?

If self-control relies on resource, an important question is what the resource is. Gailliot and Baumeister claimed that glucose was the most important (if not the only) energy source for self-control (Gailliot & Baumeister, 2007; Gailliot et al., 2007). From this perspective, the resource explanation for self-control is more than a metaphor. Specifically, the suggestion of glucose as the resource has three hypotheses (Gailliot & Baumeister, 2007; Gailliot et al., 2007). First, engaging in a specific self-control activity would lead to reduced glucose level in the bloodstream because it has consumed certain amount of glucose. Second, after initial exertion of self-control, the remaining glucose level would be positively correlated with following self-control performance, such that the less glucose left in the bloodstream for further exertion, the worse following performance would be. Third, glucose ingestion (i.e., real replenishment) would help to redeem the impaired self-control performance. Gailliot et al. (2007) provided supporting evidence for all the three hypotheses through nine experiments.

Although Gailliot et al. (2007) reported seemingly consistent evidence, it might have been "too consistent". Given their small sample sizes and thus very low statistical power, it was very unlikely for Gailliot et al. (2007) to consecutively find 9 significant results. According to Schimmack's (2012) calculation, Gailliot et al.'s (2007) probability to get 9 statistically significant results was indeed less than 1%. Further, after a re-analysis of Gailliot et al.'s (2007) data, Kurzban (2010) showed that the first hypothesis might not be true. Although in Gailliot et al.'s (2007) Study 1, there was a reduction of glucose level after the initial self-control task, none of Studies 3 to 6 showed a significant decrease. Instead, there were slight increases after initial exertion of self-control in Studies 4 to 6.

Because Schimmack's (2012) argument was on the theoretical level and it might be easy to retort that implausibility does not mean impossibility, it has not been mentioned by Baumeister and colleagues. However, Kurzban's (2010) re-analysis, which was based on Gailliot et al.'s (2007) data, is difficult to bypass. Therefore, Baumeister conceded that the first hypothesis might be wrong but the second and third hypotheses were correct (Baumeister, 2014; Baumeister & Vohs, 2016b). However, these three hypotheses are tightly intertwined. They are actually different dimensions of one thing. Certainly, this is still on the theoretical level and there is still space for retort. So I will return to the empirical level.

A recent meta-analytic article using the *p*-curve analysis found even within studies yielding significant results, there was no evidence showing an association between glucose and self-control (Vadillo, Gold, & Osman, 2016). However, this research might not be convincing due to its limitations. First, it did not directly test all three hypotheses of the glucose view. Second, besides studies testing the three hypotheses, it also included studies that examined the association between glucose and self-control in non-depletion contexts (e.g., Wang & Dvorak, 2010). Third, the *p*-curve analysis only focuses on statistically significant results and thus has its own inherent shortcomings. I addressed these limitations in another meta-analysis in which I directly tested the three hypotheses by using the random-effects model with strict inclusion criteria (Dang, 2016). It was found that none of the hypotheses was supported (the first hypothesis: $k = 11$, $N = 386$, $g = 0.05$, 95%CI [-0.13, 0.23]; the second hypothesis: $k = 8$, $N = 275$, $r = 0.15$, 95%CI [-0.16, 0.42]; the third hypothesis: $k = 15$, $N = 660$, $g = 0.23$, 95%CI [-0.08, 0.54]). The results for the second and third hypotheses also showed signs of the small-study effects, such that almost all experiments that reported high effect sizes were conducted in very small samples. In contrast, experiments with larger sample sizes tended to find null effect or reverse effect. Although the number of studies included in

this meta-analysis was rather small and a strong empirically based conclusion might not be drawn, it at least indicates that it might be the time to change our mind from the glucose view to new perspectives.

The glucose view may also not withstand theoretical analysis. In the context of the continuous overall energy expenditure of the brain, energy consumption expended on any one particular task is negligible (as little as 1%, Raichle & Mintun, 2006) and unlikely to result in noticeable decreases in peripheral blood glucose (Clarke & Sokoloff, 1998; Kurzban, 2010). Ironically, short vigorous physical exercise, which does consume a large amount of energy and lead to decreases in blood glucose level, has been demonstrated to improve, rather than impair, subsequent tasks requiring cognitive control of attention (Hillman et al., 2009; Tomporowski, 2003). Therefore, the glucose explanation of self-control can hardly be supported, empirically as well as theoretically.

3.1.3.3 How do moderators restore resource?

One may argue that the implausibility of glucose as the physiological substrate of self-control does not necessarily falsify the strength model, anyhow there might be other substrates that are responsible for depletion, such as dopamine, norepinephrine, serotonin, or some combinations of these. Although researchers suggested that there was no evidence supporting this speculation (Evans, Boggero, & Segerstrom, 2016) and this way of thinking was distracting and misleading (Hockey, 2011), I try to be open-minded and temporarily accept this possibility. That is to say, I assume some resource anyhow no matter what exactly it might be.

In the updated version, Baumeister and colleagues argue that more resource could be mobilized in case of need, such as when an individual is highly motivated to engage in a self-control task and when belief of having unlimited resource is manipulated. Besides these, there are many other factors that can moderate the ego depletion effect. A prominent one is positive emotion induced by a comedy video or a surprise gift, which was first reported by Baumeister and colleagues (Tice, Baumeister, Shmueli, & Muraven, 2007). Similar findings were found in subsequent studies (Ren, Hu, Zhang, & Huang, 2010; Wenzel, Conner, & Kubiak, 2013). In addition, self-affirmation (e.g., Kang & Sundar, 2013; Schmeichel & Vohs, 2009), self-awareness (e.g., Alberts, Martijn, & de Vries, 2011), high-level-construal (e.g., Agrawal & Wan, 2009), goal priming (e.g., Martijn et al., 2007), goal monitoring (e.g., Wan & Sternthal,

2008), personal prayer (Friese, Schweizer, Arnoux, Sutter, & Wänke, 2014), and meditation (Friese, Messner, & Schaffner, 2012) have also been found to reduce ego depletion.

How does the strength model explain these effects? In Tice et al.'s (2007) article, they wrote: "we cannot be sure whether positive mood actually replenished the resource that had been depleted by the initial self-regulation, as opposed to merely making participants more willing or motivated to continue self-regulating despite their depleted state" (p. 384). These two possible mechanisms apply to all moderators mentioned above in the framework of the strength model, because they are the only two potential explanations offered by the strength model. However, both of them are difficult to defend. It is hard to reason why and how watching a video (positive emotion), writing why one values something (self-affirmation), or unscrambling several sentences that start with "I" (self-awareness) have the function of supplying extra energy. It is likewise hard to reason why and how these activities could motivate people to increase their self-control without any other mechanisms. May be it is really hard to reconcile, in most articles introducing the updated version of the strength model, Baumeister and colleagues did not explicitly address these moderating effects (Baumeister, 2014; Baumeister & Vohs, 2007; Baumeister et al., 2007). In their most recent work, they listed some of these moderators but did not give deliberate explanation (Baumeister & Vohs, 2016b).

