
Self-Regulatory Strength: Neural Mechanisms and Implications for Training

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4.1 Introduction

Exhausted with fatigue...the sailor on a wreck throws himself down to rest. But hardly are his limbs fairly relaxed, when the order “To the pumps!” again sounds in his ears. Shall he, can he, obey it? Is it not better just to let his aching body lie, and let the ship go down if she will? So he lies on, till, with a desperate heave of the will, at last he staggers to his legs, and to his task again.

William James, *The Principles of Psychology* (1890/1950, p. 562)

When considering this sailor’s plight, one can easily draw parallels to the common experience of a battered will in the face of life’s relentless stream of demands and responsibilities. While human beings possess the capacity to exert self-control in the service of long-term goals, health, and well-being, failure is common and

appears in many domains—from eating and drug-seeking behaviors to pathological gambling and infidelity in relationships (Baumeister et al. 1994). In the case of the aforementioned sailor, without “a desperate heave of the will,” failure is imminent and probably would mean that he would go down with the ship.

A predominant theory that has yielded many investigations of how and when people experience self-regulation failure is the limited resource or strength model of self-control (Baumeister and Heatherton 1996). The strength model proposes that the capacity to exert self-control draws upon a limited resource that, when reduced, increases the likelihood of giving in to unwanted and often unhealthy behaviors. By this reasoning, the capacity to regulate one’s behavior is likened to a muscle, which can become fatigued with overexertion. Following this overexertion, there is a lack of self-regulatory resources that prevents people from carrying out tasks that requires effortful cognitive and attentional control.

Since the strength model was originally proposed, a large body of behavioral work has generated supportive evidence of the model. Specifically, this line of research has identified many instances in which people show a conspicuous lack of self-regulatory strength and resources, what is commonly known as depletion. When people are in a depleted state, they are more likely to experience self-control failure across domains. Despite these established depletion effects, it is still not fully understood how exactly depletion exhausts self-regulatory capacity and

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which attendant cognitive processes are affected. Researchers in social and cognitive neuroscience have begun to tackle this issue by examining putative neural mechanisms for how self-regulatory strength is weakened by depletion, resulting in self-control failure. In doing so, they have begun to identify independent brain markers of the underlying cognitive processes impacted by depletion manipulations.

In this chapter, we first review supporting evidence from behavioral studies for the strength model. These studies have well established the means by which depletion weakens self-regulatory capacity and compromises future attempts at self-control. Next, we review recent investigations of the brain bases of self-regulatory strength and depletion. These investigations have given rise to three neurobiological explanations. The first account focuses on the idea that resource depletion disrupts top-down control processes within the prefrontal cortex (PFC) that are broadly associated with planning and regulation of behavior. A second account suggests that depletion may compromise the self-regulatory capacity through potentiation of the brain's emotion and reward circuitry. The third account draws upon the first two by suggesting that, depending on the demands in a given self-control context, depletion can undermine the regulatory functioning in the PFC, as well as potentiate emotion and reward systems.

We then explore the possibility of whether people can improve their self-regulatory strength and capacity, both in the short and long term by incorporating certain brain markers as an index to track training effects. We conclude with a roadmap suggesting future studies to assess domain-general versus domain-specific accounts of self-regulatory strength, as well as the extent to which training effects might cut across domains.

4.2 Behavioral Studies of Self-Regulatory Strength and Depletion

After the strength model was first proposed in the mid-1990s, experimental psychologists set out to identify the various ways people experience

self-regulatory depletion. Among the first, laboratory manipulations of depletion used thought suppression, an act presumably requiring strenuous mental effort. Specifically, Muraven and colleagues (Muraven et al. 1998) found that after participants actively suppressed thoughts about a white bear (see Wegner et al. 1987), they were less likely to persist on a difficult, unsolvable anagrams task. The researchers interpreted this effect as support for the limited resource account of self-regulation failure, with the thought suppression task depleting resources that would otherwise be allocated for persistence in a later task or for resisting the temptation to quit that task. This finding challenges folk theories and self-help programs that instruct people to ignore or suppress undesirable thoughts and emotions.

Other forms of suppression also seem to tap self-regulatory resources. For example, suppressing stereotypes predicts poor task performance on subsequent tasks (Gordijn et al. 2004). Additionally, inhibiting the physical expression of emotions (e.g., stifling one's laughter) also produces reliable depletion effects (Baumeister et al. 1998; Schmeichel et al. 2003; Vohs and Heatherton 2000).

