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The dual component theory of inhibition regulation: A new model of self-control

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ABSTRACT

Self-control is one of the most extensively studied topics in psychology and the resource or ego depletion model is one of the most popular. Although evidence supports some aspects of this model, other evidence is problematic for the notion that self-control is a limited resource. Herein, a new theory is proposed: the Dual Component Theory of Inhibition Regulation (DCTIR). The following paper will highlight key issues in self-control, describe the DCTIR, demonstrate how the DCTIR can account for the existing body of findings concerning limits to self-control, and provide novel predictions and avenues for further research.

1. Introduction

Self-control is the ability to inhibit, override, or otherwise circumvent responses motivated by short-term rewards in order to pursue more long-term benefits (Fujita, 2011; Hofmann, Friese, & Friese, 2009; Mischel, Shoda, & Rodriguez, 1989; Vohs & Heatherton, 2000). Although there are a number of strategies that one can use to accomplish self-control (see Fujita, 2011), here we are concerned specifically with the ability to inhibit prepotent or impulsive responses, which is at the heart of self-control. One of the more popular theories concerning this type of self-control is the resource or ego depletion model. The central tenet of this model is that self-control is a limited resource that can be depleted through use (Baumeister & Heatherton, 1996; Heatherton & Baumeister, 1996; Vohs & Heatherton, 2000). That is, engaging in a self-control task results in depletion of the willpower resource, leading to decreased performance on subsequent self-control tasks. This effect is referred to as *ego depletion*.

In a classic demonstration of the ego depletion effect, Baumeister, Bratslavsky, Muraven, and Tice (1998) presented hungry participants with cookies, candies, and radishes on a table. The experimental group was instructed to eat the radishes, but not the cookies or candies. The control group was asked to eat some of the cookies or candies. Participants in the experimental group thus had to resist the temptation to eat the more desirable food items (i.e., apply self-control), whereas the control group (minus the occasional radish lover) did not have such a temptation and thus did not need to apply self-control. Participants were then given an unsolvable geometry task as an assessment of subsequent self-control. Supporting the ego depletion model, participants in the experimental group gave up sooner on the unsolvable task.

Subsequent research has investigated the ego depletion effect across a host of domains, including emotion regulation and aggression (DeWall, Baumeister, Stillman, & Galliot, 2007), dieting/eating (Vohs & Heatherton, 2000), and cheating behavior (Mead, Baumeister, Gino, Schweitzer, & Ariely, 2009).

However, there are also problems with the ego depletion model. First, the model relies heavily on metaphor. The model does not specify the nature of the mechanism underlying the ego depletion effect. Glucose was offered as a candidate for the resource that was being depleted, potentially providing a more mechanistic account (Gailliot et al., 2007). However, this explanation has subsequently been shown to be a poor one (see Beedie & Lane, 2012; Molden et al., 2012; Kurzban, 2010a).

Second, multiple studies call into question basic premises of the model. For example, motivating participants (Muraven & Slessareva, 2003) or convincing participants that they have willpower resources remaining (Clarkson, Hirt, Jia, & Alexander, 2010)

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is enough to eliminate the depletion effect. Moderating effects like these (see also Magen & Gross, 2007; Job, Dweck, & Walton, 2010) are inconsistent with the notion that self-control is energetically limited.

Third, there has been disagreement about the strength of the depletion effect. Hagger, Wood, Stiff, and Chatzisarantis (2010) found in their meta-analysis that the depletion effect was robust (d = .62). However, Carter and McCullough (2014), employing statistical techniques to correct for small-study effects and publication bias, concluded that the depletion effect is much smaller and may not exist. It should be noted that the bias-correcting procedures employed by Carter and McCullough (2014) have themselves come under criticism. In particular, these procedures appear to perform quite poorly and suggest that effects are smaller than they really are when publication bias and heterogeneous effects are present in the literature (see Moreno et al., 2009; Reed, Florax, & Poot, 2015). Given that these conditions are likely to exist in the ego depletion literature, Inzlicht and Berkman (2015) have argued that Carter and McCullough's (2014) conclusions are premature. We would add that these discussions highlight the need for more consistent conceptual and operational definitions of self-control. For example, the same tasks have alternatively been employed as depletion tasks and control tasks (see for example the three-digit by three-digit multiplication task, Muraven, Tice, & Baumeister, 1998; Stillman, Tice, Fincham, & Lambert, 2009). A more clear and consistent conceptual view would aid in understanding when to expect or not expect a depletion effect.

Given these problems, we argue that a theory more specifically describing the functional nature of the self-control mechanism is needed. With a well-specified model of the self-control mechanism comes the ability to explain how we identify tempting situations to inhibit, how we inhibit, why we stop inhibiting, when and when not to expect a depletion-like effect, and why certain variables like motivation would affect self-control. Although there have been other recent attempts to conceptualize self-control (e.g., Inzlicht & Schmeichel, 2012; Hofmann, Baumeister, Förster, & Vohs, 2012), we argue that none of them completely solve these issues. To address this vital need for a strong theory of self-control, we propose the Dual Component Theory of Inhibition Regulation (DCTIR). We discuss key features of the model as well as the meta-theory from which the model is derived. We then present a description of the DCTIR, discuss how it explains existing findings in the literature, and outline future directions for testing the model.

2. Dual component theory of inhibition regulation

2.1. Key features of self-control

Any theory that seeks to provide a functional mechanism for applying self-control should address certain fundamental issues. First, we assume that it is functional to apply self-control in certain situations, in order to regulate impulsive behaviors. The theory therefore ought to explain when it is appropriate to use, or not use, self-control. Moreover, the theory ought to provide a mechanism that could accomplish the identification of these situations. In other words, the theory should explain how and when we identify the need to inhibit a prepotent behavior.