3.1.3.4 Can the resource be fully depleted?

Even if one assumes that the strength model possesses the capacity to reconcile those moderating effects just mentioned, it still has difficulty to reconcile other relevant findings. Although the updated version acknowledges the roles of motivation and belief manipulation, in the updated version A it draws a bottom line that may not be crossed because the resource is anyhow limited. That is to say, when depletion is severe, further control seems unlikely to be successful no matter how strong the motivation is, just as Vohs et al. (2012) has shown. However, Vohs et al. (2012) failed to control the experimental duration for different conditions and might have introduced confounding factors. For example, in their Study 2, participants in the control condition only did a simple version of the *e*-crossing task before the final task. Those in the mild depletion condition completed a demanding version of the *e*-crossing task following the simple version, and those in the severe depletion condition finished an emotion suppression task followed by a binary choice task and the demanding *e*-

crossing task. In a recent study, we controlled the duration of each condition but varied the level of depletion by manipulating different numbers of demanding task (Xiao, Dang, Mao, & Liljedahl, 2014). We found engaging in two demanding tasks did not lead to more depletion effect but offset the ego depletion effect. Tempel, Schwarzkopp, and Mecklenbräuker (2016) also reported similar finding. Certainly, these studies all employed infrequently used tasks. By using frequently used tasks, Converse and DeShon (2009) even found a reverse ego depletion effect after two initial demanding tasks. Importantly, in a meta-analysis that included studies empolying frequently used tasks, Article II found the weight average effect size of multiple depletion (i.e., engaging in two initial self-control tasks) was not statistically significant, thus providing evidence against the resource constraint hypothesis.

The proponents of the updated strength model might argue that two or three demanding tasks are still not taxing enough to make the "tank" become completely empty. However, it is very difficult to determine how many tasks or how long depletion would drain our self-control resource so no further resource could be mobilized by extra motivation. There was a study showing that engaging in an antisaccade task lasting for 40 minutes, which was much longer than the typical depletion manipulation lasting for 5-10 minutes as well as multiple depletion using several tasks, did not lead to ego depletion (Brewer, Spillers, McMillan, & Unsworth, 2011). And, very importantly, all studies mentioned here found either reverse ego depletion effect or no ego depletion effect without resorting to extra manipulations of motivation or perception, which is especially challenging for the strength model because this model predicts exacerbated ego depletion for the manipulation of multiple depletion. Similarly, a study in the area of mental fatigue showed that motivated participants were able to keep their performance on the flanker task for 60 min without gradual decline (e.g., Bonnefond, Doignon-Camus, Hoeft, & Dufour, 2011). Therefore, it seems very difficult to draw a bottom line under which the so called self-control resource is drained. By contrast, it has been argued that the brain has both sufficient resources and resource delivery mechanisms supporting self-control but these resources are allocated in accordance with personal priorities (Beedie & Lane, 2012). This view seems more consistent with the empirical evidence.

Certainly, there is still space for dispute because engaging in a demanding task for one hour or even longer may not be taxing enough. "Extremes states of depletion are not typically achieved with laboratory procedures, for ethical and practical reasons" (Baumeister & Vohs, 2016b, p. 88). However, evidence from work places where real exhaustion might happen could shed light on this debate. Using longitudinal field observations of 4,157 hospital

caregivers who experienced more than 13.7 million hand hygiene opportunities, Dai, Milkman, Hofmann, and Staats (2015) found hand hygiene compliance rates dropped by 8.7% from the beginning to the end of a typical 12-hr work shift. This decline in rule compliance was intensified by increased work intensity but could be offset by longer breaks between work shifts. This seems highly consistent with the strength model. However, the story does not end here. Subsequently, the same group found electronic monitoring was able to raise hand hygiene compliance rates in a group of 5,247 caregivers (Staats, Dai, Hofmann, & Milkman, 2017). This finding indicates that even facing exhaustion after a workday with high workload, we are still able to mobilize our energy as long as there is a need.

3.1.3.5 Do we really need the concept of resource?

If we accept that there is no real bottom line, as described in the updated version A, there is still a life-saving straw, the updated version B, which suggests ample energy for depleted people who just do not want to exert because they tend to conserve energy. Yet the question here is why people tend to conserve energy despite having ample energy. The only possible reason is that people think energy is limited. If so, however, it would have nothing to do with the resource itself but would just be a matter of perception or belief, as Job and colleagues have shown (Job et al., 2010). Actually, there are not only people who believe energy is unlimited for exerting, which leads to cancelled ego depletion, there are also individuals who believe exerting is energizing and thus can bring more resource, which leads to reverse ego depletion (Savani & Job, 2017). Therefore, it seems we do not really need the concept of resource that is often vague and misleading.

It is important to note I am not implying individuals can continuously exert self-control or engage in demanding tasks as long as they are sufficiently motivated. The body itself does have its physiological constraints that limits our capacities. However, energy is only a small part of the whole story. These constraints are much more complex. Within the body's physiological limit, the concept of resource is not necessary for understanding self-control. However, although the strength model may be incomplete, its contribution cannot be denied because it sparked volumes of studies in self-control and made self-control a hot topic these days.

3.2 Opportunity Cost Model

Kurzban et al. (2013) argued against the strength model and developed a model emphasizing opportunity cost. According to these authors, prioritization, which means choosing what to do at the expense of other options, is necessary when facing the problem of simultaneity that not everything can be done at once. “In the context of behavior, one cannot work toward multiple goals at the same time to the extent that there are incompatibilities in reaching those goals” (p. 664). Solving the problem of prioritization requires computing the costs and benefits of candidate options and comparing them in order to reach the best result. These authors proposed using opportunity cost to prioritize. That is to say, the allocation of mental processes to a task carries opportunity costs equal to the value of the alternative use of these mental processes. These opportunity costs are perceived as unpleasant sensations such as effort, fatigue, and boredom, which would in turn determine whether the mental engagement to a specific task should be continued or not.

When it comes to explaining ego depletion, the opportunity cost model suggests that initial self-control evokes a sense of effort that is uncomfortable and makes participants in the depletion condition feel they have discharged more of the obligation of participation than those in the control condition. That is to say, the benefit of doing further control (e.g., gaining credit points or money), which is the opportunity costs of engaging other activities such as daydreaming, has reduced. Therefore, participants in the depletion condition tend to disengage from the subsequent self-control task to some extent and devote part of their mental processes toward other rewarding activities, which thus leads to a performance decline in subsequent control.

