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An opportunity cost model of subjective effort and task performance

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Abstract: Why does performing certain tasks cause the aversive experience of mental effort and concomitant deterioration in task performance? One explanation posits a physical resource that is depleted over time. We propose an alternative explanation that centers on mental representations of the costs and benefits associated with task performance. Specifically, certain computational mechanisms, especially those associated with executive function, can be deployed for only a limited number of simultaneous tasks at any given moment. Consequently, the deployment of these computational mechanisms carries an opportunity cost – that is, the next-best use to which these systems might be put. We argue that the phenomenology of effort can be understood as the felt output of these cost/benefit computations. In turn, the subjective experience of effort motivates reduced deployment of these computational mechanisms in the service of the present task. These opportunity cost representations, then, together with other cost/benefit calculations, determine effort expended and, everything else equal, result in performance reductions. In making our case for this position, we review alternative explanations for both the phenomenology of effort associated with these tasks and for performance reductions over time. Likewise, we review the broad range of relevant empirical results from across sub-disciplines, especially psychology and neuroscience. We hope that our proposal will help to build links among the diverse fields that have been addressing similar questions from different perspectives, and we emphasize ways in which alternative models might be empirically distinguished.

Keywords: evolutionary psychology; mental effort; neuroeconomics; phenomenology; self-control

> *I have no expectation that the laws of mental fatigue will be formulated in the immediate future.*
> — Raymond Dodge (1917, p. 89)
>
> *Remarkably, given that fatigue has been studied formally for well over 100 years, there is still no scientifically mature theory of its origins and functions.*
> — G. Robert J. Hockey (2011, p. 167)

1. Introduction

For some of the brain's functions, such as the regulation of body temperature and heart rate, performance is maintained without noticeable impairment over time. Similarly, the visual system executes its functions, from the retina to V1 to object recognition systems, and so on, more or less continuously during waking hours. The operation of these systems carries no phenomenology of effort, and performance reductions, if any, are slight. These observations imply that at least some of the brain's functions can continue over sustained periods with minimal reduction in performance and without any conscious sensation of effort. In contrast, other mental tasks (e.g., scanning a display for infrequent, subtle signals, doing mental arithmetic, etc.) give rise to the conscious sensation of effort and seem difficult to execute continuously over time (Ackerman 2011).

Why are some, but not all, mental operations performed without the sensation of effort and without performance loss? Our goal here is to sketch a computational explanation for both the subjective phenomenology of mental effort and the associated behavioral performance reductions. Our interest ranges broadly, from tasks such as the Stroop (Webb & Sheeran 2003), to math problems (Arai 1912), to complex decision-making (Masicampo & Baumeister 2008; Vohs et al. 2008). We propose that both phenomenology and performance in these mental tasks rest on a common foundation: *computations of their benefits and costs relative to other operations to which the same processes might be applied*. Subjective effort, on this view, is the conscious, experienced measurement of the costs – especially the opportunity cost – of continuing the task. The subjective experience of mental effort, which is generally aversive, in turn motivates reallocation of computational processes to relatively more valuable tasks. Our explanation contrasts with proposals that attribute performance reductions to depletion of a resource or to "willpower" (e.g., Gailliot & Baumeister 2007).

1.1. Phenomena to be explained

In one of the earliest studies of mental effort, Arai (1912) practiced multiplying pairs of four-digit numbers in her head until, after several months, she had reached a plateau in performance. She then completed a four-day marathon of solving multiplication problems continuously, 12 hours per day, observing that it took her longer to solve problems over each successive day's session and concluding that "difficult and disagreeable continued work brings about a decrease in the efficiency of the function exercised" (p. 114). In 1946 Huxtable et al. replicated Arai's experiment with three graduate student participants. Performance decrements over the course of each day were measurable but slight in magnitude and not as consistent as participants' reports of extreme weariness, restlessness, and boredom. In retrospect, one participant commented that she "[w]ould not repeat these four days for $10,000" (Huxtable et al. 1946, p. 52).

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1.1.1. Within-task performance reductions and associated phenomenology. More recently, vigilance tasks, which require monitoring visual displays or auditory streams for infrequent signals (e.g., Mackworth 1948), have been shown to reliably induce decrements in performance over time and concomitant increases in perceived mental effort (Scerbo 2001; Warm et al. 2008). Likewise, after long periods of time in flight simulators, pilots are more easily distracted by non-critical signals and less able to detect critical signals (Warm et al. 2008). Ratings of boredom in vigilance tasks increase rapidly above pre-task levels typically (Scerbo & Holcomb 1993), but the increase in boredom can be delayed by minor variations in task parameters, such as increasing stimulus variety (Scerbo 2001).

Performance reductions have also been observed in a variety of other tasks that require sustained attention. In "flanker tasks," for example, subjects are asked to respond to a central target stimulus (e.g., to indicate the direction of an arrow), while adjacent stimuli with incongruent information (e.g., arrows that point in the opposite direction from the target) make the task more difficult. In one version of the task, where the central target is a letter and flanking stimuli are other letters, performance generally worsens after 90 minutes (Lorist et al. 2005). Likewise, performance (as measured by reaction time and accuracy) decreases over time in "task-switching" paradigms, in which subjects are asked to respond to different features of the stimulus (e.g., the color or the size) depending on the trial (Lorist et al. 2000). Similarly, in a data entry task intended to induce fatigue, Healy et al. (2004) found that accuracy declined over time.

Broadly, tasks that engage executive functions show performance decrements over time (Holding 1983; van der Linden et al. 2003). Notably, rewards improve performance in executive function tasks (e.g., Krebs et al. 2010), suggesting that performance reductions are not mandatory, as one might expect if reductions were due to processes akin to mechanical breakdowns.

1.1.2. Between-task performance reductions and associated phenomenology. A separate experimental literature shows that performance reductions also occur when subjects perform two *different* tasks in sequence. In a typical experiment, subjects in the *experimental* condition are asked to perform a first task (sometimes referred to as the "depleting task," though so naming the task prejudges the issue) that is assumed to require volitional control of attention, emotion, behavior, or cognition, and, immediately thereafter, a second task (sometimes referred to as the "dependent task") that is assumed to require volitional control in a different domain. Subjects in the *control* condition typically perform an "easy" version of the first task and the same dependent task. This dual-task paradigm (Baumeister et al. 1998) is generally used to test the prediction that performing the first, so-called depleting task will reduce performance on the second.

