supports the selection and execution of context-specific sequences of goal-directed behavior, called "options," over extended periods of time (Holroyd & Yeung 2012). This view holds that the ACC integrates rewards and punishments across time to learn not whether individual actions are worth performing, but rather, whether the task itself is worth carrying out. Thus, the ACC would be responsible for motivating subjects to participate in a psychology experiment until its completion, as opposed to implementing subtle behavioral adjustments along the way.

Options are comparable to mental actions to the extent that both represent extended, task-related activities such as playing a board game, doing math homework, and jogging. Both are also selected (prioritized) based on their learned costs and benefits. Yet the two theories have an important difference: Unlike the opportunity cost theory, the HRL theory does not set the resource-depletion and cost-benefit accounts of effortful behavior in opposition. Recent HRL computational work from our laboratory (unpublished) simulates a "dual system" approach to behavioral regulation (Heatherton & Wagner 2011; Hofmann et al. 2009) whereby "top-down" control is applied by the ACC over a relatively impulsive, basal ganglia mechanism for action selection. Control is maintained via an energy factor that depletes with use (Ackerman 2011; Van der Linden et al. 2003) such that optimal task performance is maintained with the minimal level of control necessary (Kool et al. 2010; Yeung & Monsell 2003). Contrary to assertions in the target article, our simulations illustrate that – at least in principle – momentary increases in control can occur in the presence of a strictly decreasing resource (Muraven et al. 2006; Muraven & Slessareva 2003).

But do mental resources actually exist? The opportunity cost model would seem to invoke separate resource-dependent and resource-independent mechanisms for *physical* versus *mental* control, respectively. This distinction may be artificial: Even when actions involve only minimal energetic costs, people still prefer doing nothing over something (Baumeister et al. 1998; Brockner et al. 1979), and when the costs between actions are equated, they choose actions that minimize control – indicating that mental actions, like physical actions, exact costs (Kool et al. 2010). Doubts about glucose utilization notwithstanding (Schimmack 2012), mental costs must reflect in part the simple fact that the brain is a biophysical system that obeys thermodynamic laws. For instance, metabolic processing of the neurotransmitter glutamate is a highly energy-consuming process, so synapses operate on a principle of resource optimization that maximizes the current released per glutamate molecule (Savtchenko et al. 2013). A parsimonious theory would posit a unitary mechanism for maintaining control over the task at hand, whether this entails overcoming neural fatigue in a chess marathon or muscle fatigue in a long-distance marathon (Boksem & Tops 2008).

It has been suggested that the resource-depletion theory originated as an ill-conceived metaphor for the essential role that energy played during 19th-century industrialization (Hockey 2011). Ironically, in this contemporary age of dwindling natural resources, the energy metaphor may be even more apposite than before. Natural resource deposits are finite entities that become increasingly difficult to mine as the easiest resources to develop are extracted first. The decline can be masked with economic incentives that temporarily increase production, but doing so comes at the expense of an ultimately faster depletion rate (Youngquist 1997). By analogy, studies of resource depletion in humans have typically involved shorter time frames (i.e., minutes) when, presumably, the resource in question is still plentiful and easy to extract (Hagger et al. 2010a). The HRL account suggests that the ACC energizes behavior over extended periods – on the order of hours or longer – rather than on a moment-to-moment basis. Experiments that utilize longer time-horizons may discover that the short-term performance gains resulting from motivational incentives, response conflicts, and so on, come at the expense of longer-term decrements in performance once the resources upon which they draw are ultimately depleted.

Formal models of "resource depletion"

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Hilde M. Huizenga[a,b] Maurits W. van der Molen[a]
Anika Bexkens[a,b] and Wery P. M. van den Wildenberg[a,b]

[a]*Department of Psychology, University of Amsterdam, 1018 XA, Amsterdam, The Netherlands;* [b]*Cognitive Science Center Amsterdam, University of Amsterdam, 1018 WS Amsterdam, The Netherlands.*

h.m.huizenga@uva.nl m.w.vandermolen@gmail.com
a.bexkens@uva.nl w.p.m.vandenwildenberg@uva.nl
http://home.medewerker.uva.nl/h.m.huizenga/
http://home.medewerker.uva.nl/m.w.vandermolen/
http://home.medewerker.uva.nl/a.bexkens/index.html
http://home.medewerker.uva.nl/w.p.m.vandenwildenberg/

Abstract: The opportunity cost model (OCM) aims to explain various phenomena, among which the finding that performance degrades if executive functions are used repeatedly ("resource depletion"). We argue that an OCM account of resource depletion requires two unlikely assumptions, and we discuss an alternative that does not require these assumptions. This alternative model describes the interplay between executive function and motivation.