3.2.1 Pros and cons

The opportunity cost model dispenses with the vague concept of resource and starts to pay attention to the important role of the sensations that result from initial exertion, which is a theoretical advance. However, its main focus is the computation of opportunity cost. The variance of option sets would lead to different computations of opportunity costs and thus different levels of uncomfortable sensations. This kind of view has several drawbacks. First, it is unlikely that our mind is able to estimate the opportunity costs for all alternatives, even implicitly. Second, there are numerous circumstances in which we cannot voluntarily

distribute our attention due to many powerful distractors that would inevitably capture our attention but provide no benefit at all for us no matter in the short run or in the long run. These two issues were raised by Navon (2013) and acknowledged by Kurzban et al. (2013) themselves. Third, in my opinion, this model mistakes importance as necessity. That is to say, available options might influence subjective feelings, which is important, but subjective feelings result from not only computations of opportunity costs of available options but also many other factors such as weather and social interactions, therefore the computation of opportunity cost is not the necessary condition of subjective feelings. Actually, subjective feelings such as effort and fatigue mainly result from engaging in demanding tasks itself because effortful control is intrinsically aversive (Kool, McGuire, Rosen, & Botvinick, 2010).

Further, when it comes to the specific explanation of ego depletion, the opportunity cost model is also very limited. On one hand, although it might explain the ego depletion effect in the lab, it would have difficulty to explain this effect in daily life. For example, by using experience sampling method, Hofmann, Vohs, and Baumeister (2012) found frequency and recency of engaging in prior self-control negatively predicted subsequent success at resisting desires on the same day. In the case, there is no obligation to discharge. On the other hand, even for ego depletion in the lab, evidence does not support the opportunity cost model. As shown by Hagger et al.'s (2010) meta-analysis, there was no moderation of the ego depletion effect as a function of whether the first task and the second task were described as two separate studies. Therefore, the opportunity cost model fails to provide a reasonable explanation for ego depletion. However, it challenged the strength model, introduced controversy, and turned research focus towards the role of effort and related phenomenology.

3.3 Process Model

Similar to Kurzban et al. (2013), Inzlicht and colleagues also developed an explanation focusing on the aversiveness of effortful control and prioritization (Inzlicht & Schmeichel, 2012, 2016; Inzlicht et al., 2014). Because this explanation specifies the psychological processes that lead to ego depletion, it is called the process model. According to this model, self-control wanes overtime because people's preferences or priorities have changed rather than the resource has been depleted. Because effortful control is intrinsically aversive, people generally tend to avoid it (Desender, Buc Calderon, Van Opstal, & Van den Bussche, 2017; Kool et al., 2010). As exerting effortful control, the aversive feeling would accumulate, which

leads people to more strongly avoid further control but more strongly value rewards that can bring gratification (Kool & Botvinick, 2014). That is to say, "although people generally avoid hard work and cognitive exertion, they may be especially unmotivated to engage such effort after having recently worked, instead preferring to pursue more inherently pleasurable activities" (Inzlicht et al., 2014, p. 129).

According to these authors, on one hand, this motivational shift from "have-to" goals, which are out of obligation and duty, to "want to" goals, which are fun, personally enjoyable, and meaningful, seems evolutionarily adaptive because it allows an organism not only to mentally engage in a task to attain rewards and resources, but also to disengage from it and seek activities that may be even more gratifying. One the other hand, this motivational shift also influences all information-processing modalities such as perception, attention, memory, and emotion (Inzlicht & Schmeichel, 2016). For example, Schmeichel, Harmon-Jones, and Harmon-Jones (2010) found initial exertion made people more sensitive to rewarding signals such as a dollar sign.

3.3.1 Pros and cons

The core idea of the process model is not something new. Thirty years ago, Navon (1989) expressed almost the same thought. "Effort is not any scarce commodity. It is the aversive valence of the operation of decoupling. The more sustained decoupling is, the more aversive it is…because effort is aversive, motivation is needed to override the aversion" (p. 203). This does not mean that the reinstatement of this idea in self-control by Inzlicht and colleagues is trivial. Instead, it is of great importance and might be seen as the best alternative explanation of ego depletion without considering the new model that will be proposed later.

First, it focuses on motivation itself and thus is very easy to explain the cancelling effect of extra motivations, either intrinsic or extrinsic motives (e.g., Muraven & Slessareva, 2003), perceptions of depletion (Clarkson et al., 2010), and beliefs about self-control resource (e.g., Job et al., 2010) mentioned above. Second, this model emphasizes the aversiveness of effortful control and treats it as the driver of the motivational shift. From this perspective, factors that can soothe the aversive feeling after initial control would help to offset the ego depletion effect. Therefore, the moderating effects of positive emotion (e.g., Tice et al., 2007), self-affirmation (e.g., Schmeichel & Vohs, 2009), personal prayer (Friese et al., 2014), and meditation (Friese et al., 2012) are also compatible with this model. Third, the motivational

shift hypothesis has gained empirical supports. Although in the literature there is little evidence showing that ego depletion is directly mediated by changes in motivation or goals, "the absence of evidence should not be confused with evidence of absence" (Inzlicht & Schmeichel, 2016, p. 174). A group of recent findings are consistent with the motivational shift hypothesis. For example, individuals in a state of depletion reported low commitment to (Walsh, 2014) as well as low importance of (vanDellen, Shea, Davisson, Koval, & Fitzsimons, 2014) their control goals. In contrast, the rest goal becomes more accessible after initial depletion, especially for these believing having limited self-control resource (Job et al., 2015). More directly, chronic dieters showed increased food-cue-related activity in a brain area associated with coding the reward value after having engaged in effortful control (Wagner, Altman, Boswell, Kelley, & Heatherton, 2013).

However, this model also has limitations. First, this model is hard to reconcile a group of findings derived from a cognitive control perspective (see below). For example, it is difficult for the process model to explain why there is a reverse ego depletion effect when the two consecutive tasks require similar control processes (Dewitte et al., 2009) and why engaging in a short period of the Stroop task leads to ego depletion while engaging in a long period of the Stroop task cancels ego depletion (Dang, Dewitte, Mao, Xiao, & Shi, 2013). Second, for the moderating effects of self-awareness (e.g., Alberts et al., 2011), high-level-construal (e.g., Agrawal & Wan, 2009), goal priming (e.g., Martijn et al., 2007), and goal monitoring (e.g., Wan & Sternthal, 2008), the process model's explanation is not straightforward. Although it might accommodate these effects by assuming that the re-activation of overarching goals highlights the importance of these goals and thus instigates further motivation, it does not specify the underlying mechanisms.