A recent meta-analysis by Hagger et al. (2010a) identified 83 published experimental studies that included 198 independent tests of this effect. The overall effect size for performance impairment in the dependent task as a function of condition was medium-to-large (d = .62, $p < .001$), with substantial heterogeneity across studies ($I^2 = 35\%$). The same meta-analysis found that in such studies, participants rate the experimental task as more demanding than the control task, with medium-to-large effect sizes on self-reported effort (d = .64), perceived difficulty (d = .94), and self-reported fatigue (d = .44) (Hagger et al. 2010a). In contrast, other dimensions of subjective experience, including positive affect ($d = -.03$) and negative affect (d = .14), are minimally changed in such experiments (Hagger et al. 2010a).

As with within-task studies, manipulating participants' motivation (e.g., incentives for performance) can attenuate or eliminate performance decrements in dual-task studies. Hagger et al. (2010a) found that in three studies comprising 10 independent tests of the effect of motivational strategies on performance in dual-task experiments, the effect size for the interaction was d = 1.05.

1.2. Outline

To explain the above patterns surrounding the phenomenology of effort and concomitant reductions in task performance, we proceed as follows. In the first part of section 2, we describe key assumptions underlying our model: that the mechanisms that comprise the mind have evolved functions, that some version of the computational theory of mind is true, and that subjective experience can be understood as functioning to motivate adaptive behavior.

Next we describe the adaptive problem of *simultaneity* and its general solution, *prioritization*. We argue that certain mental processes can be flexibly deployed to multiple purposes – but not all at the same time. Choosing to do one thing with such a mental process necessarily requires choosing not to do another, and making such trade-offs optimally entails prioritizing options of greatest net value. We propose that the conscious experience of mental effort indexes opportunity costs, motivating the reallocation of computational processes toward the best alternative. We also link our account with similar, previous proposals.

In section 3, we discuss alternative accounts for both the phenomenology of effort and reductions in task performance, highlighting some potential difficulties with these models and articulating predictions that follow from our account that diverge from those made by alternative accounts. In section 4, we review empirical findings from neuroscience, especially regarding brain metabolism and representations of value, which collectively raise doubts about alternative explanations but are consistent with our view.

The final section summarizes and concludes.

2. Our model: Mental effort as opportunity cost computation

2.1. Assumptions

Our argument rests on three basic assumptions. First, we assume the brain is functionally organized to generate adaptive behavior. Because evolution by natural selection is the only known natural explanation for complex functional organization, we assume that all aspects of biological design, including the human brain, have an explanation in terms of evolved function (Pinker 1997; Tooby & Cosmides 1992). We note that this assumption does not commit us to the view that all behavior is adaptive (Symons 1992), to the position that all traits are adaptations, or to the view that the mind is optimally designed. Among other reasons, systems designed for ancestral environments can have positive or negative effects in modern environments because our contemporary circumstances differ in any number of ways from those of our evolutionary ancestors (Burnham & Phelan 2000). Likewise, an adaptation that promotes functional behavior in most situations can in certain situations generate dysfunctional behavior.

Second, we assume that some version of the computational theory of mind is true (see Pinker 1997). That is, we embrace the view that the mind is an information-processing system. Understanding these computations – including the functions they serve and the details of the way the brain implements these functions – is required for explaining behavior.

Third, we assume that subjective experience can be understood computationally as motivating the organism to behave adaptively (Lazarus 1993; Tooby et al. 2008). We reject the view, occasionally referred to as "naïve realism," that the external (or internal) world is directly and veridically experienced (Brain 1951). Instead, we suggest that qualia are the experiential component of computational outputs or measurements, information that serves a function in the context of decision-making (Damasio 1999). For example, the emotion of jealousy can be understood as indexing the potential loss of a valued relationship, motivating actions to reduce the likelihood of such loss (Buss et al. 1992). Another example is the sensation of hunger. Hunger is a mental representation of the body's current caloric needs, integrating signals from organs in the periphery and the stomach, and, in virtue of those needs, the present marginal value of eating. This computation gives rise to the conscious sensation we label "hunger," motivating appropriate behavior toward food. (For two excellent reviews, see Barsh & Schwartz [2002] and Grill & Kaplan [2002].)

Because we take these three ideas to be our assumptions, we do not defend them here. Instead, we draw on them to consider the puzzle of mental effort. Specifically, given that many tasks associated with feelings of mental effort seem to have good outcomes – for instance, working hard yields professional success, resisting chocolate leads to good health – one might have supposed that engaging in such tasks would generate positive, rather than negative, sensations. Why, if revising a manuscript contributes to the achievement of key long-term goals, does it feel aversively "effortful"? What might the sensation of effort be measuring, and what adaptive outcomes might it be designed to bring about?

2.2. Adaptive problem: Simultaneity

In this section, we sketch the basics of our model. Following the usual process in adaptationist analysis (Williams 1966), we begin by specifying the adaptive problem that we believe the computational mechanisms in question might be designed to solve (Tooby & Cosmides 1992). We then address the computations, along with inputs and outputs, that might be able to solve the problem we identify (see also Marr 1982; Pinker 1997). Subsequent to this analysis, we review the existing data and how our proposal might explain previous results.

At the most general level, the adaptive problem we believe to be at stake here is the problem of *simultaneity* – not everything can be done at once – and the concomitant solution of *prioritization* – that is, choosing what to do at the expense of other options. In the context of behavior, one cannot work toward multiple goals at the same time to the extent that there are incompatibilities in reaching those goals.

Simultaneity is a problem that confronts any system designed to accomplish multiple goals. In the mechanical (as opposed to computational) domain, the problem is clear in cases such as ducking versus jumping. Doing one precludes the other. We hasten to add that some goals can be advanced simultaneously. For instance, fleeing from a predator might well accomplish an immediate survival goal, and at the same time have beneficial effects on cardiovascular health. The problems of simultaneity and prioritization depend on the tasks in question and the processes required for their execution.

