effort as a cost input may vary dynamically and intra-individually. For example, people low in dispositional executive functioning, or need for cognition, or those who believe in limited willpower, may generally assign larger weights to effort as a cost than people dispositionally high in executive functioning (Kool et al. 2010), high in need for cognition, and believing in unlimited willpower (Job et al. 2010). Many resource-depletion findings (e.g., Muraven & Slessareva 2003) can be explained this way—as the effects of prior effortful task performance on the net utility of a subsequent effortful activity, mediated via a change in the weight assigned to task effort as a cost.

In sum, we believe that the phenomenology of effort as an output of a relative utility comparison among alternatives may need to be distinguished from the notion of task-specific effort as a potential cost input. In making everyday decisions about which courses of action to take and continue, people appear to care about the effortfulness of each of these activities in more than just a relative manner. How much they care about the effort dimension may depend on how resourceful they feel at a given point in time. When tired and faced with two effortful options that are otherwise high in benefits (e.g., exercising, doing the laundry) we may sometimes choose to not engage in such options at all.

Theories of anterior cingulate cortex function: Opportunity cost
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Abstract: The target article highlights the role of the anterior cingulate cortex (ACC) in conflict monitoring, but ACC function may be better understood in terms of the hierarchical organization of behavior. This proposal suggests that the ACC selects extended goal-directed actions according to their learned costs and benefits and executes those behaviors subject to depleting resources.

Kurzban et al.’s provocative and compelling theory of effortful behavior links the psychological literature on self-control with a parallel literature in cognitive neuroscience. Their opportunity cost model suggests that the anterior cingulate cortex (ACC), prefrontal cortex, and other frontal brain areas compose a neural substrate that prioritizes mental actions based on their learned costs and benefits, an assertion that should be uncontroversial given this system’s well-known role in high-level decision making (Silvetti & Verguts 2012). Yet the rapidly evolving literature on cognitive control suggests that aspects of their proposal require further development.

In particular, although the conflict-monitoring theory of ACC function provides much of the neural foundation for Kurzban et al.’s proposal, accruing evidence appears inconsistent with it (Mansouri et al. 2009; Nachev 2011; Rainer 2007; Yeung 2013). The conflict theory was motivated largely by functional neuroimaging data (Botvinick et al. 2004), but other neuroimaging findings have been less supportive of the theory (e.g., Erickson et al. 2004; Roelofs et al. 2006). Studies in nonhuman primates have also failed to reveal conflict-related activity in ACC neurons, and ACC damage in monkeys and humans tends to spare conflict processing (Mansouri et al. 2009). By contrast, recent human functional neuroimaging (Dosenbach et al. 2007; Hysafl et al. 2009; Kouneiher et al. 2009), human lesion (Picton et al. 2007), and nonhuman primate (Hayden et al. 2011; Johnston et al. 2007) studies suggest that the ACC is responsible for task initiation and maintenance and for motivating or “energizing” behavior.

We have recently proposed a novel theory of ACC function that seems more amenable to the opportunity cost model (Holroyd & Yeung 2012). This idea links a previous suggestion that the ACC acts as a high-level decision-making mechanism that learns to choose between action plans according to principles of reinforcement learning (Holroyd & Coles 2002) with recent advances in reinforcement learning theory that utilize a hierarchical mechanism for action selection called hierarchical reinforcement learning (HRL) (Botvinick 2012). According to the HRL account, the ACC

| Case A: Conditions of resource plentifulness (e.g., no prior engagement in effortful activity, high dispositional executive functioning; belief in unlimited willpower) |
| Benefits (+) / Costs (−) | Judgment Weights (importance) |
| Doing math problems | Challenge/Exercise | +5 | 0.5 |
| Perceived Task Effort | −3 | 0.5 |
| Net Utility: | (5 × 0.5) + (−3 × 0.5) = 1 |

| Case B: Conditions of resource scarcity (e.g., prior engagement in effortful activity; low dispositional executive functioning; belief in limited willpower) |
| Benefits (+) / Costs (−) | Judgment Weights (importance) |
| Doing math problems | Challenge/Exercise | +5 | 0.5 |
| Perceived Task Effort | −3 | 1 |
| Net Utility: | (5 × 0.5) + (−3 × 1) = −0.5 |

* The “cost” of effort varies dynamically as a function of situational and dispositional boundary conditions such as prior engagement in effortful activity, low executive functioning (i.e., low ability), or varying beliefs in willpower. Changes in the importance of effort are modeled as a change in the judgment weight assigned to effort as a cost.
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 (Savetchenko 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 (Boksom & 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 apt 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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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
We look forward to future work that illuminates questions that remain open, including the nature and details of the computations that underlie mental effort, the neurophysiological structures involved, and, of course, whether computations of opportunity costs play the sort of central role that we propose. Our hope is that our proposal will serve to focus debate on these open questions. While resource models have stimulated substantial amounts of research effort, our hope is that by moving beyond resource accounts, further progress can be made in understanding the origins and function of sensations of mental effort. We believe that situating this work in the context of evolved function and the language of computation might go some way towards giving the various communities working on this important question common ground from which to operate and collaborate productively in the years ahead.

References


Ach, N. (1935) "A" and "r" before author’s initials stand for target article and response references, respectively.

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