Self-regulation refers to the ability of people to make plans, choose from alternatives, control impulses, and regulate behavior (Heatherton, 2011). Those who are better able to self-regulate enjoy success in many aspects of social life, such as improved relationships and increased job success (Duckworth & Seligman, 2005; Tangney, Baumeister, & Boone, 2004), whereas failures of self-regulation are a leading cause of many health problems, such as obesity (Calle, Rodriguez, Walker-Thurmond, & Thun, 2003; Mela, 2001) and tobacco use (Shmueli & Prochaska, 2009). Research in social and personality psychology has long explored how people differ in self-control capacity (e.g., Mischel et al., 2011), as well as situational factors that support (or disrupt) self-regulatory processes; however, it is only recently that researchers in the cognitive neurosciences have begun to examine the neural mechanisms that underlie different forms of self-regulation and self-regulation failure (for reviews, see Cohen & Lieberman, 2010; Heatherton & Wagner, 2011; Somerville, Jones, & Casey, 2010). Findings from this body of work suggest that effective self-regulation, particularly within the domain of impulse control, relies upon a balance between brain regions involved in representing the rewarding or emotional value of a given temptation or situation (e.g., the ventral striatum and amygdala) and regions of the prefrontal cortex (PFC) that are implicated in top-down control. Many of these findings have emerged from investigations of the regulation of appetitive desires (e.g., food and drug cravings), emotions (e.g., regulation of negative affect), and thoughts (e.g., suppression of stereotypes and unwanted thoughts). Here, we summarize research on the neural systems involved in self-regulation and its failure by focusing on three of the most common ways in which self-regulatory capacity can become impaired, namely, (1) exposure to tempting cues (e.g., fattening food), (2) emotional and social distress, and (3) depletion of limited self-regulatory resources.

Cue Exposure

In the modern world, human beings have unprecedented access to many pleasurable activities and, accordingly, often experience impulses to engage in certain behaviors that may be otherwise inappropriate or in conflict with their goals. An impulse typically refers to an urge or desire to consume a particular item or engage in a pleasurable behavior. Impulses also tend to be inherently rewarding behaviors that occupy people’s attention and require self-regulatory effort to inhibit (Metcalf & Mischel, 1999). One of the most common ways an impulse can arise is from viewing an activating stimulus (or cue), such as food advertisements or the sight and smell of a cigarette. A long history of research shows that physiological measures such as heart rate and salivary responses are increased following exposure to food cues in dieters (Brunstrom, Yates, & Witcomb, 2004; Klajner, Herman, Polyvi, & Chhabra, 1981) and cigarette cues in smokers (Drobes & Tiffany, 1997; Payne, Smith, Adams, & Diefenbach, 2006).

Neuroimaging research has identified several neural mechanisms associated with cue-induced impulses. First, functional neuroimaging research has shown that activity in the ventral striatum and orbitofrontal cortex increases when viewing cues associated with appetitive rewards such as food and attractive faces, as well as abstract rewards such as money (Cloutier, Heatherton, Whalen, & Kelley, 2008; Due, Huettel, Hall, & Rubin, 2002; Garavan et al., 2000; Knutson, Taylor, Kaufman, Peterson, & Glover, 2005; Somerville, Hare, & Casey, 2010; Van der Laan, de Ridder, Viergever, & Smeets, 2011). Additionally, this research demonstrates that increased striatal responses to food (Demos, Heatherton, & Kelley, 2012; Stice, Yokum, Blum, & Bohon, 2010) or drug cues (Janes et al., 2010; McClernon, Kozink, & Rose, 2007) are predictive of real-world behavior. For example, individuals who are highly sensitive to rewards demonstrate heightened activity in the ventral striatum and orbitofrontal cortex when viewing images of appetizing foods (Beaver et al., 2006). The increased recruitment of these brain regions in the face of temptations appears to be predictive of real-world behavior as demonstrated by Demos et al. (2012) in a research showing that individual differences in ventral striatal responses to food cues and erotic scenes could be used to predict subsequent weight gain and degree of sexual activity 6 months later (Demos et al., 2012). This suggests that neural measures of cue reactivity may reflect a stable sensitivity to rewards, which may be used to predict which individual will go on to show self-regulation failure when confronted with temptations.