2.3. General solution: Prioritization

The solution to the problem of simultaneity is *prioritization*. For example, with a sprained ankle, prioritizing rest is sensible when there is no pressing need, such as escaping the presence of a predator. But if a predator is present, the cost/benefit computations change, and resting the ankle (reducing the chance of continued damage) is less important than using it to flee. Decision making in this respect is in part driven by a weighing of the motivational outputs – the pain of putting weight on the ankle set against the fear of a predator, which motivates fleeing.

The problem of prioritization exists for mental operations as well. The mind accomplishes many tasks at the same time because there are a large number of mechanisms that act in parallel (Alexander & Crutcher 1990; Evans 2008; Fodor 1983; Minsky 1985; Nassi & Callaway 2009; Rousselet et al. 2002; Rummelhart et al. 1986; Sigman & Dehaene 2008; Sperber 1994). To the extent that two different tasks require the same computational mechanisms, they cannot both be accomplished simultaneously with uncompromised effectiveness. Consider decisions about where to direct one's gaze. The rich, high-resolution perceptual apparatus in the fovea is finite, and it cannot be used at the same time for the entire visual field. The eyes must be directed somewhere, and foveating one part of the world necessarily precludes foveating other parts of the visual scene. The fovea and the computational apparatus downstream of it cannot simultaneously be applied to everything.

Working memory is similarly constrained in a way that mirrors the deployment of the fovea. A limited number of data structures can be actively maintained in working memory at any given time (Evans 2008; Miller 1956; Miller & Cohen 2001), leading naturally to the necessity of decisions about what gets maintained. Given the problem of simultaneity, a means is needed to evaluate the value of using computational systems such as working memory for mutually exclusive tasks. To return to the example above, attending to what is in the visual array might reduce processing of information in the auditory stream. Limited attention, in this sense, can be thought of as a trade-off in extracting information between these two information channels.

These considerations locate the solution to the adaptive problem of simultaneity in *prioritizing among possible computations* – that is, identifying which of the possible actions or computations ought to be performed. In turn, solving the problem of prioritization, very generally, requires the assignment of *costs and benefits* to candidate options. In the context of computations, this means, of course, computing the costs and benefits of candidate computations, and comparing these.

A computational challenge for making these trade-offs is that costs and benefits come in many different currencies. From a functional standpoint, the ultimate (evolutionary) value of an act depends on its eventual net contribution to fitness. Computational mechanisms, of course, cannot directly compute fitness outcomes, so they must use proxy variables, evaluating the benefits of possibilities in terms of local variables (Symons 1992). That is, the design of these mechanisms can be understood in the context of selection for systems that assigned weights in a way that maximized reproductive success (Glimcher 2003).

2.3.1. Specific solution: Prioritization using opportunity costs. The problem of simultaneity is illustrated by foraging animals which can feed in only one patch at any given time and, therefore, must decide when to stay in their current patch and when to leave it in search of a new one (Charnov 1976). Feeding at the current patch carries *opportunity costs* – that is, the value of the next-best alternative to the current choice. When foraging organisms change location, they do so because the rate of return falls below some threshold (Gallistel 1990); for instance, the running average rate of return of foraging in similar patches. To implement this, the minds of organisms contain counters, of sorts, that monitor benefits over time (Gallistel 1990).

For the present model, we propose that the allocation of mental processes to a task carries opportunity costs equal to the value of the next-best use of those mental processes. For example, the Stroop task engages the visual system and word recognition systems, among other mechanisms. It might not be possible to simultaneously perform other tasks that require one or more of the same systems. Similarly, working memory, we presume, cannot simultaneously be used for two different tasks that require it. Computations to prioritize its use must be made, and the analysis is identical to the analysis for behavioral options. Thus, in the context of tasks such as the Stroop, the costs of performing the task X include *the potential benefits of doing those other tasks (A, B, C, etc.) that are precluded because the systems required for the task X cannot be used for alternatives A, B, or C*. Performing any given task carries opportunity costs, and the size of these opportunity costs depends on the details of the systems recruited by the task. To the extent that a task recruits many systems, particularly those systems that are required for a large number of other tasks, it carries a large opportunity cost.

2.3.2. Phenomenology of perceived opportunity cost. We have argued that phenomenology can be understood as the felt or experienced output of motivational systems, directing behavior toward net positive fitness outcomes and away from net negative fitness outcomes. We argue that felt sensations are the outputs of mechanisms designed to produce inputs to decision-making systems. This view resonates with other approaches to phenomenology (Bloom 2010; Thornhill 1998). Positive experiences in the domains of food (Rozin & Vollmecke 1986), environments (Orians & Heerwagen 1992), bodies (Buss 1989; Singh 1993), the arts (Kurzban 2007; 2012), and, of course, emotions (Tooby et al. 2008) can all be neatly explained in this way.

Using the same logic, and similar to recent proposals (Boksem et al. 2005; Boksem & Tops 2008; Botvinick 2007; Hockey 2011; Kool et al. 2010; Lorist et al. 2005), the crux of our argument is that *the sensation of "mental effort" is the output of mechanisms designed to measure the opportunity cost of engaging in the current mental task* (Kurzban 2010b); see our Figure 1 here. The function of these cost representations is to direct the allocation of particular computational mechanisms away from the present task and toward the task which yields greater benefits.