3.4 Cognitive Control Account

From a cognitive control perspective, the ego depletion effect can be considered as a phenomenon similar to "switch costs" (Kiesel, et al., 2010). That is to say, after initial exertion of effort, the control processes being recruited to engage in the first self-control task would linger and interfere with the operation of the control processes required by the subsequent self-control task (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Dewitte et al., 2009). For instance, after struggling with the resistance of a high-calorie food, a dieter would find it difficult to control his/her anger toward someone who is provoking, because the control

system is still geared towards resisting temptations, which impedes the recruitment of control processes for regulating emotions. The control inertia that results from initial engagement and leads to interference for following performance is also referred to as “attention residue” (Leroy, 2009)

This reconceptualization has several important implications (Dang et al., 2014). First, although the control inertia is detrimental for subsequent control if the two consecutive tasks require different control processes, it is beneficial when the two tasks recruit similar control processes because the required control processes for the second task are already activated, thus leading to a reverse ego depletion effect. Empirical evidence from both lab experiments (Dewitte et al., 2009; Duh, Grubliauskiene, & Dewitte, 2016) and ecological momentary assessment (EMA) studies (O'connell, Schwartz, & Shiffman, 2008) supported this corollary. For instance, pre-exposure to candies induced resistance that then spilled over to successful intake restraint for other unhealthy food (Duh et al., 2016).

Second, even if the two consecutive tasks recruit different control processes, the interference is not inevitable. One on hand, although the interference is strong right after switching to the second task, it becomes weaker and weaker as the control inertia wane over time. Therefore, ego depletion is stronger at the beginning of the second task than at the later phase (Barutchu, Carter, Hester, & Levy, 2013). One the other hand, allowing people sufficient time to adapt to the initial task decreases the control inertia. Consistent with this idea, Dang et al. (2013) found engaging in a short period of the Stroop task led to ego depletion while engaging in a long period of the Stroop task cancelled ego depletion. Interestingly, there was also a negative correlation between the adaptation level and the depletion effect, such that the more respondents adapted to the first task (i.e., smaller Stroop effect), the less errors they made on the second task (Dang et al., 2013). From this adaptation perspective, Brewer et al.’s (2011) failure to find ego depletion by using a 40 minutes antisaccade task as the depleting task is not surprising but rather reasonable. In addition, when people chronically control their responses to temptations, some of them can gradually adapt to a module of resisting these temptations. For example, successful dieters could develop an automatic asymmetric activation association such that food temptation representations activate dieting goal representations whereas goal representations inhibit temptation representations spontaneously (Fishbach, Friedman, & Kruglanski, 2003; Papies, Stroebe, & Aarts, 2008). These people would not suffer from ego depletion when food intake is used as

the depleting task or the outcome measure, which was first speculated by Dang et al. (2013) and then demonstrated by Friese, Engeler, and Florack (2016).

Third, factors that reduce switch cost and facilitate switching should offset ego depletion. For example, dopamine D2 follows an inverted-U-shaped relationship with task switching ability (Stelzel, Fiebach, Cools, Tafazoli, & D'Esposito, 2013). Correspondingly, a recent study found individuals with medium level of dopamine D2, as measured by spontaneous eye blink rate, were protected from ego depletion, whereas those with high or low levels showed typical ego depletion (Dang, Xiao, Liu, Jiang, & Mao, 2016). The moderating effect of positive emotion can also be understood in this way to the extent that positive emotion is related to enhanced flexibility of switching to new cognitive sets by directing attention to novel information (Dreisbach and Goschke, 2004). This should be in addition to the soothing effect of positive emotion mentioned above. As Wenzel et al. (2013) showed, positive emotion neutralized ego depletion in the typical paradigm where the two consecutive tasks required different control processes but led to ego depletion when similar control processes were recruited by these tasks. Further, preparation has also been shown to attenuate switch costs (Kiesel, et al., 2010). The meta-analytic result of multiple depletion reported in Article II could be explained in this way considering the requirement of continuous exertion helps respondents get more prepared for switching to the following demanding task.

3.4.1 Pros and cons

The cognitive control account provides a purely cognitive explanation for ego depletion. Not only does it explain findings that are incompatible with both the strength model and the process model (e.g., the null effect of multiple depletion), but it also generates novel hypotheses that beyond the explanation of these two models (e.g., Dang et al., 2013; Dang et al., 2016; Wenzel et al., 2013). However, it alone is not sufficient to explain the ego depletion effect, especially the moderating effects of motivation (e.g., Muraven & Slessareva, 2003), and belief about self-control resource (Job et al., 2010). Therefore, in the following section I propose a new model that integrates the cognitive control account, the process model, and the cybernetic theory.

3.5 A New Explanation: The CoMo Model

On the basis of these theoretical analyses, I propose a new fine-grained model that specifies two channels and a more proximal mechanism through which following self-control performance is influenced, as can be seen in Figure 1. The first channel is a cognitive channel drawn from the cognitive control account. This channel suggests that the control processes activated by initial exertion of self-control would linger for a while. These attention residues would interfere with the control processes required by the subsequent self-control, providing these two self-control tasks recruit different control processes. The second channel is a motivational channel drawn from the process model, which suggests that the aversive sensation resulting from initial exertion leads to a motivational shift from exerting more control to seeking more reward. Because of cognitive interference and motivational shift, people's ability to effectively maintain the goal of exerting further self-control, monitor the mismatch between the goal and the actual state, and take actions to reduce the mismatch would be impaired. Note that in the cybernetic theory, goal and monitoring are prerequisites of operation, therefore goal and monitoring are primarily influenced by cognitive interference and motivational shift.

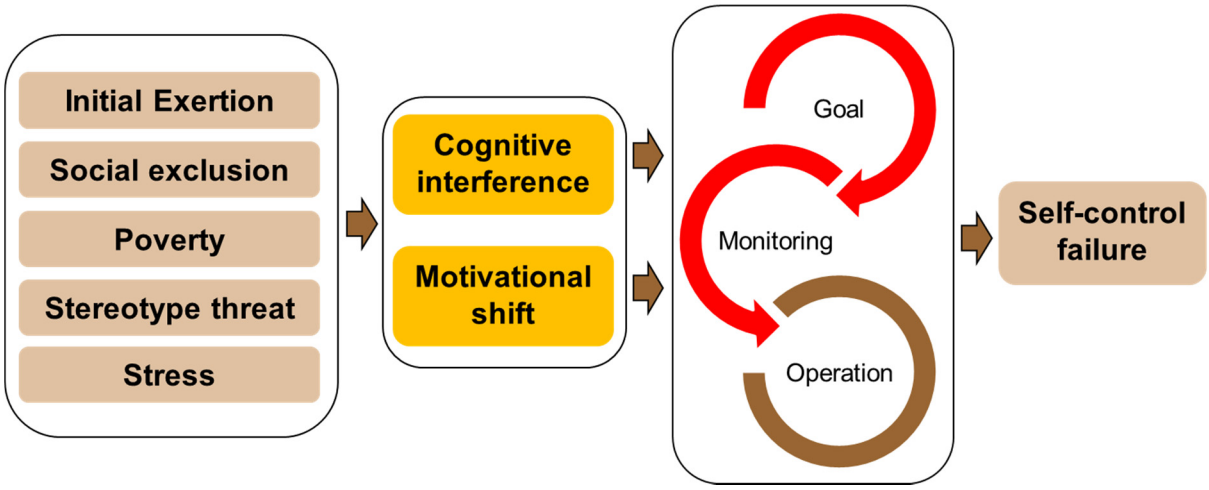

Figure 1. The CoMo model.