Second, we assume that it is undesirable for self-control to be applied indefinitely. That is, self-control must eventually come to a halt. Thus, a functional theory must also explain when it would be beneficial to stop (or not stop) using self-control. The theory should provide a mechanism capable of making this determination. It is worth noting that this assumption challenges some common ways of thinking about self-control. Much self-control research has been pervaded by the ideology that stopping self-control necessarily represents a failure. That is, impulsive responses are equated with bad decision making, whereas using self-control is equated with good decision making. However, there could be advantages to both exerting inhibition and eventually stopping it. For example, even people on a diet need to eventually eat. Calling the cessation of inhibition a "failure" of self-control is thus misleading, as it would depend on the situational context.

A third feature of self-control is that there is variation across contexts. That is, people may show high self-control performance for one behavior, but low self-control performance for another (Cohen & Lieberman, 2010; Cortes, Kammrath, Scholer, & Peetz, 2014). Someone may control their emotions well, but have difficulty sticking to a diet. Even for the same behavior, individuals do not exhibit high or low self-control in every situation. Yet, there seems to be a common mechanism responsible for inhibiting these different behaviors. Accounting for this variation in self-control across situational contexts is of key importance.

In summary, we assume that the functional application of self-control requires knowing when to apply self-control, knowing when to stop applying it, and involves a common processing mechanism. These fundamental assumptions should guide the basic design features of a proposed self-control mechanism. A more computational approach can be used to meet these assumptions and generate specific predictions concerning the application of inhibitory self-control.

2.2. Meta-theory of the DCTIR

The meta-theory of the DCTIR is based primarily in modularity. Modularity was first used in the arena of artificial intelligence. A module was described as a mechanism designed to carry out a specific function (Ermer, Cosmides, & Tooby, 2007). This functional specialization is the conceptualization of modularity that evolutionary psychologists follow (Ermer et al., 2007; Kurzban, 2010b; Pinker, 1997). According to this view, the mind is composed of information processing mechanisms designed to solve particular problems. This conceptualization of modularity is used here (as opposed to the information encapsulation definition most associated with Fodor, 1983). Unlike the resource model, which assumes mostly general purpose mechanisms, the DCTIR assumes there are many domain-specific, content-dependent mechanisms. With the theoretical foundations of our theory detailed, we now present our modular theory of self-control.

2.3. The DCTIR

The DCTIR proposes that there are numerous, domain-specific modules working to carry out certain behaviors. Some of these are short-term or "impulsive" modules that are focused on the here and now. These modules motivate immediate behavior. The purpose of self-control is to regulate these impulsive modules. Specifically, the DCTIR proposes that these impulsive modules are regulated by a computational inhibition module, composed of a monitor and a threshold component. By computation, it is meant, "the organized causation of patterned information input–output relations" (Tooby & Cosmides, 2008, p. 115). By inhibiting particular modules, an individual is better able to regulate multiple systems, some of which have conflicting outcomes. For example, impulsive "short-term" modules to aggress may conflict with more long-term systems to manage interpersonal relationships. By inhibiting the impulsive modules, the long-term system is given priority. Thus, although there is no monitoring of goal conflict, the conflict is resolved by inhibiting one of these mutually exclusive behaviors (e.g., you can eat or not eat, but not both). The inhibition module proposed is conceptualized as an algorithm. That is, it is a step-by-step procedure that has specific inputs and outputs designed to arrive at a solution (Merriam-Webster, 2014). It can also be conceptualized as a series of decision rules. Below is a simplified visual representation of the inhibition module proposed by the DCTIR.

The monitor component is designed to detect the output (i.e., the computational product) of particular impulsive modules. That is, the monitor detects that an impulsive behavior needs to be inhibited. The "cost" or output of the impulsive module is then measured, reflecting the temptation experienced by the person. A signal in the form of inhibition effort is produced by the monitor and then sent to the threshold component. This signal is the sensation of effort that individuals feel when inhibiting. The threshold component then processes this signal of inhibition effort to determine whether threshold has been met. The threshold represents the individual's tolerance for applying inhibitory effort. In other words, the threshold component assesses whether the cumulative magnitude of inhibitory effort matches the individual's tolerance or level for applying inhibition. If the threshold is not met, meaning the magnitude of inhibitory effort is below the tolerance or level for applying inhibition, a signal is sent from the threshold component to continue to inhibit the "impulsive" module. If the threshold is met, meaning the magnitude of inhibitory effort has reached the tolerance for applying inhibition, then the inhibition module stops inhibiting, and the "impulsive" module carries through with its output. In other words, the person stops inhibiting and the prepotent behavior is carried out. Thus, the monitor component solves the problem of determining when and how much to inhibit, and the threshold component solves the problem of when to stop inhibiting. The output from the threshold is not hypothesized to be sent directly to the "impulsive" modules. Rather, the output from the inhibition module likely feeds into a hierarchical control system that relays the signal to the "impulsive" modules. Thus, the inhibition module is just one control mechanism that, along with other mechanisms (e.g., conflict regulation, goal feedback, and attentional control), forms a regulatory network.

The DCTIR explains the ego-depletion effect by suggesting that individuals who show a decrease in self-control performance have met threshold, and thus have stopped inhibition. The model suggests that the length of time that self-control will be applied is a function of both the strength of the inhibitory signal (i.e., how much inhibition is required) and the overall level of the threshold (i.e., tolerance for inhibition).