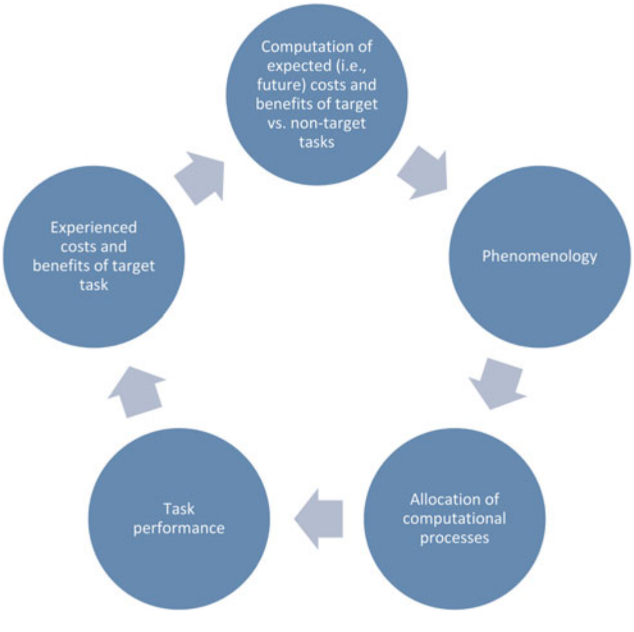

Figure 1. A schematic diagram of the proposed opportunity cost model. The expected costs and benefits of target and non-target tasks are estimated (top). These computations give rise to phenomenology (e.g., qualia such as frustration, boredom, flow), which, in turn, motivates the allocation of computational processes to tasks that are expected to optimize costs and benefits. This allocation determines performance, both on the target and the non-target tasks. The experienced costs and benefits then recursively feed into another iteration of the same sequence, with continued adjustment of allocation decisions but without depletion of any physical resource.

Our view resembles that of Kool et al. (2010), who proposed "that cognitive demand weighs as a cost in the cost/benefit analyses underlying decision making (p. 677)." Similarly, Hockey (2011) suggested that fatigue is "an adaptive state that signals a growing conflict in control activity between what is being done and what else might be done" (p. 168). Hockey's (2011) model similarly posits an "effort monitor," which functions to evaluate the value of pursuing the current goal, relative to alternative goals: "Maintaining a specific cognitive goal means suppressing all others (investigating novel environmental events, attending to emerging thoughts, making a phone call, replying to an email). It is argued that the fatigue state has a metacognitive function, interrupting the currently active goal and allowing others into contention" (p. 173). In the same vein, van der Linden (2011) has suggested that "fatigue might be considered as a *stop emotion*" (p. 153, italics original), an idea proposed more than a century earlier by Thorndike: "Feelings of fatigue … serve as a sign to us to stop working long before our actual ability to work has suffered any important decrease" (quoted in Arai 1912, pp. 72–73).

Our model explains the well-documented experiences of boredom and mental effort associated with vigilance tasks. Performing such tasks requires deploying attention to the stimulus object. Monitoring the Mackworth Clock, for example, requires computations to determine whether the movement of the clock corresponds to the motion specified by task instructions, which presumably recruits working memory and other systems, which therefore cannot otherwise be engaged. To the extent that there are no offsetting benefits – other than, for example, compliance with experimenter requests to persist – the relationship between perceived costs and benefits can become less favorable over time, just as in the foraging case discussed earlier.

We can also apply this idea to the experimental psychology literature on "self-control" (Baumeister et al. 2007). The tasks used in this literature, such as those that require making complex choices (as opposed to simply remembering), keeping an instruction in working memory (e.g., "Don't think of a white bear"), inhibiting pre-potent responses, math problems, and so on, all require systems that have many possible uses (Miller & Cohen 2001; Miyake et al. 2000; Stuss & Alexander 2000). As in the case of the vigilance tasks, we believe that it is useful to conceptualize executing self-control tasks as carrying the opportunity costs associated with these systems, and the phenomenon of effort to be the felt output of a motivational system designed to optimize the deployment of computations that cannot be used simultaneously, especially those associated with executive function.

In sum, many experiences, particularly the more or less unpleasant sensations discussed here (e.g., effort, boredom, fatigue), can be profitably thought of as resulting from (1) monitoring mechanisms that tally opportunity costs, which (2) cause an aversive state that corresponds in magnitude to the cost computed, which (3) enters into decision-making, acting as a kind of a "vote," influencing the decision ultimately taken.

2.4. Simple formal model

Here we sketch a formal model of our proposal to explain how our theory can account for the perception of effort, corresponding performance decrements, and the dynamics of both of these. Developing more detailed computational models that make quantitative predictions in specific tasks should be a critical aim of future research, but goes beyond our goal here.

We start with the assumption that organisms solve the prioritization problem by estimating the utilities of different possible actions, and then selecting the action that has maximal expected utility. (See section 4.2 for neural evidence supporting this assumption.) We therefore start with the standard assumptions of rational choice, applying this logic to prioritizing *mental* actions. These assumptions are analogous to the approach in psychophysics, in which value maximization is (likely) the "ideal observer" solution for trade-off and prioritization problems. This makes it a natural starting point for thinking about the computations involved in solving trade-off and prioritization problems from a *functional* point of view. Of course, as is often the case in psychophysics (and elsewhere), cognitive mechanisms might only approximate the ideal observer solution.

2.4.1. An illustrative example. Consider, as an illustrative example, a research participant asked to perform a set of simple math calculations of the sort Arai (1912) and Huxtable et al. (1946) investigated. We can think of this participant as having a choice between performing those calculations or, alternatively, daydreaming (and therefore not performing the problems). Performing the math calculations leads to various benefits in different currencies (e.g., monetary, class credit, social approval). Daydreaming's benefits are more difficult to identify but may include reflection upon past experience and scenario planning for the future (Gilbert & Wilson 2007). The costs of these mental activities are simply their opportunity costs. In situations like these, the opportunity cost of a chosen action is the value of the next-best possible action. Thus, the opportunity costs of doing the math calculations are the foregone benefits of daydreaming. (Note that we take daydreaming as only one example of the kinds of "background processes" that one's brain could engage in. Others might be planning future activities, re-evaluating past actions, scanning the environment, etc.)

Suppose that we add a third possible action for our research participant. Sitting next to him (or her) is his smartphone, which he could use to check his email, log into Facebook, or check sports scores, and so on. We assume that people are motivated to do these activities because they derive from them lots of valuable social information (e.g., who is trying to get in touch with them, who likes their latest status update, whether their team is winning the soccer match, etc.); but in this context, these activities carry the potential cost of social disapproval from the experimenter. So let's assume playing with the smartphone is more valuable than daydreaming but less valuable than doing the experiment, and that we can attach a single number to each activity that is proportional to its expected utility (*U*). (See Fig. 2.)

With the smartphone available, the opportunity costs of doing the math problems are now greater, since the foregone benefits of using the smartphone are greater than those of daydreaming. Our model predicts that doing the math problems in the presence of the smartphone *will be perceived as more effortful* than when the smartphone is absent because the opportunity costs are higher.