Kurzban et al.'s opportunity cost model (OCM) is proposed to explain the origins and adaptive nature of mental effort. The authors argue that if current and competing tasks both require executive functions, these tasks will be compared on their value. If the value of a competing task exceeds that of the current task, mental effort is experienced. This experience of effort is adaptive in nature, as it signals that executive functions should not be used for the current task but are better applied to the competing task. Kurzban et al. argue that their model can explain a wide variety of phenomena, including the finding that performance degrades if executive functions are used repeatedly, a phenomenon known as "resource depletion." We argue that the OCM account of resource depletion requires three assumptions, two of which are likely not to be satisfied. We therefore discuss an alternative model that does not require the two unlikely assumptions.

However, before doing so, it is necessary to specify our interpretation of two key OCM concepts: "task value" and "effort." In general, Kurzban et al. seem to define *task value* in terms of the positive aspects of a task (cf. sect. 2.4.1), yet in some instances they seem to allude to negative aspects as well (cf. Fig. 1). In addition, *effort* is generally defined as the discrepancy between current and alternative task values (cf. Abstract), yet occasionally the term seems to refer to a property of a single task (e.g., "might explain why subjects in self-control conditions exert less effort"; sect. 3.1, para. 10). In the following we adhere to the authors' general interpretations: Task value is defined only in terms of positive aspects, and effort is an index of the discrepancy between current and alternative task values.

The effects of repeated usage of executive functions are often taken to suggest that resources for executive function become depleted, hence the name "resource depletion" (Muraven & Baumeister 2000). Yet, this interpretation is subject to debate, as it has been suggested that the effects of repeated use of executive functions are better explained in terms of a depletion of motivation, rather than by a depletion of resources (Hagger et al. 2010a). Accordingly, Kurzban et al. provide an OCM account of the effects of repeated usage of executive functions, an account in which task value, a concept related to motivation, plays a key role. Below we argue that this OCM account relies on three assumptions, two of which are unlikely.

The OCM's first assumption is that a preceding executive function task reduces the value of a current executive function task. Kurzban et al. suggest one potential mechanism for this reduction: In the beginning of an experiment participants may feel obliged towards the experimenter, and therefore task value is high. But as the experiment proceeds, obligations are gradually fulfilled, and therefore task value decreases. The second assumption of the OCM account is that task value is compared to the value of a competing task also requiring executive functions; the authors focus specifically on the competing "task" of daydreaming. However, to our knowledge, there is no convincing evidence that daydreaming requires executive functions, and therefore it is not likely that this assumption is satisfied. A third assumption of the OCM account is that task value is defined only in terms of its positive aspects, and not by its negative ones, as, for example, task difficulty. This would imply that tasks differing in difficulty can have equal value and, thus, should lead to an equal experience of effort. As this corollary of assumption 3 is to our knowledge not supported by empirical evidence (Morsella et al. 2009), we conclude that assumption 3 is not likely to be satisfied.

We therefore argue that a model of the effects of sequential usage of executive functions is needed that does include motivation, yet does not rely on the aforementioned unlikely assumptions. A recently proposed simple formal model satisfies these requirements (Huizenga et al. 2012). In this model, motivation determines the fraction of required resources that will be allocated to tasks, in which required resources depend on task difficulty. It is assumed that motivation decreases with repeated usage of executive functions, and as a result, performance will decrease also. This model does not require the unlikely second assumption, as there is no comparison of motivation ("value") associated with current and alternative tasks. In addition, it does not require the unlikely third assumption, as task difficulty is explicitly incorporated into the model.

The model, however, does require the first assumption, as it is assumed that motivation decreases with repeated usage of executive functions. This assumption certainly needs further investigation, at a behavioral as well as at a neurophysiological level. At a behavioral level, it needs to be investigated whether indices of experienced motivation (e.g., Carlson & Tamm 2000) mediate the effects of sequential use of executive functions. At the neurophysiological level, the effect of repeated use of executive functions on dopamine, a "motivational" neurotransmitter (Salamone & Correa 2012) that improves executive functions (Pessoa 2009), needs further consideration. For example, in simple learning tasks, phasic dopamine releases decrease with repeated exposure to stimuli that are associated with expected reward (Schultz et al. 1993). An intriguing possibility is that these dopamine levels would also decrease with repeated performance on executive function tasks (Boksem & Tops 2008; Lorist et al. 2005).