In addition to thought and emotion suppression, there are several other means by which self-regulatory capacity is reduced, compromising future self-control attempts. In the domain of judgment and decision making, Vohs and associates (Vohs et al. 2008) conducted a set of studies revealing that the engaging decision-making processes and making autonomous choices deplete self-regulatory resources. Depletion effects also appear in and impact social behaviors. For example, the act of socially conforming is depleting (Kahan et al. 2003), as is being the target of prejudice (Inzlicht et al. 2006; Johns et al. 2008). As a social perceiver, managing impressions of others is a depleting act (Richeson et al. 2003; Vohs et al. 2005).

By the mid- to late 2000s, researchers across separate labs had implemented multiple methodologies and manipulations to test the strength model of self-regulation. Around that time, Hagger and colleagues (Hagger et al. 2010) carried out a meta-analysis that found that the evidence

supported the strength model, and that this model served as the best explanation of depletion effects as compared to other competing models (e.g., motivation-based theories).

In addition to confirming the validity of the strength model over and against other theories, self-control researchers sought to identify physiological substrates of self-regulatory strength and depletion. One prominent body of research has identified circulating levels of blood glucose as a potential biomarker of self-control (Gailliot et al. 2007). As glucose becomes depleted after successive self-control attempts, failure becomes more likely. By this reasoning, ingestion of glucose should reverse the short-term effects of depletion.

Before being implicated in self-regulation, glucose had previously been associated with cognitive benefits and enhancements. For example, early work by Benton et al. (1994) demonstrated that glucose ingestion improved attention and memory (inferred from faster reaction times). More recently, Parent and others (Parent et al. 2011) conducted a careful double-blind study to test the effects of blood glucose (vs. placebo) on memory processes. They found that elevated glucose levels facilitated memory encoding in the hippocampus, and that this was predictive of subsequent episodic recall. Furthermore, Smith and colleagues (Smith et al. 2011) reviewed the literature on ingested glucose's effects on memory and cognitive performance, noting consistent effects across populations (younger and older adults, and those with clinical syndromes that have accompanying cognitive impairment). They also observed that the biggest benefit was in the domain of verbal episodic memory, with glucose enhancing memory in young adults but only in contexts with increased cognitive demands (i.e., dual tasking). Consequently, researchers reasoned that glucose-mediated improvements in memory may appear in self-regulatory attempts following depletion. This glucose account has generated some debate, and interested readers should consult thoughtful rejoinders by Beedie and Lane (2012), Kurzban (2010), and Sanders et al. (2012).

4.3 Proposed Neural Mechanisms Underlying Self-Regulatory Strength and Depletion

Despite these behavioral studies providing ample evidence for the strength model and identifying glucose as a potential biomarker of self-regulatory strength, the underlying neural mechanisms of depletion—namely in terms of how it negatively impacts self-control—remained elusive. Thankfully, with the spatial resolution afforded by modern brain-imaging techniques (e.g., functional magnetic resonance imaging, fMRI), researchers can localize brain regions associated with self-regulatory strength and depletion. In addition to shedding light on general mechanisms, these regions and their activation patterns can serve as markers to help identify those individuals who are especially prone to depletion effects and self-control failure. Moreover, this brain-marker approach to understanding individual differences in self-regulatory strength may help clinicians who aim to develop individualized self-control training programs.

In this section, we consider the following three neural mechanisms of depletion that give rise to strained efforts to exert self-control: (1) compromised executive functioning in PFC, (2) increased impulse strength due to enhanced reward processing, and (3) an interplay between compromised executive functioning and increased impulse strength. These mechanisms can be likened to theories that conceptualize self-control as a struggle between desires and impulses on the one hand, and inhibitory forces on the other (Heatherton and Wagner 2011; Hofmann et al. 2009). Even Freud had a similar idea with his metaphor of the rider and his horse representing the ego and id, respectively (Freud 1923). Accordingly, one can compare the first mechanism (compromised executive functioning) to an incompetent rider, or the second mechanism (increased impulse strength) to a giddy and intractable horse.