To give an example of how the inhibitory module works, consider a dieter named Eric. Eric goes to the fridge to see what he has to eat. He sees a chocolate cake and some carrots. Upon seeing the chocolate cake, the monitor component detects that the food temptation modules need to be inhibited, and produces inhibition effort. The threshold component processes this signal of inhibition effort. If threshold is not yet met, an inhibitory signal is sent to the food temptation module. In this case, Eric would inhibit his desire to eat the tempting cake and eat carrots instead. If threshold has been met, no inhibitory signal is sent. That is, Eric would carry out the prepotent behavior and eat the cake. With this broad sketch of the model, each component can now be discussed in greater detail (see Fig. 1)

2.4. The monitor component

Within the monitor component is a set of detection subroutines (i.e., a program within a program). These detection subroutines are created when there is a conflict between an impulsive or "want" module and a long-term or "should" module. As previously mentioned, there is no monitoring of conflict; the impulsive modules are what are being monitored. Conflict is only involved in the creation of the detection subroutines and there is no active monitoring for conflict. Once a detection subroutine is created, its function is to detect the activation of a particular impulsive module, thereby allowing the system to inhibit it. In this manner, the individual can pursue the long-term goal. If the output from that specific module is detected, the subroutine sends a signal to the measurement subroutine. If not detected, then no signal is sent. The detection subroutines essentially address the question "does module 'A' need to be inhibited?" If so, a message is sent to the measurement subroutine (see Fig. 2 below). In this manner, the detection subroutines solve the problem of identifying a tempting situation.

The input of the detection subroutines is thus the output from "impulsive" modules. As hypothesized in other types of modular systems, the "impulsive" modules are publicly broadcasting their output in parallel (see for example Kurzban, 2010b). This is likened to a bulletin board by Barrett (2005; 2007), or what Pylyshyn (1999) called black board architecture. An information processing model familiar to most and used here to exemplify the information processing mechanism of the DCTIR is the pandemonium model (Selfridge & Neisser, 1960). Just like the pandemonium model, there are devices inside of devices (demons in the case of the pandemonium model) that perform specific functions, and work together to accomplish a more complex function. In the monitor component, each detection subroutine searches for its specific module without interference from other detection subroutines. Consider for example, the likely hundreds of thousands of computations that are being carried out simultaneously in visual perception. Edge detectors, color perception, and motion perception are just a few processes that run simultaneously. Nonetheless, detecting edges does not make one slower to perceive colors.

These subroutines are also proposed to function in a lock-and-key fashion, such that a detection subroutine (the lock) is only

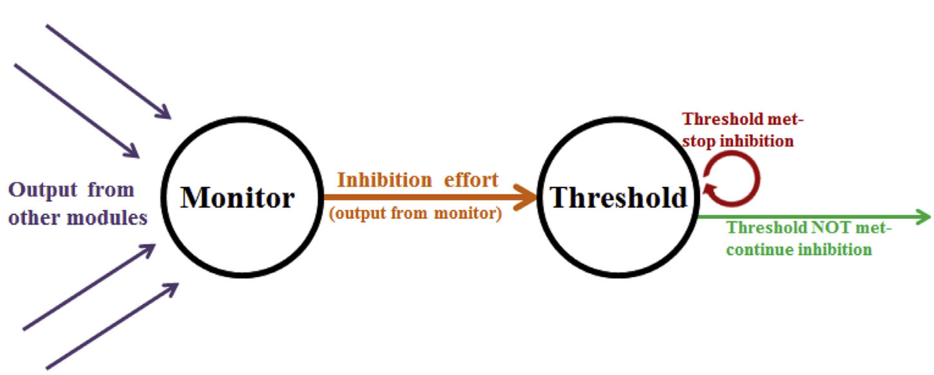

Fig. 1. A model of the mechanism proposed by the dual component theory of inhibition regulation.

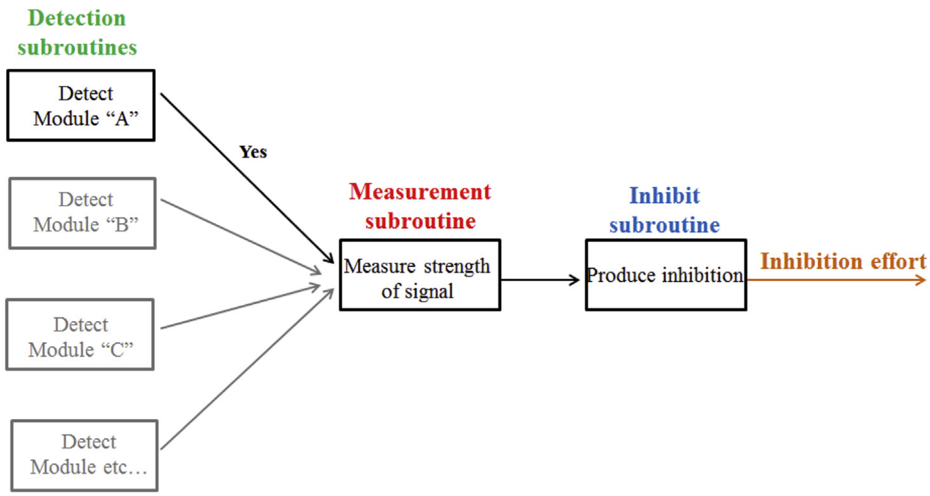

Fig. 2. A model of the monitor where specifically module "A" has been detected.

activated by the corresponding impulsive module (the key). Barret (2005; 2007) employs the enzymatic metaphor to describe how such modular systems work. The matching of inputs in a computational system (for example, feature recognition in categorization systems) is like substrate binding in an enzyme. Thus, a detection subroutine for food temptation will only be activated when a tempting food is salient, and so on. If there was a high degree of interaction among these subroutines, whereby one subroutine affected another, rather than each processing in parallel, this subroutine as specified would be untenable. For example, a detection subroutine for avoiding the distraction of your cellphone should not be invoked in the presence of tempting food.