3.5.1 Pros and cons

The CoMo model integrates the cognitive control account, the process model, and the cybernetic theory, therefore it is able to explain almost all counterintuitive findings in this

area, as shown in Table 3. It can explain the moderating effects of motivations (e.g., Muraven & Slessareva, 2003), perceptions of depletion (Clarkson et al., 2010), beliefs about self-control resource (e.g., Job et al., 2010), positive emotion (e.g., Tice et al., 2007), self-affirmation (e.g., Schmeichel & Vohs, 2009), personal prayer (Friese et al., 2014), and meditation (Friese et al., 2012). It can also explain the null effect of multiple depletion found in Article II as well as the adaptation effect (Brewer et al., 2011; Dang et al., 2013) and related findings (e.g., Dang et al., 2016). In addition, the moderating effects of self-awareness (e.g., Alberts et al., 2011), high-level-construal (e.g., Agrawal & Wan, 2009), goal priming (e.g., Martijn et al., 2007), and goal monitoring (e.g., Wan & Sternthal, 2008) are also compatible with the CoMo model, because these factors are able to make the reduced control goal and the mismatch between the goal and the actual state salient or accessible again, thus facilitating further control.

Table 3

Explanabilities of Each Theory

Finding	Original strength model	Updated strength model	Opportunity cost model	Process model	Cogntive control account	CoMo model
Typical ego depletion	√	√	√	√	√	√
Moderating effect of rest	√	√	√	√	√	√
Moderating effects of motivation, belief, and perception		√	√	√		√
Moderating effects of positive emotion, self-affirmation, prayer, and meditation			√	√	√	√
Null effect of multiple depletion					√	√
Adaptation effect					√	√
Moderating effects of self-awareness, high-level-construal, goal priming and goal monitoring						√

Regarding the pragmatic implications about how self-control could be improved, the strength model suggests only one way, to practice, often by engaging in activities overriding strong habits. However, a very recent meta-analysis including 33 studies and 158 effect sizes questioned the effectiveness of practicing self-control (Friese, Frankenbach, Job, & Loschelder, 2017). Although the overall raw effect was significant, $g = 0.30$, 95%CI = [0.17, 0.42], the bias-corrected estimate was much smaller, $g_{correct} = 0.12$ to 0.24. Importantly, unpublished studies led to a non-significant result, $g = 0.13$, $p = .338$, although results from published studies were significant, $g = 0.37$, $p < .001$. Studies with pre-post design, which led to more precise estimate for the training effect, yield a non-significant result, $g = 0.18$, $p < .069$, although studies with only post intervention measures led to a significant result, $g = 0.31$, $p < .001$. Interestingly, studies conducted by proponents of the strength model yield much higher estimate ($g = 0.51$, $p < .001$) than did studies conducted by non-proponents ($g = 0.22$, $p = .004$). Therefore, whether self-control could be improved by training is pending.

However, from the perspective of the CoMo model, there are various ways to help people avoid self-control failure. Any factors that can soothe the aversive feeling or negative mood resulting from initial control activities, that can provide extra motivation, that can promote switching to a task, that can facilitate adaptation to task demands, that can help people main the control goal and monitor the mismatch between the goal and the behavior, would be useful. Therefore, the CoMo model depicts a very positive but also realistic picture for self-control intervention.

4 Summary of Empirical Studies

4.1 Article I

4.1.1 Background

In 2015, Martin Hagger and Nikos Chatzisarantis initialized a multi-lab replication of Sripada et al.'s (2014) ego depletion experiment. Twenty three laboratories ($N = 2141$) participated but failed to replicate the ego depletion effect (Hagger et al., 2016). The overall effect size was almost zero, $d = 0.04$, 95% CI [-0.07, 0.15], without using any bias-correcting method.

The depletion manipulation was a modified version of the *e*-crossing task. In the depletion condition, participants were presented with a series of words on a computer screen and were required to press a button when a word with the letter "e" was displayed and withhold the response if the "e" was next to or one letter away from a vowel. Participants in the control depletion were only required to press a button whenever a word with the letter "e" was displayed. The task comprised 150 trials and lasted for 7.5 minutes. After the depletion manipulation, participants completed self-reported manipulation check items measuring effort, fatigue, difficulty, and frustration on the *e*-crossing task.

Subsequently, all participants were required to complete a multi-source interference task (MSIT). The stimuli were sets of three digits on the screen. Participants were asked to place their index, middle, and ring fingers of the right hand on three keys on the keyboard corresponding to three target digits (1, 2, 3), and respond to the identity of the target digit rather than its postion in the set of digits. The target digit was the one different from the other two digits in the set. In control/congruent sets, the target digit always matched its position (e.g., 100, 121, 113). In interference/ingruent sets, the target digit never matched its position (e.g., 131, 233, 212). There were 200 trials (100 congurent and 100 incongruent trials) in total, which lasted for approximately 10 mitutes. The dependent measures were reaction times (RT) and reaction time variability (RTV) on incongruent trials.

4.1.2 Method and Results

Article I was a re-analysis of Hagger et al.'s (2016) data. Datasets from different labs were collapsed into a single dataset. First, I examined the difference in the manipulation check items between the depletion condition and the control condition. These two conditions did not differ with each other in one of the four manipulation check items (i.e., fatigue). Although they differed in the other three items, scores on only one item (i.e., effort) were above the midpoint the scale (i.e., "4"). That is to say, even in the depletion condition, the *e*-crossing task was generally considered not "depleting", thus questioning the effectiveness of the depleting task.

Next, I examined the interaction between experimental condition and each manipulation check item and found an significant interaction between condition and perceived effort on both RT and RTV. Simple slopes analysis showed that, in the control condition effort predicted neither RT nor RTV, whereas in the depletion condition the simple slope was

positive and differed significantly from zero, for both RT and RTV, indicating that the more effort participants exerted during the initial depleting task, the worse they performed on the subsequent self-control task. The interactions between experimental condition and other three manipulation check items were not statistically significant.