4.3.1 Depletion Compromises Executive Functioning

The first mechanism was inspired by social neuroscience research and proposed that the self-regulatory resource that depletion taps and “drains” with repeated use consists of executive functions supported by regions in the PFC, such as the dorsolateral prefrontal cortex (DLPFC) that previously had been implicated in working memory processes. This account assumes that if someone completes a task that places strong processing demands on executive functioning, then performance on a subsequent task that requires self-control will diminish, presumably because both tasks draw from the same “pool” of executive functions. Additionally, the extent to which the first task depletes and weakens executive functioning should predict the magnitude of impaired performance in the second task.

Richeson and colleagues (Richeson et al. 2003) prompted the initial development of this account by conducting an fMRI study in which they measured neural correlates of self-regulatory depletion following a face-to-face interracial exchange (i.e., white participants, black confederates). They identified two regions, DLPFC and anterior cingulate cortex (ACC), that were activated in response to black faces and were correlated with implicit racial bias. Both regions had been linked with dissociable executive functions, with the DLPFC involved in cognitive control and the ACC responsible for detecting conflict between competing neural representations (MacDonald et al. 2000). In addition to DLPFC and ACC activity associated with implicit bias, participants who showed greater recruitment of these two regions also showed more self-regulatory depletion following an interracial exchange—as measured by Stroop interference (Stroop 1935). Richeson and coworkers concluded that the executive functions supported by DLPFC and ACC, presumably due to detecting (ACC) and inhibiting (DLPFC) implicit racial bias, were depleted and not available to be recruited during the

Stroop task. In this way, more activation of DLPFC and ACC served as an index of depleted (i.e., non-available) resources and predictive of poorer task performance (i.e., higher Stroop interference; see Richeson et al. 2003, Fig. 3).

More recent studies lend support to this account of executive functions in the PFC serving as a key brain basis of self-regulatory strength and depletion. Hedgcock et al. (2012) conducted an fMRI study to investigate the neural correlates of depletion by testing whether self-regulatory capacity was compromised based on a two-stage model of self-control (Hedgcock et al. 2012). This model characterizes self-control as proceeding first by way of conflict identification (e.g., “This cake is tempting but I have to follow doctor’s orders and stick to my diet”), followed by an implementation stage in which a person attempts to regulate behavior (e.g., “I am going to put the cake away and eat something else instead”). As mentioned, there are regions in the PFC that are associated with these two stages: the ACC for conflict identification and DLPFC for implementation, respectively. Hedgcock and colleagues found that participants showed diminished activity in the right middle frontal gyrus (a subregion within DLPFC) after prior exertion of attentional control. They interpreted this reduced DLPFC activity as a likely neural correlate of depletion, potentially indicative of weakened self-regulatory capacity.

In the emotion domain, Wagner and Heatherton (2013) found that participants who became depleted after completing a taxing attention-control task (adapted from Gilbert et al. 1988; Schmeichel et al. 2003) showed diminished communication between the ventromedial prefrontal cortex (VMPFC) and the amygdala upon viewing negatively valenced affective stimuli (Wagner and Heatherton 2013). The depleted group also exhibited greater activity in the amygdala in response to these negative stimuli, and one possible interpretation of this is that without top-down, regulatory “supervision” by the VMPFC, amygdala reactivity becomes exaggerated.

4.3.2 Depletion Increases Impulse Strength

A second account lays out another route by which depletion affects self-regulatory strength. This account claims that whenever a person's capacity to exercise self-control is compromised (e.g., during depletion), a key precipitating factor that leads to failure may be amplified activity associated with bottom-up reward and emotional processing—giving rise to increased impulse strength. Initial behavioral work suggests this possibility. Schmeichel and others (Schmeichel et al. 2010) conducted a set of studies revealing that the exercise of self-control increases approach motivation and attention to rewarding stimuli. More recently, Vohs and colleagues (Vohs et al. 2012) conducted a comprehensive set of field and in-lab studies showing that prior exertions of self-control led to heightened subjective feelings of emotion and desire. The authors claimed that depletion causes a broad shift in cognitive processing, from chronic monitoring and restraint-based processing to more evaluative processing, in turn weakening self-regulatory capacity. In fact, this seems to be a prevalent phenomenon that people experience in daily life (Hofmann et al. 2012).

Taken together, these findings allowed social brain scientists to make predictions about post-depletion neural activity in response to rewarding sensory cues, especially in populations that are more prone to depletion effects. For example, those who chronically restrain their eating tend to overeat when in a depleted state (Hofmann et al. 2007; Vohs and Heatherton 2000), but it remained unclear as to how depletion changed dieters' processing of food cues so as to drive overconsumption.