The next process in the monitor component is the measurement subroutine (see Fig. 2). This process is triggered by the output from a detection subroutine. A measurement of the signal (i.e., the output from the detected module) is taken. These computations are hypothesized to take the form of costs, motivation, or temptation. Thus, whereas the detection subroutines determine if a situation requires self-control, the measurement subroutine determines how tempting the situation is.

The representation and evaluation of costs is an important aspect of many decision making models, both behavioral and neural. Evidence that people take specific costs into account for specific behaviors suggests plausibility for this mechanism in the proposed model (Basten, Biele, Heekeren, & Fiebach, 2010; Singer et al., 2014). If people were unable to reliably represent temptation in self-control situations, this subroutine as specified would be untenable. Monitoring of some kind is also common to several models in the area of cognitive control. For example, models that involve monitoring (whether it is conflicts, discrepancies, or costs) include the conflict monitoring model (Botvinick, Braver, Barch, Carter, & Cohen, 2001), negative feedback loop models (Carver & Scheier, 1998), and the effortometer (Kurzban, 2010b).

The final step, the inhibit subroutine (see Fig. 2), is triggered by the output from the measurement subroutine. The inhibit subroutine uses the level of temptation and cost to produce a relatively commensurate amount of inhibition effort. Thus, a greater temptation registered in the measurement subroutine means greater inhibition effort will be produced by the inhibit subroutine. This final output from the monitor component is then sent through the threshold component, and onto the module that needs to be inhibited. In this manner, the monitor component solves the problem of when and how much to inhibit.

To give an example of the operation of the monitor component, suppose that Mike is hungry. There is a delicious piece of chocolate cake in the fridge, and Mike has just come back from a 20-mile bike ride. However, Mike is on a diet and has the option of eating carrots instead. Thus, the chocolate cake represents a temptation. The modules involved with temptations arising from food would register a strong signal, representing a strong temptation that would require considerable inhibition. Now consider a different dieter named Joe. Joe is also hungry, and also has the option of eating carrots or a piece of chocolate cake. However, Joe has not just expended hundreds of calories. The measurement subroutine would register a weaker signal (holding other factors constant) in this case than it would in the case of Mike. Thus, the strength of the signal registered by the measurement subroutine is commensurate with the temptation/motivation/costs/etc. of engaging in the behavior associated with that module(s). Anthropomorphizing, we could say the impulsive modules of Mike are shouting louder than the impulsive modules of Joe. As a consequence, the inhibit subroutine would produce greater inhibition effort in Mike's case than in Joe's case (assuming equivalence on other factors like goal strength and motivation).

2.5. The threshold component

The threshold component processes the inhibition effort sent from the monitor. With greater or more sustained inhibition effort being sent by the monitor, threshold is more likely to be met. If threshold is triggered, inhibition ceases. Therefore, we no longer inhibit and engage in the tempting situation. If threshold is not met, inhibition can continue to be applied until the tempting situation is resolved or the person leaves the tempting situation.

The threshold in this case is a representational threshold rather than an energetic one.

An example of an energetic threshold is the neuron. The neuron (membrane, specifically) has a resting state of typically −70 mV (mV) (Gazzaniga, Ivry, & Mangun, 2014). When depolarized to approximately −55 mV, threshold has been met, and an action potential is triggered. An example of a representational threshold can be found in explanations of the tip of the tongue (TOT) state. As explored in a classic experiment by Brown and McNeill (1966), participants asked to produce a word based on the definition of a sextant could only produce some correct information (like the first syllable). The word did not have sufficient activation to reach the retrieval threshold. However, when participants were primed with phonologically related words, recall of the target word increased (James & Burke, 2000). This improved recall may be the result of sufficient activation to meet threshold (but see Schwartz & Metcalfe, 2011, for other hypotheses regarding the resolution of TOT states). In a similar fashion, the threshold component of the DCTIR is not as precise as an energetic threshold. Whereas depolarizing a neuron to threshold will very reliably produce an action potential, the threshold component proposed here is not so precise. As depicted in Figs. 3 and 4, the dotted portion represents the projected range of the threshold. Thus, we can computationally represent the threshold T as falling in between the range of X and Y or: $X < T < Y$. Shifts in the threshold between the threshold ranges (X and Y) are predicted to occur throughout the day and would be affected by numerous factors, such as sleep.

As with the monitor component, there are other theories that use a similar concept to the threshold. For example, Botvinick, Huffstetler, and McGuire (2009) discuss reference-dependent reward processing in effort discounting. Specifically, the reference point is the cost of effort as measured against rewards. Carver and Scheier (1998) discuss a standard, goal, or reference value in their feedback models. Reference points or values are *similar* to the construct of the representational threshold as implicated in the DCTIR. To show that the threshold is untenable, it must be demonstrated either that individuals cannot represent (either explicitly or implicitly) their tolerance for inhibition effort, or that individuals continue inhibition despite meeting this threshold.

There are of course individual differences in self-control. The DCTIR hypothesizes that one of the ways these differences is manifested is in the chronic "position" of the threshold. This typical threshold point may partly be expressed as trait self-control. Fig. 3 represents a person who has a lower threshold (i.e., low trait self-control). When this person applies inhibition effort, threshold is met more easily. As a consequence, the person stops inhibiting sooner. Fig. 4 represents a person who has a higher threshold (as measured by high trait self-control for example). As a consequence it takes more inhibition effort to reach threshold, meaning that the person stops inhibiting later. As an illustration, consider Mike from the earlier example. If Mike had a high threshold (as in Fig. 4), he would be able to resist eating the chocolate cake. That is, he would continue to apply inhibition effort, even though his "food temptation modules" registered a strong temptation. Thus, Mike would be more likely to eat the carrots. If Mike had a low threshold (as in Fig. 3), he would meet threshold easily and stop inhibiting. Mike would be more likely to eat the cake in this case.