Many of the effects of cue exposure likely operate below the level of conscious. For example, tempting cues can prime people to experience positive hedonic thoughts about using the substance (Hofmann, van Koningsbruggen, Stroebe, Ramanathan, & Aarts, 2010; Sayette & Hufford, 1997) and capture people’s attention even when presented incidentally as part of a film (Lochbuehler, Voogd, Scholte, & Engels, 2011). For example, research has shown that dieters and smokers show increased approach behavior toward foods and cigarettes, respectively. This is paralleled by brain imaging findings showing that smokers show greater activity in brain regions involved in action understanding and simulation when viewing the act of smoking in both video and still images (Wagner, Cin, Sargent, Kelley, & Heatherton, 2011; Yalachkov, Kaiser, & Naumer, 2009).

The results of these studies demonstrate that cue exposure elicits appetitive responses that require people to exert self-control. Across a variety of studies, in both behavioral and cognitive neuroscience, cues have been shown to capture attention, evoke approach behavior, and stimulate craving for the tempting items. Given the power cues have over behavior, it
comes as no surprise that the majority of daily acts of self-regulation actually consist of ‘self-stopping’ in which people attempt to inhibit consumption of a desired item (Baumeister, Heatherton, & Tice, 1994; Hofmann, Baumeister, Förster, & Vohs, 2012).

**Emotional and Social Distress**

In everyday life, a frequent challenge to people’s self-regulatory capacity and a potent predictor of self-regulation failure are the experience of negative emotions. Effects of distress on subsequent self-regulation have been observed across many behavioral domains, including acting aggressively (Anderson & Bushman, 2002), drinking alcohol (Wittkiewitz & Villarroel, 2009), and engaging in unprotected sex (Bousman et al., 2009) (for a review, see Wagner & Heatherton, 2013a, 2013b).

A number of brain mechanisms have been proposed to explain how emotional and social distress influence self-regulation. For instance, research in nonhuman animals has shown that social isolation in rats can lead to a subsequent increase in drug self-administration (Bowling & Bardo, 1994) and food consumption (Campbell Teskey, Kavaliers, & Hirst, 1984) thought to be due to the sensitization of the mesolimbic dopamine system to rewards. In humans, neuroimaging research has shown increased activity in the ventral striatum and orbitofrontal cortex to appetizing foods following a social distress induction (e.g., Wagner, Boswell, Kelley, & Heatherton, 2012). This suggests that a similar distress-induced sensitization of the human reward system may be at play following social distress and may help explain why negative mood can often engender disinhibited eating in dieters (Frost, Goолkasan, Ely, & Blanchard, 1982; Heatherton, Peter, & Polivy, 1991; Heatherton, Striepe, & Wittenberg, 1998).

Research on social rejection provides another mechanism by which emotional distress impairs self-regulation. For example, social rejection has been shown to increase overeating in dieters, reduce persistence on difficult tasks, and increase the preference for immediate rewards (Baumeister, DeWall, Ciocenco, & Twenge, 2005; Twenge, Catanese, & Baumeister, 2003). More recently, there has been considerable research on the neural correlates of experiencing social rejection (see Eisenberger, 2012 for a review) and how this might relate to self-regulation failure. For instance, it has been shown that experiencing social rejection reduces activity in an area of the lateral PFC that is associated with cognitive control along with impaired accuracy when performing complex math problems (Campbell et al., 2006). Similarly, another study found that social rejection not only reduced activity in the lateral PFC but also was associated with increased risk-taking behavior (Peake, Dishion, Stormshak, Moore, & Pfeifer, 2013).

**Self-Regulatory Depletion**

Beginning with research conducted in the 1990s, a large number of studies have demonstrated that people’s ability to self-regulate is susceptible to fatigue by prior bouts of effortful self-control (for a meta-analysis, see Hagger, Wood, Stiff, & Chatzisarantis, 2010). Known as the strength model of self-regulation (Baumeister & Heatherton, 1996), this model suggests that self-regulation relies on a limited resource that is vulnerable to temporary exhaustion by successive acts of self-regulation. Thus, when an individual is forced to expend significant effort in order to, for example, regulate their craving for food, they may find themselves subsequently less able to persist in difficult or effortful tasks (Baumeister, Bratslavsky, Muraven, & Tice, 1998), more likely to give in to aggressive impulses (DeWall, Baumeister, Stillman, & Gailliot, 2007), and less likely to control their thoughts and avoid the use of stereotypes (Gordijn, Hindriks, Koomen, Dijksterhuis, & Van Knippenberg, 2004). Studies testing this theory have generally employed a sequential-task paradigm in which participants first complete a difficult self-control task in one domain (e.g., emotion, cognitive, and social) followed by a self-regulation task in another domain.