In recent neuroimaging work, Wagner and colleagues (Wagner et al. 2013) sought to address this issue by investigating the effects of depletion on neural responses to appetizing food images in dieters. They found that depletion affected the brain's reward and value systems, as indicated by increased activation in the orbitofrontal cortex (OFC), which has reciprocal connections with subcortical reward-related regions, namely the ventral striatum (Wagner et al. 2011).

This heightened reward activity that dieters show when depleted may also drive approach behaviors and bias eating decisions. Lopez and colleagues (Lopez et al. [submitted](#)) found that dieters showed a marked bias in their computer mouse trajectories during a food preferences task that was specific to appetitive, unhealthy foods. This bias was characterized by direct trajectories when dieters chose unhealthy foods and more curved trajectories towards unhealthy foods when healthy foods were chosen—presumably indicative of partial attraction to those unhealthy foods (cf. Spivey and Dale 2006).

Taken together, all of these findings converge on the idea that an important feature of self-regulatory depletion is an increase in reward value and impulse strength. Such an increase supports recent work by Vohs and colleagues (Vohs et al. 2012) showing that depletion leads to a global shift in evaluative processing and attendant increases in desire and impulse strength.

4.3.3 Depletion Affects both Executive Functioning and Impulse Strength

A third account proposes that in some instances, depletion may impact both bottom-up emotion and reward systems as well as top-down control processes. In their balance model, Heatherton and Wagner (2011) suggest that self-regulation failure occurs whenever the balance is “tipped” in favor of those brain areas associated with emotion and reward processing (Heatherton and Wagner 2011). As Heatherton and Wagner argue, this can happen in a bottom-up fashion, such as during exposure to tempting cues (for eating, see Jansen 1998), but it can also happen when functions associated with regulating thoughts and behavior are temporarily impaired, such as during alcohol consumption (Volkow et al. 2008).

For instance, Wagner and associates (in press) reported findings that might best be conceptualized as a “broken link” of communication between inferior frontal gyrus (IFG; an area associated with self-control of motor behaviors, Aron et al. 2004) and two reward-related regions, OFC and

ventral striatum, during exposure to food cues. This broken link implies that monitoring and control functions in the PFC may no longer reach brain regions associated with reward, allowing evaluative processing to take over and drive up the intensity of an impulse (cf. Vohs et al. 2012). This broken link has also been observed in the emotion domain. Wagner and Heatherton (2013) found that, following depletion, there was a different pattern of communication between PFC and the amygdala (a key region involved in emotion processing; Wagner and Heatherton 2013).

Additional studies are needed to investigate how prefrontal regions communicate and connect with emotion and reward systems, and how individual differences in this connectivity might predict self-control success (and/or failure). Even so, the evidence coming in thus far suggests that a brain-based account of self-regulatory strength and depletion likely implicates both bottom-up processing of appetitive and affective stimuli (which may give rise to increased subjective feelings of desire and impulse strength; e.g., Vohs et al. 2012; Wagner and Heatherton 2013) and top-down control processes in the PFC (e.g., Hedgcock et al. 2012). Indeed, future behavioral and neuroimaging investigations may benefit from studying the interplay between these rapid, reward-related responses and more effortful, regulatory processes (e.g., see iterative reprocessing model in Cunningham and Zelazo 2007; Wiers et al. 2013). And while we have presented these mechanisms separately for explanatory purposes, we believe all three are valid since they describe likely routes by which depletion can weaken one's capacity to exert self-control.

4.4 Improving Self-Regulatory Strength in the Short and Long Term

In addition to identifying the neural underpinnings of self-regulatory strength and the instances in which people succeed and fail in their self-control attempts, it is equally, if not more, important to consider whether the capacity to self-regulate can be improved. And if this is possible,

then there should be identifiable neurobiological markers that index improvement.