4.1.3 Conclusion

In conclusion, this re-analysis implies that Hagger et al.'s (2016) manipulation may not be strong enough to work for every participant. For some participants it is considered as effortful and thus "depleting", whereas for others it is not. For those who consider it as effortful, there is an ego depletion effect. Therefore, Article I highlights the importance of the effectiveness of the depleting task and also calls for attention to individual difference variables that might moderate the ego depletion effect.

4.2 Article II

4.2.1 Background

Carter et al. (2015) conducted a meta-analysis of ego depletion and restricted their analysis to studies that involved both frequently used depleting tasks and frequently used outcome tasks, following the logic that researchers tended to select tasks that seem to be the most valid operationalization of self-control and that provide the most interpretable results. They also included results from as many unpublished experiments as possible. This resulted in a more conservative estimate of the ego depletion effect, $g = 0.43$, 95% CI [0.34, 0.52], adjusted to $g = 0.24$, 95% CI [0.13, 0.34] by using the trim and fill method. However, the results also showed statistically significant small-study effects. After accounting for the small-study effects by using the precision effect test (PET) and the precision effect estimate with standard error (PEESE), the ego depletion effect was indistinguishable from zero.

However, cautious attention must be paid to their method and conclusion. First, Carter et al. (2015) did not test the effect of each depleting task. Therefore, a more accurate estimate of effect size might be concealed because ineffective depleting tasks were confounded. Second, PET-PEESE itself and their usage of PET-PEESE were both problematic, as I decribed in Section 2.4.1. In addition, Carter et al.'s (2015) meta-analysis covered studies that were conducted before 2013. After that, many new empirical studies emerged. Therefore, a more

updated meta-analysis taking these considerations into account was needed, which was what I have done in Article II.

4.2.2 Method

I carefully inspected each study included by Carter et al. (2015) to make sure their appropriateness for inclusion. Unsuitable studies were removed and inaccurate calculations were corrected. In addition, newly conducted studies not covered by Carter et al. were included to keep the analysis up to date. To do this, on Google Scholar I went through the full text of all papers that cited the two seminal empirical articles of ego depletion (Baumeister et al., 1998; Muraven et al., 1998) and the two most important theoretical integrations (Muraven & Baumeister, 2000; Baumeister et al., 2007) between 1st January, 2013 and 29th February, 2016, which results in 30 experiments in 26 articles (23 published and 3 unpublished) that employed one of the 10 frequently used depleting tasks as well as one of the 8 frequently used outcome tasks summarized in Tables 1 and 2.

As Carter et al. (2015) did, I calculated Hedge's *g* and adopted the random effects model when doing the meta-analyses. Unlike Carter et al. (2015), however, for the effect of each depleting task, I refrained from using PET- PEESE because of the small sample size but instead focused on the trim and fill, the most frequently used method for correcting publication bias (Borenstein, Hedges, Higgins, & Rothstein, 2009).

4.2.3 Results

The effects of multiple depletion and working memory were not significant. Although the random effects model revealed a significant effect for attention video, $g = 0.21$ [0.08, 0.33], after imputing effect sizes by the trim and fill method, this effect turned out to be not statistically significant, $g = 0.13$ [-0.02, 0.28]. In contrast, although the funnel plots were not asymmetric for crossing out letters and thought suppression, their effects were still statistically significant after new effect sizes have been imputed by the trim and fill. Food temptation yielded the highest effect but with high heterogeneity. The effect of attention essay, emotional video, and Stroop might be considered as reliable because of small to medium level of effect size and low heterogeneity.

When all depleting task were included, a small to medium level of effect with medium to high heterogeneity was found, $g = 0.38$ [0.31, 0.45], $I^2 = 60.67\%$, which was kept significant after imputing new effect sizes by the trim and fill, $g = 0.24$ [0.16, 0.32]. Because the analysis identified three depleting tasks that seemed to yield reliable effects (i.e., attention essay, emotion video, and Stroop), I did a tentative analysis by only including experiments using these three depleting tasks. The random effects model revealed a significant effect without the need for imputing new experiments, $g = 0.42$ [0.32, 0.51]. The heterogeneity has been reduced to a low level, $I^2 = 25.08\%$, thus satisfying the usage of PET-PEESE. As a result, both the PET coefficient ($b = 0.79$, $p < .001$) and the PEESE coefficient ($b = 0.56$, $p < .001$) turned out to be statistically significant.

4.2.4 Conclusion

This meta-analysis showed that attention video is likely to be an ineffective depleting task whereas emotion video should be the most effective one. When the analysis was restricted to experiments using reliable depleting tasks (i.e., attention essay, emotion video, and Stroop), the heterogeneity was reduced to a level suitable for PET-PEESE, which then yielded an estimate that was very close to the estimate of the random effects model. Therefore, this article highlights the importance of the depleting task's effectiveness and also suggests ego depletion is not a trivial effect.

4.3 Article III

4.3.1 Background

Article II revealed Stroop should be an effective depleting task. A large-scale study with pre-registration was needed to verify this finding, which was what I did in Article III. Because Article I suggested individual differences should moderate the ego depletion effect, three individual difference variables that have been examined at least twice were also included in Article III: trait self-control (Imhoff et al., 2014; Wang et al., 2015), action orientation (Dang et al., 2015; Gröpel et al., 2014), and lay theories about willpower (Job et al., 2015; Job et al., 2010).

4.3.2 Method

The sample size, procedure, and analysis plan were specified before data collection in the pre-registration (https://osf.io/ydc7z/). One hundred and seventy six students from a Chinese university were recruited. In the experiment, participants first completed a short questionnaire measuring those three individual difference variables. Next, they received the depletion manipulation (i.e., the Stroop task). In the depletion condition, they finished a Stroop task in which most trials were incongruent (256 trials, 75% incongruent, four different colors). In the control depletion, all trials were congruent. After the Stroop task, they answered four manipulation check questions regarding effort, difficulty, fatigue, and frustration on a 7-point scale (Hagger et al., 2016).