To conclude, an advantage of the OCM account of "resource depletion" is that it includes motivation (value). A disadvantage, however, is that the OCM account relies on two unlikely assumptions. Therefore, an alternative model, relying only on the assumption that motivation decreases with repeated usage of executive functions, requires further investigation, both at a behavioral and at a neurophysiological level.

Beyond simple utility in predicting self-control fatigue: A proximate alternative to the opportunity cost model

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Michael Inzlicht[a] and Brandon J. Schmeichel[b]

[a]*Department of Psychology, University of Toronto, Scarborough, Toronto, Ontario M1C 1A4, Canada;* [b]*Department of Psychology, Texas A & M University, College Station, TX 77843-4235.*

michael.inzlicht@utoronto.ca **schmeichel@tamu.edu**
www.michaelinzlicht.com
https://sites.google.com/site/bjschmeichel/

Abstract: The opportunity cost model offers an ultimate explanation of ego depletion that helps to move the field beyond biologically improbable resource accounts. The model's more proximate explanation, however, falls short of accounting for much data and is based on an outdated view of human rationality. We suggest that our own process model offers a better proximate account of self-control fatigue.

The opportunity cost model proposed by Kurzban et al. is thought provoking, and we agree with much of it. It offers an ultimate explanation for why self-control *seems* limited, and it has the potential to move the field beyond simple and biologically improbable resource accounts of fatigue. However, we found the more proximal account of the limits of self-control to be lacking (see Scott-Phillips et al. 2011). Specifically, the notion that opportunity costs drive self-control fatigue does not account for a number of relevant findings as they relate to the proximate processes underlying self-control and its failure. Most critically, the model's proximate account is based on a modern *homo economicus* that risks being just as inscrutable as the limited-resource model it is trying to replace. We discuss the strengths of the proposed model and its shortcomings, contrasting it with our own mechanistic revision of the limited-resource model of self-control (Inzlicht & Schmeichel 2012).

We start by clarifying what we are and are not debating. We are not debating the consistent finding that engaging in self-control at Time 1 leads to declines in performance at Time 2. This basic effect has been replicated more than 100 times in independent laboratories across the world (Hagger et al. 2010a). It also maps onto the commonsense view that mental fatigue can lead to decrements in performance over time (Hockey 1983). We are also not debating the role of blood glucose as the physical resource underlying self-control and its depletion (Gailliot et al. 2007). The mounting evidence points to the conclusion that blood glucose is not the proximate mechanism of depletion, even if the presence of glucose in the oral cavity can moderate the depletion effect (Hagger & Chatzisarantis 2013; Kurzban 2010a; Molden et al. 2012). What is debatable is the *how* of depletion. The dominant account of ego depletion (Muraven & Baumeister 2000) suggests that performance on self-control tasks decreases over time because it recruits and depletes a limited inner resource. Although results of many and varied experiments using the sequential-task paradigm are consistent with a limited-resource view, the resource in these studies is inferred, but never measured (Hagger et al. 2010a). So how does ego depletion work?

Kurzban and colleagues suggest that people engage in some complex, mostly unconscious calculation of the costs and benefits of continuing to pursue the current task versus the costs and benefits of pursuing some competing task. Some version of this view seems likely to be correct, but this account does not help us to understand or anticipate changes in the cost-benefit ratio. Nor does it explain why people sometimes engage in seemingly costly and effortful behavior following periods of high subjective effort; for example, going to lengths to aggress against others or to find and consume drugs (e.g., Muraven et al. 2002; Stucke & Baumeister 2006). The proposed model also implies that people who monitor and who are generally aware of their phenomenological states should be especially likely to withdraw effort as subjective effort increases. But research has found the opposite: with people who are more self-aware being *less* influenced by previous acts of control (Alberts et al. 2011; Wan & Sternthal 2008); with people more aware and accepting of their emotions particularly good at executive control (Teper & Inzlicht 2013); and with self-control fatigue being mediated by deficits in what can be construed as a form of self-awareness (Inzlicht & Gutsell 2007). These results are not easily explained by the opportunity cost model, but they can be explained by our own process model (Inzlicht & Schmeichel 2012).

Like others (Botvinick et al. 2001; Strack & Deutsch 2004), we construe self-control as being initiated by the competition between two opposing forces: the force that motivates the expression of an impulse versus the countervailing force that