As we discussed earlier in this chapter, glucose has been proposed as a possible biomarker of self-regulatory strength, which may be used to index training effects. As mentioned before, the glucose account has been challenged, with some citing the metabolic properties of how the brain consumes glucose (Kurzban 2010). Others have claimed that merely rinsing with carbohydrates is sufficient to reverse depletion effects and propose that the act of rinsing triggers striatal dopamine pathways and signals future, anticipated reward (Kringelbach 2004; Molden et al. 2012). Neuroimaging techniques are well suited to identify the precise neural mechanisms underlying these reversal effects, especially as to whether glucose ingestion (versus rinsing) differentially affects activity in subcortical reward systems and/or regulatory regions in PFC. Positron emission tomography (PET) in particular may be useful to test whether glucose metabolism increases during depletion and predicts subsequent self-control failure (see Heatherton and Wagner 2011, Box 2). Unlike fMRI, which measures blood-flow dynamics in terms of how the brain utilizes oxygen, PET detects and measures radiopharmaceuticals that emit positrons as they circulate in the blood stream and brain. These chemicals act as markers of brain metabolism, with the amount of a marker's uptake indicative of the metabolic demands from nearby brain regions. One of these chemical markers commonly used in PET is fludeoxyglucose (18 F), which means that the use of glucose-PET methods could determine if certain brain regions show especially high glucose uptake in the context of a depleting task (vs. a baseline task), and whether this uptake is a reliable marker of depletion and self-control failure.

An additional body of research has considered biological markers of self-regulation in the peripheral nervous system that may serve as targets of improving self-regulatory strength in the short term. For example, with PFC implicated in successful self-control, and since subregions within PFC have been shown to regulate autonomic nervous system (ANS) activity (Groenewegen and Uylings 2000), investigators have measured

ANS-specific processes in self-regulatory contexts.

Segerstrom and Nes (2007) collected heart rate variability (HRV) data while participants were instructed to eat certain foods and refrain from eating others. The group that had to exert the most self-regulatory effort (i.e., eat carrots in the presence of chocolate and cookies) showed the greatest HRV compared to the other groups who did not need to engage in self-control. Participants with higher baseline HRV also tended to persist longer in a subsequent anagrams task. From these findings, Segerstrom and Nes concluded that HRV can serve as a valid physiological marker of self-regulatory strength. The implication is that current/state-based HRV serves as an index of available self-regulatory capacity at the moment, while more tonic/trait-based HRV might predict successful self-control across multiple attempts and contexts.

Another important line of work has utilized other cardiac-related measures as independent biomarkers of effort during tasks with varying difficulty. Gendolla and Richter (2010) review studies showing that cardiac reactivity changes in response to self-involvement and task difficulty. These two factors are undoubtedly present and relevant in self-control contexts since these situations require active monitoring of one's own behavior (self-involvement) and place strong demands on self-regulatory strength (task difficulty). Moreover, these cardiac reactivity effects have been documented using multiple measures and across task domains. For example, preinjection period and systolic blood pressure track with difficulty of a memory task (Richter et al. 2008), and prior exertion during a difficult arithmetic task leads to depletion effects as measured by several cardiovascular responses (Wright et al. 2003). Wright and colleagues (2008) extended this finding, showing that blood pressure was modulated by the level of mental fatigue, both for a regulatory task that required response inhibition (i.e., a Stroop task) and a nonregulatory (arithmetic) task (Wright et al. 2008)—supporting the idea that these cardiovascular biomarkers are domain general and therefore relevant in self-regulatory task settings. In this volume, Gendolla

and Silvestrini summarize more recent empirical work highlighting the role of motivational processes and their automatic effects on physiological activity (e.g., preinjection period) and task performance.

Collectively, these cardiovascular effects are consistent with the idea that PFC activity—in of itself a likely brain marker of self-control—modulates downstream autonomic activity in the periphery. But future studies should confirm this by employing multi-method paradigms (e.g., electroencephalography (EEG) coupled with recording cardiac reactivity) to identify central–peripheral nervous system interactions, specifically in self-regulatory contexts.

The studies discussed so far in this section highlight physiological correlates of self-regulatory strength and how they might be used as a barometer by which individuals can monitor and potentially improve their self-control on a moment-by-moment basis. These correlates consist of peripheral nervous system processes that become active when people flexibly exert self-control in response to contextual and task-based features. This knowledge is critical for our understanding of the biological substrates of self-regulatory strength, but whether tonic self-regulatory strength can be trained and increased over time is another crucial question. Indeed, this question may hold the most clinical import in populations for whom self-control failure is the norm rather than the exception.