Perception of mental effort might correspond to different specific computational parameters, including the opportunity cost of the current action (6, in the smartphone example), the ratio of that opportunity cost to the utility of the current action (6/10 = 0.6), or the difference between them (10–6 = 4). We do not take a position here on exactly which of these the perception of mental effort most closely corresponds to, but believe that this question could be answered empirically.

Experiencing mental effort does not *always* result in ceasing the current activity, and in the above example the participant should continue to do the (now more effortful) math problems. In some cases, though, the experience of mental effort precedes abandoning a task altogether. Returning to our example, imagine the experimenter leaves the room, changing the calculus of benefits for doing the experimental task (social disapproval for shirking is now less of an issue), as shown in Figure 3. The

Possible activities	***U***
Doing math problems	10
Daydreaming	2

→

Possible activities	***U***
Doing math problems	10
Playing with smartphone	6
Daydreaming	2

Figure 2. Hypothetical utilities of different actions a research participant might engage in, illustrating how opportunity costs depend on the set of actions available.

Experimenter Present

Possible activity	***U***
Doing math problems	10
Playing with smartphone	6
Daydreaming	2

→

Experimenter Absent

Possible activity	***U***
Doing math problems	5
Playing with smartphone	6
Daydreaming	2

Figure 3. How hypothetical utilities of different actions might change for a research participant with the experimenter present/absent, illustrating opportunity costs and the optimal action changing in different contexts.

participant in this example should then cease doing math problems and shift to playing with his smartphone.

2.4.2. Allocating computational processes. The foregoing assumes that only one task at a time can be executed. In this section, we assume that the critical computational processes necessary for task performance can be divided among multiple tasks, that these processes can be allocated in different proportions to different tasks, and that task performance varies with the degree to which computational processes are allocated to the task. We stress that in this view, mental "resources" are finite, *dynamic*, and *divisible* at any given point in time, rather than finite and *depletable over time*. A good analogy would be a computer with multiple processors that are dynamically allocated to computational tasks; the brain similarly has a finite number of mental "processors" that can be allocated to different tasks.

To see how these additional assumptions can explain decrements in task performance, consider again the math problems. Take the simplest possible case, in which there are just two mental processors and two possible activities (task 1, task 2). As shown in Figure 4, the value or *utility* (*U*) of allocating the processors to the different tasks depends on how many processors are allocated to each task:

Two-Processor Allocation

Task on Processor 1, Task on Processor 2	*U*
Math, Math	10
Math, Daydreaming	11
Daydreaming, Daydreaming	2

Figure 4. Hypothetical utilities of dedicating computational processes to one task or dividing them between two tasks, illustrating how opportunity costs apply not just to the selection of tasks but also the allocation of processes among tasks.

Under the conditions shown in Figure 4, the participant with both mental processors allocated to the math problems (U=10) should shift to having the processors divided between doing math problems and daydreaming (U=11). If performance on math problems varies monotonically with the number of mental processors dedicated to a task, which is a likely assumption, then such a shift would result in decreased performance.

In this simplified case, dividing processors between two mental tasks should occur only if the marginal utility *gained* by devoting one processor capacity to the next-best task is greater than the marginal utility *lost* by reallocating one processor from the best task to the next-best one.

To illustrate this with a simple mathematical example, consider the case where a person can focus on only one task or perform two tasks at once, when doing two tasks simultaneously

$$U(a_1, a_2) = \beta \times (U(a_1, a_1) + U(a_2, a_2))$$

where a_1 and a_2 are two tasks; $U(a_1, a_1)$ is the value gained from doing only task a_1; $U(a_2, a_2)$ is the value gained from doing only task a_2; and $U(a_1,a_2)$ is that value gained from doing both a_1 and a_2 at the same time. β is an index of diminishing marginal utility, where $1 \geq \beta \geq 0$. When β is high (near 1), the person already receives most of the possible value from a task under conditions where processing capacity is simultaneously divided between two tasks.

We can define the relative utility (RU) of the next-best action (a_2) as the fraction of its utility relative to the utility of the best action (a_1),

$$RU(a_2) = \frac{U(a_2, a_2)}{U(a_1, a_1)}$$

The conditions under which a person should do both tasks simultaneously is expressed thus:

$$U(a_1, a_2) > U(a_1, a_1) \text{ when } \beta + \beta \times RU(a_2) > 1$$

Figure 5 shows the parameters under which the person should divide processing capacity between two actions rather than devote processing capacity exclusively to the highest-valued action. This occurs when the relative utility of the next-best action ($RU(a_2)$) is high, and when there is diminishing marginal utility to devoting processing capacity entirely to one task relative to dividing it between two tasks (β is high). These two parameters control the opportunity cost of devoting processing capacity exclusively to the most valuable task. When the marginal value gained from the best task by dedicating processing capacity entirely to it is *less than* the marginal value gained from the next-best task by dividing processing capacity, processing capacity should be divided between the two tasks.

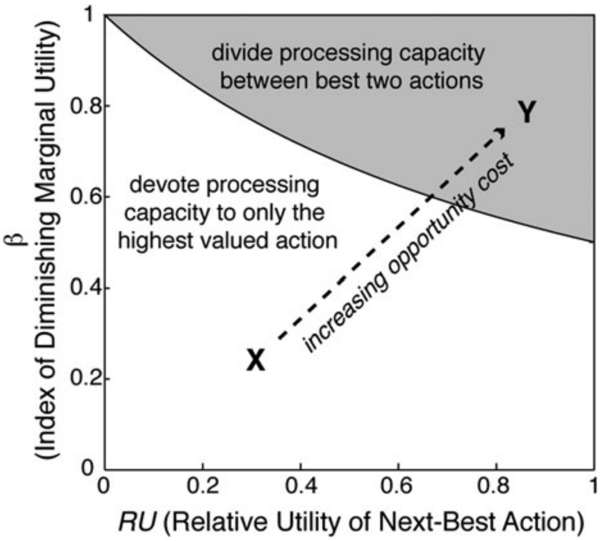

Figure 5. For the simple model outlined in the text, whether processing capacity should be dedicated to only the highest valued action or divided between the two best actions, as a function of the relative utility (RU) of the next-best action and the fraction of the value (β) gained from a task when dividing processing capacity. These two factors determine the opportunity cost, and it is better to divide processing capacity when the opportunity cost is high. The locations x and y provide an example of how to think about the dynamics of effort and performance. A person will feel an increased sense of effort, and shift so that processing capacity is divided in a way that reduces task performance, when the perceived costs and benefits of the task move from position x to position y.