Importantly, the DCTIR posits that, just as there is only one common monitor component, there is one common threshold component. All determinations of whether to continue inhibition are accomplished by the same mechanism, regardless of the original source of the temptation. In most circumstances, this has little practical consequence as it is rare that individuals simultaneously face multiple temptations. Indeed, we probably had even fewer instances of multiple temptations in the ancestral environment that shaped the development of this inhibition module. In most instances, one threshold was efficient and suitable. The primary concern of this module is therefore when to stop inhibiting and carry out the short-term behavior.

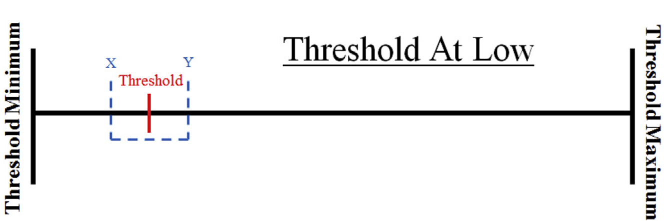

Fig. 3. Model of the threshold component from someone with a low threshold.

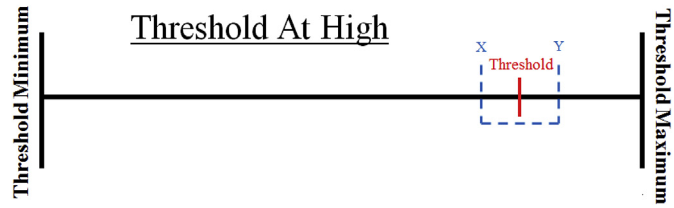

Fig. 4. Model of the threshold component from someone with a high threshold.

Past work has shown that "depletion" can carry over to other domains. For example, completing an emotion inhibition task is associated with performance decrements on a subsequent cognitive inhibition task (Baumeister et al., 1998). From the perspective of the DCTIR, the initial inhibition task brings the person closer to meeting threshold. As a result, they are prone to stopping inhibition sooner on a subsequent self-control task, even if that task is unrelated. If there were multiple thresholds, then having separate inhibition tasks should not bring someone closer to stopping inhibition. However, this does not mean that threshold is insensitive to situational constraints. As we detail later, one's tolerance for applying inhibitory effort can be changed. For example, given a particular context, like working out at a gym, one might temporarily increase threshold, and thus inhibit pain for a longer time.

3. Past findings reinterpreted

The DCTIR suggests that ego depletion effects result from an individual who has met threshold, and therefore discontinues inhibition. For example, DeWall et al. (2007, Study 4) studied ego depletion effects with regard to likelihood of aggressing (a behavior viewed as involving self-control) in a hypothetical scenario. All participants completed measures of trait self-control. There were two task conditions, depletion (i.e., the crossing "e"s task) or control. Participants were then asked to imagine a scenario in which someone flirts with their boyfriend/girlfriend at a bar. They were asked how likely they would be to smash a bottle over the person's head. Trait self-control was shown to moderate the effects of depletion. Specifically, only participants low in trait self-control had an increase in likelihood of aggressing as a result of depletion. The DCTIR interprets this result by suggesting that participants who had high self-control were able to continue to apply inhibition because they had not yet met threshold, despite completing the depletion task (see also Schmeichel & Zell, 2007). Participants low in self-control were more likely to meet threshold as a result of the depletion task, and therefore stopped inhibiting. As a consequence, they had an increased rating of likelihood to aggress.

Tice, Baumeister, Shmueli, and Muraven (2007) found that positive emotion reduced the ego depletion effect. They interpreted this effect as consistent with the resource model, arguing that positive emotion effectively restores the depleted energetic resource. The DCTIR would instead suggest that positive emotion is affecting the monitor component by reducing the evaluation of the strength of the temptation. In other words, positive emotion may reduce the temptation to engage in the impulsive behavior. For example, food might be tempting because eating it is rewarding. If one is already in a positive mood upon encountering the tempting food, they may experience less temptation to eat it.

In addition to accounting for effects that may be consistent with the resource metaphor, the DCTIR can also account for findings that do not fit well with this metaphor. Using the standard two task methodology, Magen and Gross (2007) instructed some participants that the subsequent task (grip strength) measured a desirable internal quality. They found that construing the task in this manner eliminated the depletion effect. Job et al. (2010) found that only individuals who believe self-control is limited show the depletion effect. Finally, Muraven and Slessareva (2003) found that motivating participants by making them believe the task would benefit themselves or other people eliminated the depletion effect. A truly energetically limited resource could not simply increase with additional motivation to perform the task. We discuss how the DCTIR can account for these anomalies below.

It is hypothesized that framing of the task affects the monitor component. Consider, for example, research showing that imagining a marshmallow as a cloud in a delay of gratification test leads to a greater ability to resist it (Mischel, 2014). Representing the task in a less tempting manner translates to a smaller cost in the measurement subroutine, and therefore reduces the amount of effort that needs to be exerted to successfully inhibit. The cumulative effect of this reduced inhibitory effort is that it takes longer to reach threshold, and inhibition can be sustained for a longer period of time. The DCTIR predicts that any variable that affects the representation of the temptation will influence the application (and eventual termination) of self-control.