Initial behavioral investigations of self-control training have yielded some promising effects in multiple domains. Muraven (2010) found that smokers who practiced self-control (either by avoiding tempting foods or squeezing a handgrip) for 2 weeks prior to quitting smoking showed higher abstinent rates and were less likely to relapse (Muraven 2010). Also in the smoking domain, Kober and colleagues (Kober et al. 2010) trained smokers to implement a self-control strategy that consisted of focusing on the long-term, negative health consequences of smoking. This strategy was effective in reducing the craving for cigarettes, and an fMRI study by the same group identified a neural mechanism (i.e., a pathway between the PFC and the ven-

tral striatum) that underlies regulation of craving (Kober et al. 2010).

Another study by Hui and others (Hui et al. 2009) administered a training protocol consisting of a Stroop task and mouthwash rinse task, both of which require exercising inhibitory control. Those who completed this training (compared to weak and no training groups) performed better at in-laboratory self-control tasks and engaged in more frequent health behaviors in daily life (e.g., dental care and hygiene). Another study applied self-control training to the regulation of aggressive behaviors (Denson et al. 2011). In this case, the training protocol consisted of a manual regulation task in which participants were instructed to use their nondominant hand in a number of common, everyday activities (e.g., teeth brushing, opening doors, etc.). This training was effective in reducing aggression, specifically among those with high levels of trait aggression. Presumably, this subset would be most amenable to training, since they had the relatively weakest (trait-level) self-regulatory strength to begin with and therefore could show the greatest improvement in self-control.

These findings across behavioral domains are consistent with Baumeister and Heatherton's (1996) strength model of self-control, in that these training effects reflect self-regulatory capacity that can be strengthened with repeated use and practice over longer time intervals (this strengthening is to be distinguished from short-term self-regulatory fatigue; Baumeister and Heatherton 1996, p. 3). While these effects are encouraging and suggest that people can indeed improve their self-control of a wide range of behaviors, less is known about the neurobiological substrates of training, especially the following: which brain regions support successful self-control, whether these regions undergo structural and/or functional changes during training, and the extent to which these changes may persist over time.

First, it is important to consider whether there are reliable brain regions that are linked with successful self-control, since these regions would most likely be indices of self-regulatory capacity as it improves during training. In a neuroim-

aging study, Berkman et al. (2011) investigated the neural predictors of self-control of smoking by measuring event-related activity during a go/no-go response inhibition task and then had participants report on their daily smoking behaviors for several weeks following initial fMRI scan. They found that the IFG moderated the relationship between reported craving and subsequent smoking in everyday life, such that greater IFG recruitment in the no-go versus go task attenuated the relationship between craving and subsequent smoking (see Fig. 4 in Berkman et al. 2011). The authors interpret these findings as evidence for neural markers of self-regulatory capacity, since greater activation predicted successful control of craving that led to decreased smoking.

This study's methodology represents a recent development in how researchers analyze neuroimaging data (termed the "brain-as-predictor" approach; Berkman and Falk 2013), which treats brain activation as an independent variable within a model to predict behavioral outcomes of interest (Bandettini 2009; Berkman and Falk 2013). A recent study that also used this approach found that IFG activity associated with successful response inhibition modulated resistance to food desires in everyday life (Lopez et al. *In Press*). Not surprisingly, participants who resisted the desire to eat frequently gave in to temptations to eat, but critically those participants who showed greater IFG recruitment while inhibiting prepotent responses in a go/no-go task were even less likely to act upon their impulses to eat. The study's authors interpreted this finding as possibly indicative of a state-trait interaction, with successful self-control most likely when participants actively resisted desires in the moment (state) and showed overall higher IFG recruitment (trait) associated with response inhibition.

These two studies, which predicted outcomes in different behavioral domains, both identified inhibition-related IFG activity as a crucial individual difference supporting self-control success in daily life. The fact that IFG has been implicated in regulating smoking and eating behaviors represents preliminary evidence for a brain-based model of training self-control proposed by Berkman et al. (2012). Their model builds on the

strength model of self-regulation and makes the prediction that an intervention intended to increase self-regulatory strength (or inhibitory control) in one domain (e.g., motor control) should show transfer effects in other domains, such as emotion regulation. For example, if people were trained to increase their motor control via a standard response inhibition task, then they should show improvements in their working memory capacity and/or ability to control their emotions.