Our examples above are clearly simplifications, but these examples have been intended to be illustrative only. Microeconomic models could provide a much richer framework to model these kinds of effects, a framework which does not depend on restrictive assumptions such as the utility from a task being directly proportional to performance, or the utility functions of the two tasks being similar in form. This richer framework would involve "production functions" that describe performance on multiple tasks as a function of the number of "processors" allocated to them, and "utility functions" that describe one's preferences over performance levels on the different tasks. Such a framework was already offered some time ago, as an alternative to "resource theories" of attention (Navon 1984). Our hope here is that such a framework will gain greater traction in the field by being reintroduced.

2.4.3. Dynamics of effort and performance. Empirically, cumulative time on task has been found to be the best predictor of sensations of fatigue (Kanfer 2011; see also Boksem et al. 2006). Why are some tasks perceived as progressively more and more effortful over time? Related, why does performance on vigilance tasks decline over time? And, why would performance on a second task decline after having done a first one?

Our view is that a person's experience with a task over time provides information which updates estimates of expected utility. Figure 5 illustrates the optimal allocation between two tasks. Dynamics arise in *how* one reaches that optimal allocation. For example, imagine someone is currently devoting her (or his) entire processing capacity to one task, but would, because she is "at" point *y*, in the shaded portion of Figure 5, be better off dividing her processing capacity between the two tasks. In this case, we would expect the person to experience a sense of effort that would cause her to shift allocation and divide processing capacity between the two tasks.

A situation where processing allocations are suboptimal can arise for at least two reasons. First, the relative utility of the next-best action might be stable, but the person does not know this value with any certainty, and so he or she has to learn it over time. This situation likely obtains anytime someone begins performing a novel task for the first time. Second, the relative utility of the next-best action might be changing over time, such that a previously optimal allocation is no longer optimal (as illustrated in Fig. 5 with a change from point *x* in the white portion of the figure to point *y* in the shaded portion). Thus, our theory explains dynamics of effort and performance as a result of learning the utilities and opportunity costs over time, as opposed to dynamic changes in the level of a resource.

Finally, we note that a framework explaining changes in mental effort and task performance as the result of dynamic learning processes can easily be expanded to incorporate trade-offs between exploration and exploitation. Even when the perceived utilities of the two best tasks are stable, it could be adaptive for there to be a small bias away from continuing to allocate processing capacity to the same task over time, which would also contribute to decrements in performance over time. As discussed extensively in the literature on reward learning (Cohen et al. 2007), such an exploration bonus would trade off exploitation of knowledge about the current task for gaining new and potentially valuable knowledge about different tasks.

3. Comparing our model with previous models

Broadly, two types of explanations have previously been proposed for reductions in performance in tasks that require vigilance or "effort" over time. One view is that information-processing *resources* or *capacities* are dynamically allocated in response to task demands. These resources/capacities have been conceptualized as unitary and domain-general (Kahneman 1973; Moray 1967) or multiple and domain-specific (e.g., Gopher et al. 1982; Navon & Gopher 1979; Wickens 2002). Some accounts have hypothesized that mental effort and task performance decrements are caused by the literal depletion of a resource (Gailliot & Baumeister 2007; Gailliot et al. 2007). Other accounts have located their explanation in the notion of *motivation* (Boksem et al. 2006; Boksem & Tops 2008; Hockey 2011; Nix et al. 1999; Robinson et al. 2010), positing that the repetitive, tedious nature of the task leads observers to withdraw effort over time and instead divert attention to other tasks. Some accounts combine these two approaches; still others draw on other computational frameworks (Gonzalez et al. 2011; Gunzelmann et al. 2009). Although it is beyond the scope of this article to address all alternative conceptualizations, this section describes how our model explains existing data, and distinguishes our model from some of these previous accounts.

Accounts of mental effort and task performance that rely on some notion of "resources" or "capacities" use these concepts with varying degrees of specificity, falling into two broad categories. Some accounts use the idea of resources loosely and analogically, where researchers infer from task performance outcomes that the underlying cognitive system of interest behaves "as if" it were constrained by a limited resource, or that it has a "limited capacity" of some sort. Less common but recently rising in prominence are limited resource accounts in which the resource is specified. These two categories of resource/capacity accounts are briefly described below.

The most prominent account of mental effort as a limited capacity is probably Kahneman's (1973) capacity model of attention. Kahneman's account does not seek to explain the phenomenology of effort; rather, in his model, *effort* (which he refers to interchangeably as "attention" or "capacity") is an assumed constraint for certain kinds of tasks with particular characteristics and thus a constraint on task performance. The total amount of effort that can be used at any one time is limited and is used according to an allocation policy that changes over time based on task demands. Effort is thought to increase in response to demands such as the relative task "difficulty," time pressure, and especially when two tasks are being done at the same time. In this model, effort is not literally a resource; it is *dynamic* (allocated in response to changing task demands) but is not *depletable*. In this sense it is similar to models of attention that preceded it, most notably Moray's (1967) model of attention, and also to later models of working memory (e.g., Baddeley & Hitch 1974; Posner & Snyder 1975; Posner et al. 1980).

Whereas Kahneman's (1973) model of effort relied on a unitary and limited capacity (see also Moray 1967; Rolfe 1971), other models posit *multiple* capacities or resources. For example, Navon and Gopher (1979) proposed a model of multiple capacity usage analogous to the production of a firm, whereby performance on two simultaneous tasks depends on trade-offs resulting from shared inputs, the degree of demands on those inputs, and the chosen allocation policy (see also Gopher et al. 1982; Gopher & Navon 1980). In Navon and Gopher's model and other multiple capacity models (e.g., Wickens 2002), the putative resources are *dynamic* but, as in Kahneman's (1973) model of effort, not depletable.