One of the strongest pieces of evidence against the resource metaphor is the finding that lay beliefs concerning self-control and willpower moderate the ego-depletion effect (Job et al., 2010). Specifically, only individuals who believe that self-control is limited show the depletion effect. Even more problematic, these beliefs can be manipulated experimentally. People induced to believe that willpower is unlimited actually show improved performance on the second task.

According to the DCTIR, self-control beliefs are hypothesized to affect the threshold component. The DCTIR hypothesizes that self-control beliefs have the effect of lowering or raising ones threshold. Specifically, those who believe they can exert self-control for a longer period of time or that they have remaining "resources" could be said to have a higher threshold (Clarkson et al., 2010; Job et al., 2010). Whereas this evidence contradicts the resource model, the DCTIR can readily account for it.

We should also note that some variables may affect both the monitor and the threshold components. Task motivation may be one such variable. Increased motivation may change the framing of the task such that impulsive behavior does not feel as tempting. Thus, as with task re-framing, the monitor is registering a less costly or tempting measurement. However, motivation directed towards applying inhibitory control is hypothesized to affect threshold. As in a previous example, if someone is working out at the gym, they may be particularly motivated to inhibit pain. This motivation may temporarily increase threshold, such that they are able to inhibit pain longer. Conversely, if someone is highly unmotivated to inhibit, this may have the effect of lowing threshold.

An important point to stress is that these hypotheses can be critically tested. Whether a particular variable has effects on the monitor, threshold, or both, the model holds that individuals can represent (explicitly or implicitly) the inhibitory effort they are putting forth and their tolerance for this inhibitory effort. In other words, the model can be falsified to the extent that positive mood or task motivation influence the termination of inhibitory effort without affecting either inhibitory effort (monitor) or tolerance (threshold).

4. Implications

One of the important implications of the DCTIR is that inhibitory self-control is viewed as an information processing mechanism. Thus, the DCTIR is a departure from the resource model in which self-control is viewed as energy. The inhibition module posited by the DCTIR is just like any other cognitive system, representing and processing information. This more mechanistic conceptualization of inhibition also avoids the recursive nature of the term "self-control". The resource model, for example, holds that "refraining from behaving requires an act of self-control by which the self alters its own behavioral patterns so as to prevent or inhibit its dominant response" (Muraven & Baumeister, 2000, p. 247). This definition treats the self as a homunculus, with no description of the nature of the mechanism that accomplishes this change in behavior. In contrast, the DCTIR proposes the use of the term inhibition regulation (the process by which computational mechanisms produce and adjust inhibition effort). This definition does not imply the operation of a self-as-executive and proposes a theoretical process mechanism. The implication is that self-control is accomplished with a structured mechanism, rather than requiring a volitional act of the "self". This is not to say that individuals cannot enact strategies to moderate inhibitory control, but that the operation of the mechanism specified here need not be a controlled or conscious process. In the same manner, the term "ego depletion" can be discarded, as there is no ego or depletion involved. The "inhibition termination effect" is more descriptive and avoids these problematic implications.

One of the most significant departures from prevailing views of self-control (including the resource model), is that the DCTIR does not view ceasing self-control effort as necessarily a failure (Baumeister, 2002; Vohs & Baumeister, 2011; Vohs & Heatherton, 2000). On the contrary, the DCTIR posits that when individuals meet threshold and thus do not inhibit further, the inhibition module is functioning as designed. Despite our evaluation of a behavior as "good" or "bad", if the mechanism is functioning as designed, we should not consider these failures. There are times when the application of self-control does not optimally match the environment. However, whether this is "good" or "bad" is a matter of context. Eating chocolate cake might be less optimal, or it might be a perfectly reasonable thing to do. To further understand this point, one must appreciate the difference between past and present environments.

Crawford (2008) points out that, when comparing our current environment to that of the hunter-gatherers, there are many differences. These differences include higher population densities, more complex social and economic structures, and larger group sizes. As a result, some adaptations are not well matched with the present environment. How our past and current environments differ, and what consequences these difference have for current physiology and behavior, is addressed by environmental mismatch theory (Bailey, 1995). The DCTIR holds that this environmental mismatch plays a crucial role in understanding why inhibition regulation is not always optimized. In a modern environment, there are many more and greater temptations than there were for our ancestors. Eating behavior once again provides a useful example. In our evolutionary past, resisting eating a high calorie meal in order to choose a low calorie meal was probably not frequent. Indeed, people who repeatedly refused a fatty, high calorie meal probably lowered their chances for survival and successful reproduction. In today's modern environment, high calorie foods are available on every corner at any hour, and obesity is rampant (Bassett, Pucher, Buehler, Thompson, & Crouter, 2008). We are presented throughout the day with the option to eat high calorie foods. Thus, it is now necessary to inhibit a behavior that, for much our evolutionary history, was quite functional. Similar arguments can be made for other types of self-control behaviors, such as aggression or casual sex, depending on the context. Moreover, it is unlikely that our ancestors had to inhibit multiple temptations serially presented within a short time period. A single mechanism to inhibit the occasional temptation would likely suffice.

From this perspective, it is important that self-control matches the environment, rather than that all impulsive behaviors are inhibited for as long as possible. Even though some of the outcomes are not always viewed as socially desirable, this does not mean the mechanism is not functioning the way it was designed. In the largely wealthy and stable United States, thinking long-term is often useful. Having high inhibition in this environment is necessary. However, in many other parts of the world, the environment is dangerous and unpredictable. Inhibiting in order to accomplish long-term goals may be disadvantageous in these situations. A mechanism that allows the “impulsive” modules to carry through with their output is therefore advantageous. This is a direct implication from the functional DCTIR perspective.