This is in line with a key tenet of the strength model, namely that self-regulatory capacity draws from a domain-general resource that impacts many types of behavior. With regard to the two studies discussed above, the IFG may be an appropriate neural target of self-control training. And even though the IFG might activate most robustly during inhibitory control tasks, these tasks can be the primary component of a training regimen for improving self-control of a wide range of behaviors. That is, while “cold,” cognitive control is being trained up, training effects may translate to the domain of “hotter,” appetitive and addictive behaviors like eating, smoking, and drug use. From this line of reasoning, an outstanding question arises: For those individuals who do not tend to activate IFG during a response inhibition task, can training facilitate and increase IFG recruitment? Moreover, would such increases predict successful outcomes during, for instance, the control of food or drug cravings?

Thus far, empirical forays into the neural correlates of successful self-control have converged on the PFC, specifically the IFG, as being a reasonable target of self-control training. Given how important self-control is for life outcomes (e.g., Mischel et al. 1988) and its special role in theories of the self (Higgins 1996), however, it seems likely that there are multiple, diverse brain regions that support self-control—and therefore would be implicated in self-control training. For example, research by Hare and associates (Hare et al. 2009; Hare et al. 2011) has shown that the VMPFC is a key player in evaluative processing, with increased VMPFC activity associated with poorer self-control. With this in mind, the

VMPFC may also serve as a neural marker of self-control training regions.

4.5 Final Considerations for Improving Self-Regulatory Strength

The prospect of improving people’s self-regulatory strength, whether in the short or long term, should be grounded in brain-based accounts. These accounts make specific predictions about how depletion alters cognitive processing and impacts self-regulatory strength. Accordingly, we sketch out some final avenues of research that we believe will be particularly fruitful as the social brain sciences continue to mature throughout the twenty-first century.

First, we propose that future studies should ultimately aim to categorize subpopulations of individuals who experience repeated self-regulation failure but by different means. That is, by employing various neuroimaging techniques, researchers can identify those for whom self-regulation failure is triggered by (1) higher reward sensitivity and/or impulse strength generated by emotion and reward systems, (2) impaired functioning in the PFC, or (3) disconnection between prefrontal areas and emotion and reward systems. These three scenarios correspond to the routes by which depletion compromises self-regulatory capacity and precipitates failure we have discussed throughout this chapter. For example, for those with impaired top-down functioning, a training regimen consisting of multiple sessions of inhibitory control practice might be appropriate. Or, in the case of someone who is hypersensitive to cues that signal reward and subsequently experiences overwhelmingly strong impulse strength, an intervention that involves an implicit learning or reconditioning task might make the most sense.

Another promising line of research that we hope will develop further is the brain-as-predictor approach (Berkman and Falk 2013). Specifically, we believe that state–trait interactions in populations that are prone to self-regulation failure should be explored to determine whether

there are reliable neural predictors of failure in everyday life (e.g., post-depletion reward activity in dieters; Wagner et al. 2013).

Conclusion

Science has begun to uncover the brain bases of human beings' remarkable but precarious capacity to regulate thoughts, emotions, and behaviors. This capacity has undoubtedly been paramount to the continued survival of our species. In fact, some have theorized that evolutionary pressures in the past selected for neural systems that utilized and expended energy to give rise to a stable sense of self, as well as flexible cognitive processes that allowed for self-regulation of behavior to adhere to group norms and preserve one's standing within a group (Baumeister et al. 2007; Heatherton 2011). With the advent of modern neuroimaging, scientists now have the opportunity to observe the live workings of the brain—not only as people attempt to exercise this self-regulatory capacity but also when this capacity is taxed and weakened by depletion.

We offered perspectives on how and why brain-imaging studies can extend and inform behavioral studies of self-control. One major aim of brain studies will be to provide independent markers of the depleting effects of engaging in self-control. We reviewed three neural accounts of self-regulatory depletion, and then we considered potential ways that self-regulatory strength can be improved, in both the short run with several physiological indices of interest and the long run, where we hypothesized that brain systems might be amenable to change following self-control training.

Brain science offers new perspectives on an old and perplexing problem—why is it so easy to fail at self-control? And why are some people more likely to fail at self-control than others? We have little doubt that investigations of the neural mechanisms of self-regulation will continue, as more methodologically sophisticated, interdisciplinary work takes place across the social brain sciences and continues to illuminate the neurobiological mechanisms that govern behavior.

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