Other accounts that attempt to explain diminished task performance (and, secondarily, mental effort) use the idea of resources literally. Perhaps the most prominent non-motivational account for explaining the sorts of effects we are interested here is the "ego depletion" model, found in the psychology literature on "self-control." Tasks in this literature are similar to vigilance tasks (e.g., Davies & Parasuraman 1982; Head 1923; Mackworth 1948; Warm 1984; Warm et al. 2008), showing reductions in performance over time and giving rise to the phenomenology of effort. The principal focus is on performance reductions; measurement of subjective effort is typically used as a manipulation check (e.g., Muraven et al. 1998). This account suggests that performance on these tasks relies on a resource that can be depleted. It has spawned a tremendous amount of research (recently reviewed by Hagger et al. 2010b), and arguably represents the most influential model of diminished task performance after a putatively "difficult" task in the psychological literature. More recently, researchers in this tradition have attempted to specify the resource that is depleted and that leads to subsequent performance decrements (Gailliot & Baumeister 2007; Gailliot et al. 2007).

Numerous other accounts of mental effort and task performance rely on some notion of "motivation." Although the term can be vague (see Niv et al. [2006] for a useful discussion), we believe that motivation has a role to play in explaining mental effort. (See especially Berridge [2004] for a thorough and useful discussion of motivation.) Indeed, previous models have linked costs and benefits with the notion of motivation. Among these models, the view that most closely resembles our own is Hockey's (2011) "motivational control theory of mental fatigue." Hockey suggests that the feeling of mental effort is a signal that functions to cause goal switching in humans. A rapidly growing literature echoes this focus on the adaptive nature of mental effort, whereby the expected costs and benefits motivate behavior toward more rewarding activities and away from less rewarding ones (e.g., Boksem et al. 2005; 2006; Boksem & Tops 2008; Kool et al. 2010; Kurniawan et al. 2011).

3.1. How the opportunity cost account explains existing data

As discussed above, our view bears a resemblance to proposals that explain reductions in performance as due to "motivation." However, our view of motivation is a particular one, and committed to the idea that the "motivation" to devote computational processes or attention to a task depends on the history of costs and benefits of executing the task. Our proposal also goes beyond previous motivational theories in not just specifying that mental activity is costly, but identifying the source of the cost – namely, that engaging computational processes or attention on a task entails opportunity costs. Because our proposal relies on the computation of the relative costs and benefits of persisting on a given task, and so commits to a representation of value, we refer to our account as an *opportunity cost model.* Our view resonates with models such as the "sociometer" model of self-esteem, which suggests that self-esteem can be thought of as a measure of one's value to others (Kirkpatrick & Ellis 2001; Kirkpatrick et al. 2002; Leary & Baumeister 2000; Leary et al. 1995).

So, in the context of the Mackworth Clock task, our view is that when subjects comply with experimenter requests to attend to the task, the costs of doing so are represented – specifically the opportunity costs of the computational systems required for the task. In vigilance tasks, targets are rare. As a person gains more and more experience with the task, their estimate of the probability of a target, and therefore the expected benefit of fully attending to the task, declines. (Note that this explanation predicts that vigilance should *increase* right after a target occurs; other reinforcing stimuli should have similar effects.) With learning, the representations of costs grow with time on task and, absent offsetting benefits, are experienced as the sensations of fatigue, boredom, and/or stress – aversive subjective states, which in turn encourage disengagement with the task and, ultimately, performance reductions. In short, we would explain vigilance decrements with reference to subjects' learning (implicitly or explicitly) about the value of devoting attention to the vigilance task versus dividing attention between the task and mind-wandering (Gilbert & Wilson 2007).

Similarly, our account suggests that the difference between the consistent Stroop and the inconsistent Stroop is that the inconsistent Stroop requires systems that inhibit prepotent responses that are themselves useful for a number of other computations. The recruitment of these (executive) systems carries opportunity costs, which in turn are experienced as effort, eventually reducing performance.

What about performance effects in sequential paradigms, such as when one's persistence on unsolvable anagrams is lower after having previously completed a Stroop task? Sequential effects can be explained by our account if there is some link between the expected utility of the second task and the costs and benefits of having performed the first task – perhaps because the two tasks are similar in some way, or maybe just by the virtue of both tasks being part of the same social interaction.

Feelings of mental effort are limited when extrinsic incentives are sufficiently high (Boksem et al. 2006; Lorist et al. 2005; Tops et al. 2004). Similarly, when a second self-control task is perceived as sufficiently important (e.g., it leads to money, it may help others or oneself), prior engagement with a "depleting" task has no effect on performance or perseverance (e.g., Muraven & Slessareva 2003). Because it is unclear what sort of a "resource" might be restored when the subject is paid or otherwise incentivized (see below), these effects point to a motivational account for explaining the results of studies in the self-control literature.

We propose, in short, that the phenomenology of effort is attenuated if one experiences reward of various forms. This is necessarily the other half of the cost/benefit equation. Activities will seem less aversive, and therefore allow persistence, to the extent that benefits of various forms are received. These predictions already have some support (see sect. 3.3.2).

In this framework, beliefs and perceptions can lead to *increases* in task performance, again through learning. For example, this is how our theory would explain increased effort at resisting smoking at time 2 after having successfully resisted smoking at time 1 (O'Connell et al. 2008); the first successful effort likely increases one's belief that subsequent efforts will also be successful.

Costs, of course, also matter. Consider that when subjects participate in laboratory experiments, they are doing so, generally, because they are receiving compensation either in the form of partial course credit or in the form of monetary payment. Thus, experimental sessions are explicitly exchanges in which the subjects give their time (and "effort") in exchange for credit or cash. This explicit exchange – along with implicit norms that govern the relationship between subjects and experimenters in such contexts (Orne 1962) – explains why subjects comply with experimenter instructions and requests.

There are, of course, limits to what subjects will do. Subjects' decisions to comply can be affected by the amount of effort that is appropriate, given the compensation they expect to receive (Akerlof & Yellen 1990; Fehr et al. 2009). That is, people expend effort as a function of what they construe as "just" or "fair," given the exchange relationship (Fehr et al. 2009). Studies have shown, for instance, that subjects are more likely to do favors having previously received an unsolicited gift (Regan 1971); that surveys are more likely to be completed and returned when accompanied by an up-front small payment than by the offer of a large payment upon completion (James & Bolstein 1992); and that tips are more likely when food servers offer customers a candy with their check (Lynn & McCall 2000).