5. Comparisons to other models

Although we have compared the DCTIR primarily to the resource model, there are many other models of self-control and general cognitive control to which the DCTIR could be compared. We have mentioned several, including conflict monitoring (Botvinick et al., 2001), negative feedback loop models (Carver & Scheier, 1998), and the effortometer (Kurzban, 2010b). The DCTIR is not presented as necessarily competing with these other models. For example, the DCTIR does not assume that all cognitive and behavioral regulation is accomplished by the proposed inhibition module. We have proposed a specific inhibitory regulatory mechanism, but it is not suggested that this is the only regulatory mechanism or only inhibitory mechanism individuals employ (see also Fujita, 2011). As described earlier, the module proposed by the DCTIR is just one of many that may form a regulatory network.

The approach most similar to the module proposed by the DCTIR is the effortometer (Kurzban, 2010b). The effortometer (also a module) is described as a counter, adding up the costs of behavior. The counter determines whether it is worth engaging or continuing to engage in that behavior. With greater costs, there is an increase in the effortometer, and thus less suppression of short-term modules. Although the monitor of the DCTIR is more formally specified as an algorithm, the idea of the effortometer is similar to the measurement subroutine. This similarity is by design, as the construct of the effortometer seems to capture important features of self-control. However, there are several differences between the effortometer and the module proposed by the DCTIR. First, the monitor component proposed by the DCTIR is hypothesized to consist of content-specific module monitoring subroutines. These subroutines are not hypothesized in the effortometer. Second, the measurement subroutine is hypothesized to trigger the inhibit subroutine. In the effortometer, costs are equated with any type of effort. Inhibition is not specifically discussed, whereas the DCTIR is specific to inhibition. For example, the DCTIR would predict carryover effects with multiple inhibition tasks, but not necessarily with all effortful tasks (e.g., maintaining information in memory). Third, the effortometer does not hypothesize a representational threshold in accounting for the change in self-control performance.

It is also important to contrast the DCTIR with the process model of self-control (Inzlicht & Schmeichel, 2012; Inzlicht, Schmeichel, & Macrae, 2014) and the four component framework of self-control proposed by Hofmann et al. (2012). These approaches are also valuable and the DCTIR shares a number of features with these models. Nonetheless, we believe that the DCTIR offers a more complete account of inhibition regulation and generates specific and testable predictions not easily derived from these models.

In the process model, Inzlicht and Schmeichel (2012) provide a more mechanistic account of ego depletion (see also Inzlicht et al., 2014). Specifically, they argue that engaging in self-control causes shifts in motivation, attention, and emotion. With the application of self-control, the person's motivation to exert self-control (or pursue so-called “have-to” goals) decreases and their motivation to act impulsively (or pursue so-called “want-to” goals) increases. Feelings of mental fatigue are likely to signal this motivational shift. Moreover, changes in motivation cause a shift in attention, such that there is reduced attention to cues signaling control and an increased focus on rewards, as well changes in the intensity of the emotions associated with the goal. The cumulative effect of these linked processes is the undermining of subsequent self-control (Inzlicht et al., 2014). Left somewhat unclear in the process model is *why* motivation and attention will shift as a result of applying self-control. A recent elaboration of the model suggests that shifting from one type of motivation to the other is evolutionarily adaptive (Inzlicht et al., 2014). We agree with this viewpoint. Nonetheless, the process model does not provide an account of the mechanism responsible for identification of self-control situations, the mechanism for producing inhibition, or a proximate mechanism that results in changing motivational priorities. The process model also still labels the change in self-control performance a failure. Thus, we do not deny the power of motivation, reward, and emotion proposed by the process model. Rather, the DCTIR can be viewed as complementing the process model, providing testable predictions concerning the identification of self-control situations, production of inhibitory effort, and cessation of inhibitory effort.

Another recent model of self-control and ego-depletion is the four component framework of Hofmann et al., (2012). This model considers four aspects of self-control: desire, conflict, resistance, and enactment. Desire concerns the strength of the drive to engage in the impulsive behavior. Greater desire strength is presumed to lead to greater behavioral enactment. Goal conflict with this desire is argued to lead to the application of self-control, thereby inhibiting behavioral enactment. Thus, like the DCTIR, the four-component approach views the strength of the desire or temptation as important to its inhibition. This approach has provided useful insights into the application of self-control (see for example Hofmann, Adriaanse, Vohs, & Baumeister, 2014). However, this framework otherwise maintains the view that self-control is a limited-capacity resource and is therefore subject to many of the same criticisms as the resource model. Additionally, this approach still views “ego depletion” effects as representing a failure. Finally, the four component approach does not provide a specific mechanism explaining when the application of self-control will cease.

We can see that despite some similarity with the DCTIR and these other models, the DCTIR is the only approach that makes specifically derived predictions concerning how individuals determine whether to inhibit and when they stop.

6. Future directions

A well formulated scientific theory should explain existing data and offer new insights. The resource model directed researchers to investigate a fascinating phenomenon. However, a number of findings suggest that the resource model is no longer tenable. By providing a mechanism of inhibition regulation, the DCTIR allows more specific predictions that can be tested in future research. For example, the DCTIR suggests that whether and when someone stops inhibiting an action will be a function of how tempting individuals perceive certain behaviors, how much inhibition effort they apply, and their tolerance for inhibition.

In addition to providing a framework for more precise predictions, the DCTIR also makes a number of novel predictions concerning variables that will influence when individuals will stop inhibitory control. The first set of predictions concerns variables that increase the strength of the temptation. Stronger temptation should require more inhibition, leading to meeting threshold sooner, and thus stopping inhibition sooner. Three examples of such variables include the value of the incentive, the psychological closeness of the incentive, and the representation of the incentive. Temptation, and thus the strength of the inhibitory signal, would increase as incentives go up in value, are psychologically closer, and are presented in a more concrete manner.