Finally, participants finished an antisaccade task that requires high level of attentional control (Unsworth et al., 2011) and has been used in ego depletion studies (e.g., Dang et al., 2016). The main task was to identify three target letters (B, P, and R) by pressing a corresponding key (the keys 1, 2, and 3, respectively) as quickly and accurately as possible. At the beginning of each trial, a fixation cross appeared for 200ms on the screen with a black background. A flashing white "=" was then flashed either to the left or right of the fixation cross for 100 ms, followed by a 50 ms blank screen and a second appearance of the sign "=" for 100 ms at the same location as the first one. This procedure made it appear as though the sign "=" flashed onscreen, which would easily grasp participants' attention. Following another 50 ms blank screen, the target stimulus (a letter B, P, or R) appeared in the opposite location of the flashing sign for 100 ms, followed by a letter "H" for 50 ms masking and a number "8" which remained onscreen at the same location as the target stimulus until a response was given. Participants received 30 practice trials (12 practice trials for learning the response mapping and 18 practice trials for doing the formal test) and 120 real trials. The primary dependent variable was the accuracy of the antisaccade task. The RT was also examined after trimming (i.e., longer than 200ms and short than 2000ms; Unsworth et al., 2011).

4.3.3 Results

The dependent measure (i.e., the accuracy of the antisaccade task) showed a statistically significant result. Participants in the depletion condition performed worse than did those in the control condition, Hedge's $g = 0.48$. 95%CI = [0.18, 0.78]. No significant between-group

difference was found on the RT, Hedge's g = -0.10, 95%CI = [-0.39, 0.20]. We also computed a composite index of the four manipulation check items. Across conditions, this index was not only correlated with antisaccade accuracy but also marginally significantly correlated with antisaccade RT, therefore suggesting an association between phenomenology and performance. None of the three individual difference varables moderated the ego depletion effect.

4.3.4 Conclusion

In summary, Article III demonstrated a significant ego depletion effect when the Stroop task was employed as the depleting task. The effect size is comparable to that found by the meta-analysis in Article II.

4.4 Article IV

4.4.1 Background

According to the dual-process theory of executive control (Kane & Engle, 2003; Engle & Kane, 2004), effective executive control is determined by two processes. The first process is the maintenance of the task goal in active memory whereas the second is the resolution of response competition. For instance, in the Stroop task, participants have to maintain the goal of naming the color (goal maintenance) and then overcome the prepotent response of saying the word (competition resolution). In a task context dominated by congruent trials, participants might tend to slip into reading the word rather than naming the color because they can respond both quickly and accurately on most trials even if they fail to act in accordance with the goal. Thus, the infrequent incongruent stimuli place especially high demand on goal maintenance. Participants should be more likely to make errors if the color-naming goal is temporarily lost, and/or to respond very slowly to a subset of incongruent trials if the goal is lost but then recovered from memory before committing an overt error. In contrast, in a task context in which all trials are incongruent, the need for goal maintenance is greatly reduced since all stimuli repeatedly reinforce the color-naming goal. Instead, such a task context should be more sensitive to individuals' capabilities of resolving response competition, as reflected in a consistent slowing on all incongruent trials (Kane & Engle, 2003). Article IV aimed to test which process (goal maintenance and competition resolution) was responsible

for ego depletion by using a meta-analysis that included all studies using Stroop as the second task in the ego depletion paradigm.

4.4.2 Method

On Google Scholar, we went through all research articles that cited the two seminal empirical articles of ego depletion (Baumeister et al., 1998; Muraven et al., 1998) and the two most important theoretical integrations (Muraven & Baumeister, 2000; Baumeister et al., 2007) before 31st, March, 2015. Other unpublished papers included in Carter et al.'s (2015) meta-analysis were also inspected. We calculated Hedge's *g* and two indices of publication bias, Begg and Mazumdar's rank correlation (Begg & Mazumdar, 1994) and Egger's regression intercept (β_0) (Egger et al., 1997).

4.4.3 Results

When congruent trials were included, especially when most trials were congruent, which poses high demand for goal maintenance, there was a significant ego depletion effect on Stroop errors without publication bias. This indicates that goal maintenance is impaired by intial exertion. When all trials were incongruent, which makes the task more sensitive to competition resolution, there was also a significant ego depletion effect on Stroop RT. However, the two indices of publication bias were also significant. This suggests competition resolution might also be impaired by self-control depletion but this conclusion should be drawn with caution.

4.4.4 Conclusion

According to the cybernetic theory of self-control, effective self-control depends on three major ingredients: goal/standard, monitoring, and operation (Carver & Scheier, 1982). The strength model only emphasizes the operation ingredient by arguing that this ingredient resembles a muscle or strength that could easily get depleted after engaging in an initial self-regulatory task (Baumeister & Heatherton, 1996; Muraven & Baumeister, 2000). As above mentioned, goal maintenance maps onto the first two ingredients (i.e., goal/standard and monitoring) whereas competition resolution maps onto the operation ingredient. Article IV found intial exertion impaired goal maintenance but its effect on competition resolution was

pending. Therefore, it suggests that the strength model at least needs a revision to reconcile these findings.

4.5 Article V

4.5.1 Background

The antisaccade task has also been used to disentangle goal maintenance and competition resolution (Unsworth et al., 2011). At the same time, the dual-process theory also makes predictions regarding the RT distribution, which can not be tested in Article IV because almost no study included in the meta-analysis reported the RT distribution. Therefore, in Article V the antisaccade task was employed as the outcome task and the RT distribution was also examined besides RT and error.

4.5.2 Method

One hundred and thirty-five college students (60 males and 75 females) in a Chinese university took part in this experiment. The procedure was similar to Article III. In the Stroop task, participant were required to press four buttons to indicate the ink color of the presented word on the screen. Participants in the depletion condition completed a difficult version (72 congruent trials and 72 incongruent trials) whereas those in the control condition completed an easy version (144 congruent trials). After that, they answered four manipulation check questions regarding effort, difficulty, fatigue, and frustration on a 7-point scale (Hagger et al., 2016). Finally, all of them completed the antisaccade task as the dependent measure. The antisaccade has been described in section 4.3.2 with an exception regarding the foreperiod. In Article III there was only one foreperiod (i.e., 200 ms). In Article V, there were five foreperiods (i.e., 200 ms, 600 ms, 1000 ms, 1400 ms, and 1800ms). We suspected that a medium foreperiod (e.g., 1000 ms) might be optimal for effective goal maintenance but both short and long foreperiods should pose high demand on goal maintenance (De Jong, Berendsen, & Cools, 1999; Unsworth et al., 2011).

4.5.3 Results

The shortest foreperiod (200 ms) led to a significant accuracy difference between the depletion condition and the control condition. When the foreperiod increased to 600 ms and 1000 ms, there was no observable accuracy difference between the depletion condition and the control condition. However, the disappeared difference showed up again as the foreperiod increased to 1400 ms and further to 1800 ms. By utilizing ex-Gaussian fitting, we tested the RT distribution of the antisaccade task and found initial exertion led to a longer right tail, which indicates failure of goal maintenance, but did not influence the entire distribution, which indicates no failure of competition resolution.