Over the years, there have been several attempts to specify the underlying mechanism behind depletion effects with researchers suggesting that experimental findings are due to differences in lay beliefs about self-control (Job, Dweck, & Walton, 2010) and changes in motivation (Beedie & Lane, 2012; Inzlicht & Schmeichel, 2012) or that depletion instead reflects the reduction of a real physiological resource, namely, circulation blood glucose (Gailliot et al., 2007), the ingestion of which can serve to reverse depletion effects and reinstate self-control (Denson, von Hippel, Kemp, & Teo, 2010; Gailliot et al., 2007). This last set of findings has come under considerable criticism with recent studies demonstrating that simply tasting, but not ingesting, glucose is sufficient to reverse effects of depletion on self-regulation (Molden et al., 2012).

Studies investigating the neural basis underlying self-regulatory depletion effects are still relatively few in number. Within the cognitive domain, research has shown that inducing self-regulatory depletion leads to reduced recruitment of the anterior cingulate cortex during a subsequent Stroop task, an effect that was also associated with impaired behavioral performance (Inzlicht & Gutsell, 2007). Similarly, another work has shown that the right lateral PFC – another region implicated in cognitive control – demonstrated reduced activity during a subsequent self-control task in depleted versus nondepleted individuals (Friese, Binder, Luechinger, Boesiger, & Rasch, 2013; Hedgcott, Vohs, & Rao, 2012). Together, these studies suggest that failures of self-regulation following depletion are likely due to a failure to appropriately recruit prefrontal regions involved in top-down control. Whether this failure is as a result of limited resources and changes in motivation or due to some as of yet unknown mechanism remains unknown.

Another line of research suggests that, independent of its effects on top-down control, depletion may also amplify the strength of impulses and emotions. For example, compared to nondepleted individuals, when depleted people are exposed to negatively valenced emotional scenes, they show an exaggerated response in the amygdala, a brain region involved in emotion and threat detection (Wagner & Heatherton, 2013a, 2013b). In addition, the functional connectivity between this region and the ventromedial PFC was impaired following self-regulatory depletion. In a conceptually similar study, it was also found that depleted dieters exhibited increased reward-related brain activity in the orbitofrontal cortex to appetizing food cues compared to nondieters (Wagner, Altman, Boswell, Kelley, & Heatherton, 2013), and as in the previous study, depleted
individual exhibited a breakdown in functional connectivity between the orbitofrontal cortex and prefrontal regions involved in regulating appetitive responses (Wagner et al., 2013). The result of these studies suggests that the exaggerated responses to negative emotional scenes on the one hand and appetitive food cues on the other may be a result of a failure to recruit prefrontal regions that are important for moderating and downregulating emotions and cravings.

Conclusion

Self-regulation allows people to inhibit their desires, moderate their emotions, and take control of their wayward thoughts in order to achieve personal goals and avoid violating social and societal norms. Those who are better at it benefit from improved relationships and greater job success (Duckworth & Seligman, 2005; Vohs, Finkelauer, & Baumeister, 2011), whereas those who are worse at self-control are more likely to have poor physical health and drug abuse problems (Moffitt et al., 2011). Findings from cognitive neuroscience have identified brain systems that support self-regulatory processes. Specifically, successful self-regulation often involves a balance between regions in PFC involved in executive control and cortical and subcortical areas involved in representing reward and emotional salience. When people are faced with impulses that run counter to current regulatory goals (e.g., adhering to a diet), they experience a clash between desires and self-control. Self-regulation failure occurs then when the strength of desires overwhets the current capacity to engage in control or when the capacity to engage in self-control is impaired and people are unable (or unmotivated; see Inzlicht & Schmeichel, 2012) to downregulate their impulses and desires.

References