First and foremost, a temptation will be commensurate with the height of the need within the person. For example, deprivation of a need results in an increased approach tendency (Hull, 1951; Kruglanski, Chernikova, Rosenzweig, & Kopetz, 2014; Staats & Warren, 1974) and greater attention to stimuli that can satisfy it (Aarts, Dijksterhuis, & Vries, 2001; Balcetis & Dunning, 2006). In other words, the value of the incentive is increased in a heightened need state (Soetens, Braet, Van Vlierberghe, & Roets, 2008; Verwijmeren, Karremans, Stroebe, & Wigboldus, 2012). The amount of the incentive should also directly relate to the degree to which temptation is experienced, such that larger incentives are more tempting. Context can also influence the attractiveness of an incentive. A positive hedonic contrast can result when the amount of an incentive increases relative to prior experience (Crespi, 1942; Flaherty, 1982). Conversely, control can also be improved by increasing the costs (social, monetary, etc.) of giving in to the temptation (e.g., Correia & Benson, 2006). Individuals will go so far as to self-impose such costs in order to better regulate their behavior (Trope & Fishbach, 2000). These findings suggest that individuals will not meet threshold (and thus continue inhibition) for a longer period of time if the underlying need is not as great, if the perceived size of the incentive is reduced, or if the costs of giving in to temptation are increased.

The notion of goal gradients (Hull, 1938) and force fields (Lewin, 1951) suggests that incentives are more motivating as they are closer in space and time. For example, Mischel and Ebbesen (1970) found that children were better able to delay gratification when the rewards could not be viewed, and splitting attention between multiple self-control tasks can actually improve the inhibition of impulsive behaviors (Tuk, Zhang, & Sweldens, 2015). Conversely, increased attentional focus on salient temptation cues (e.g., due to attentional myopia under cognitive load) can undermine self-control (Mann & Ward, 2007; Westling, Mann, & Ward, 2006). Finally, construal level theory has found that self-control is applied more effectively when incentives are psychologically distant (Fujita, Trope, Liberman, & Levin-Sagi, 2006). Indeed, putting off the gratification of a need until later in time is a hallmark of successful self-control (Mischel et al., 1989). These findings suggest that individuals will not meet threshold (and thus continue inhibition) for a longer period of time if the incentive is psychologically distant in time or space or if attention to the cues promoting impulsive behavior is reduced.

Representation of the incentive can also influence how tempting it is. For example, representing a temptation in a more "cold" cognitive manner improves self-control (Moore, Mischel, & Zeiss, 1976). Similar distinctions are made by models of impulsive/reflective processes (Strack & Deutsch, 2004) and abstract/concrete representations (Fujita et al., 2006). These findings suggest that individuals will not meet threshold (and thus continue inhibition) for a longer period of time if the incentive is represented in more abstract, cognitive terms.

The second class of predictions concerns the threshold component. Variables that raise the threshold will result in longer application of inhibitory control, whereas variables that lower the threshold will result in stopping inhibitory control sooner. Earlier, we discussed trait self-control as an example (de Ridder, Lensvelt-Mulders, Finkenauer, Stok, & Baumeister, 2012). Individuals high in conscientiousness may also have relatively higher thresholds. Indeed, these individuals are more likely to resist impulsive behaviors (Bogg & Roberts, 2004; Wagner, 2001) and avoid procrastination (Dewitte & Schouwenburg, 2002). Further, the DCTIR would predict that people with high versus low thresholds would have different patterns of inhibition effort.

In addition to individual differences, characteristics of the environment may affect threshold. Environmental harshness and unpredictability may make it adaptive to lower threshold, whereas the need to invest in future competitiveness may result in higher threshold. Thus, it would be adaptive to indulge cravings for food during a famine or be aggressive if there is a lot of violence. Alternatively, it would be adaptive to try to maintain one's figure or be less aggressive in a more stable and predictable environment. Consistent with this notion, individuals raised in lower SES environments have greater impulsiveness, particularly in times of economic hardship (Griskevicius et al., 2013). Similarly, deprivation of needs may over time lead to a lowering of threshold as an adaptive response (Hull, 1951).

Lastly, we would note that certain self-regulatory strategies may affect inhibition regulation by bypassing it altogether. For example, forming implementation intentions can improve self-control by planning, in advance, one's response to a critical situation (Webb & Sheeran, 2003). By automatizing one's response to a temptation, there is no longer a need for inhibition, and thus the module we have described here would not be utilized. Similarly, the self-control nature of a task can change as successful regulation becomes habitual (Wood, Quinn, & Kashy, 2002). One example would be pursuing casual sex while already in a committed relationship. Some may find giving up novel sexual encounters difficult, but as it becomes habitual, self-control is no longer required, and one may even be motivated through prior successful regulation.

7. Conclusions

The DCTIR proposes a computational inhibition module (composed of a monitor and a threshold) that can account for how we identify tempting behaviors and when we stop inhibiting. We argue that this functional approach should lead to new ways of thinking about inhibition (e.g., when stopping inhibition is advantageous) and we have made numerous predictions concerning variables that influence inhibition. The next step is to systematically test the predictions of the theory. Although the DCTIR is relatively complex, increased complexity does not equal lower verisimilitude. In light of the problems concerning the research into the ego depletion effect discussed here, these upcoming crucial tests should involve ecologically valid self-control manipulations and be aimed at falsification of the DCTIR. Although aspects of the DCTIR will inevitably be falsified, we strongly argue that a well formulated scientific theory of inhibition regulation should be grounded in modularity, positing a precise computational mechanism, and addressing the fundamental issues of how it is accomplished and why it is functional.

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