4.5.4 Conclusion

The results of both accuracy and the RT distribution suggest that initial exertion impairs goal maintenance but spares competition resolution, which contradicts the strength model because strength model predicts only competition resolution would be influenced.

5 General Discussion

In this dissertation, I reviewed the development of ego depletion, introduced current explanations, and proposed a new model that integrated various lines of research. Below I would briefly discuss the limitations of the empirical studies included here and the new CoMo model proposed here to inspire future research.

5.1 Limitations of Empirical Studies

Although Article III has demonstrated a robust ego depletion effect by utilizing strict pre-registration, it after all is a single study and in need of replications. Therefore, I invited researchers in this field around the world to do a multi-lab replication of this experiment. Thirteen labs have agreed to participate and the whole procedure of this project is transparent and open to everyone (https://osf.io/3txav/). The number of participating labs should have been higher because many researchers replied that they already committed to Vohs and Baumeister's replicating project and did not have extra resource to support participation in

this project. Although Vohs and Baumeister's replicating project is not open, I still highly appreciate their effort and am very looking forward to the results. Moreover, Article II showed the effectiveness of each frequently used depleting task. We only tested the Stroop task. More pre-registered studies are needed to verify the effectiveness of other tasks, especially the attention essay task and the emotion video task that also showed low heterogeneity.

Although Article IV and Article V provide initial evidence for disentangling the three ingredients of self-control, they are rather indirect. More direct methods are needed. Two tasks with EEG recording can be considered. The first one is the Go/No-go task. In this task, participants have to withhold a response (No-go) while the predominant tendency is to make an overt (Go) response. Compared with the Go stimulus, the No-go stimulus usually evokes a larger negative event related potential (ERP) with a maximum amplitude around 200 ms, the N2, followed by a larger positive potential with a maximum amplitude around 300 ms, the P3. These ERPs reflect different processes that underlie self-control. The N2 is thought to represent the detection of the response conflict (e.g., Donkers & Van Boxtel, 2004) while the P3 represents the subsequent inhibitory processes (Smith et al., 2008). Therefore, the N2 and the P3 are good indicators of the monitoring ingredient and the operation ingredient, respectively. If initial exertion impairs the monitoring ingredient in subsequent self-control, the N2 in the Go/No-go task would be smaller in the depletion condition than in the control condition. If initial exertion impairs the operation ingredient, the P3 would be smaller in the depletion condition.

Although the Go/No-go task is useful in disentangling the monitoring ingredient and the operation component, it does not provide a clear indicator for the goal/standard ingredient. Instead, recent research suggests that a modified version of the Continuous Performance Task, the AX-CPT, is able to provide neural indicators for all of the three ingredients of self-control (Morales et al., 2015; van Wouwe et al., 2011). This task requires participants to respond YES to every X probe following an A cue but respond NO to any probe that breaks that rule (i.e., BX, AY, or BY trials). The AX combination occurs at a very high frequency (70% of the trials), which induces a predominant tendency to respond YES. After the onset of the cue (A or B), in order to respond quickly and accurately to the following probe (X or Y), participants need to maintain the cue till the probe appears (the goal/standard component). When the probe appears, they detect whether the cue matches the corresponding probe (the monitoring ingredient), and then implement the specific response (the operation ingredient). The cue

would evoke a large positive potential with a maximum amplitude around 300 ms, the P3b, indicating the goal maintenance process. Subsequently, the probe would evoke a large negative potential with a maximum amplitude around 200 ms, the N2, followed by a large positive potential with a maximum amplitude around 300 ms, the P3a, indicating the conflict monitoring process and the control operation process, respectively. Therefore, recording the EEG during the AX-CPT after intial exertion would enable us to examine which of the three ERPs would be impaired by initial exertion of self-control and thus helps us clarify which self-control ingredient is primarily responsible for the ego depletion effect.

5.2 Limitations of The CoMo Model

The Como model specifies two channels through which initial exertion takes effect on subsequent control. Both the interference of the lingered control processes after initial exertion and the decreased motivation to engage in further effortful work contribute to impaired performance on the subsequent task. However, there might also be an interaction between there two channels. For example, successful adaptation to the initial task might gradually reduce the role of motivation-shift because adaptation attenuates the aversiveness of effort exertion that necessitates the motivated switching of task priorities, thus helping to overcome self-control depletion without recurring to additional motivation. Finding out how these two channels interact with each other during consecutive exertion is an important question for future research.

As shown in Figure 1, in addition to providing an intergrated explanation for the ego depletion effect, the CoMo model is also able to explain the detrimental effects of stress (Hamilton et al., 2014; Maier et al., 2015), social exclusion (Baumeister et al., 2005; Stenseng et al., 2015), poverty (Vohs, 2013) , and stereotype threat (Inzlicht & Kang, 2010) on self-control. All these factors have been linked with increased distractions, worries, or ruminations (e.g., Gianferante et al., 2014; Mani, Mullainathan, Shafir, & Zhao, 2013; Schuster, Martiny, & Schmader, 2015), which corresponds to the cognitive channel in the CoMo model. They also lead to aversive feelings that reduces the motivation to exert effortful control but increases the motivation to seek reward (e.g., Gerber & Wheeler, 2009; Goldberg et al., 2017; Maier et al., 2015; Neseliler et al., 2017), thus corresponding to the motivational channel in the CoMo model. As a result,executive functions, especially working memory, upon which

the three ingredients of self-control rely are impaired (e.g., Buelow, Okdie, Brunell, & Trost, 2015; Hutchison, Smith, & Ferris, 2013; Maier et al., 2015; Mani et al., 2013; Shields, Sazma, & Yonelinas, 2016), which leads to self-control failure. Similar to findings in ego depletion, variables that can soothe the aversive feeling/reduce switch costs, such as self-affirmation (Hall, Zhao, & Shafir, 2014) and social support (Pilcher & Bryant, 2016), that can provide extra motivation, such as external incentive (Baumeister et al., 2005), that can increase the important of the control goal, such as self-awareness (Baumeister et al., 2005), have been domontrated to reduce the detrimental effects of these factors. More studies are needed to test the explanability of the CoMo model.

6 Conclusion

In this dissertation, I provide solutions for the current challenge against the ego depletion effect, by analyzing how previous meta-analytic conclusion is misleading and utilizing meta-analytic tools and pre-registrations to demonstrate a reliable ego depletion effect. At the same time, I review the current explanations of ego depletion and analyze their pros and cons. On the basis of this work, I propose a new framework that not only is compatible with various lines of research in ego depletion, but can also be extended to explain the detrimental effects of many other factors, such as poverty and social exclusion, on self-control. This new framework has the potential to inspire both empirical research and practical intervention.

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