So, to the extent experimental participants in a "self-control" treatment perceive themselves as having discharged more of this obligation than those in a control treatment, participants might be expected to expend less effort on the subsequent task. Given that "self-control" tasks usually evoke a sense of effort, the perception of having discharged an obligation might explain why subjects in self-control conditions exert less effort. This locates the similarity of results across self-control tasks not in a resource, but in the felt sense of effort these tasks evoke in concert with the construal of the experimental context as an exchange.

One challenge to this argument comes from data showing that the size of "depletion" effects is not reduced by changing experimenters between the initial depleting task and the later task, nor by presenting the two tasks as a single experiment (Hagger et al. 2010a). However, if subjects find the self-control treatment aversive (Hagger et al. 2010a), and therefore understand their obligation to give a certain amount of effort in exchange for the credit that they are receiving, then they may understand their obligation to be reduced after the expenditure of effort even if a new experimenter is encountered in a second part of an experimental session. Indeed, consistent with this type of interpretation, DeWall et al. (2007), for example, reported that participants behaved more aggressively after performing a self-control task (see also Stucke & Baumeister 2006). In short, devoting attention to the task might be represented as a cost paid to offset the benefit (e.g., course credit) they are to receive. As they discharge more of the benefit over time, the residual they "owe" for the hour of credit diminishes. This might help to explain task carryover effects; over time, subjects owe less attention, and the endurance of the sensation of effort, in return for credit.

3.2. *Comparison with resource accounts*

The accounts that are perhaps most different from ours are resource models, in which performance depends on a depletable resource. A version of the resource model proposed by Baumeister and colleagues is also the most prominent explanation for performance decrements in the self-control literature in psychology. It is therefore instructive to explicitly consider their model and similar resource accounts in some detail.

Muraven and Baumeister (2000) presented five assumptions of this model:

1. Self-control "strength" is necessary for self-control.
2. Self-control strength is limited.
3. The resource on which this strength is based is used across self-control operations.
4. Task performance depends on one's self-control strength (though "impulse strength," among other factors, might also influence performance).
5. Exerting control exhausts self-control strength.

These assumptions give rise to a family of models, depending on how performance "depends on" the level of the resource (Assumption 4), as we review below.

Note that in this literature, researchers tend to use the experimental structure described above, in which a subject does one task that putatively requires the self-control resource – ranging from not eating tempting brownies, to doing an inconsistent Stroop task, to showing no emotion while watching a funny video, and so on. (Subjects who have completed such a task are referred to as "depleted.") Subsequently, subjects do a second task that also putatively requires the self-control resource.

3.2.1. Theoretical assumptions of resource models. Distinguishing our model from resource models is challenging because resource models have multiple interpretations. On one interpretation, performance could depend on the level of a resource in a very strict way, with the level of the resource putting an absolute upper limit on performance. As an analogy, consider an electric pepper grinder; as the batteries get close to being drained, operation is limited by the remaining charge. According to this model, for any given amount of resource, there is a fixed maximum level of performance. We will refer to this as the "Strict Capacity Model" because it holds that the causal locus of observed performance reductions is the capacity for performance. This model carries the very strong entailment that, as a literal and physical matter, nothing could improve performance among "depleted" subjects – those who have recently exercised self-control – as in the case of a nearly depleted battery in a pepper grinder. As Baumeister and Vohs (2007) put it, using a reservoir analogy: "If the tank were truly and thoroughly empty, it is unlikely that increasing incentives would counteract depletion" (p. 125). The large amount of data showing that incentives do counteract "depletion" is strong evidence that the Strict Capacity Model is false (Baumeister & Vohs 2007; Baumeister et al. 2007; Muraven & Slessareva 2003).

Indeed, as Baumeister and Vohs (2007) put it: "Ego depletion effects thus indicate conservation of a partly depleted resource, rather than full incapacity because the resource is completely gone." This suggests a second type of model: that the amount of the putative resource puts, in principle, an upper (capacity) limit on self-control performance, but that performance reductions are not a strict necessity (Muraven et al. 2006). This view suggests that "depleted" subjects could – perhaps by virtue of changed incentives – perform without any decrement or perform worse than controls. As an analogy, consider a soldier taking fewer shots because she is running low on ammunition, but is not yet out.

The second model, then, is that "depleted" and "non-depleted" subjects are *capable* of equal performance, but "depleted" subjects do not deploy self-control resources. This carries the implication that all of the effects in this literature are due to a *decision* by the subjects not to use self-control resources, rather than a limit on their capacity for self-control per se. In other words, this model holds that the reduction in the resource is not the immediately proximate causal variable, but is only indirectly related. As Muraven et al. (2006) write, "The moderation of depletion by motivation suggests that self-control suffers in many situations because individuals are not unable but instead are not willing to exert sufficient self-control to overcome the impulse" (p. 525).

This model implies that no data can be directly explained by the capacity restriction. Instead, all the data are explained by a reduced capacity that caused a change in motivation to persist, and that this reduction in motivation directly caused performance reductions. A related view is that the amount of the putative resource matters, but so too does motivation, such that the level of the resource and motivation jointly determine self-control performance.

Muraven and Slessareva (2003), for instance, argued that their data support the view that "depletion of self-control strength does not prevent the subsequent exertion of self-control" (p. 897). This implies that the putative resource is not necessary for self-control, or, minimally, that self-control can be exerted in the absence of some quantity of the putative resource. The problem with such a view is that any observations of performance reduction can be accommodated by the claim that something was depleted, and resources husbanded. Observation of continued performance can be accommodated by the view that something was depleted, but no husbanding took place. Without independent means of measuring the resource and motivation, no data can falsify the model. This model runs into the problem faced by resource accounts in general, as pointed out by Navon (1984), who observed that the

> frequent cases in which the predictions do not bear out are dismissed by resorting to built-in escapes in the theory, such as, data limits, *operation below full capacity*, disparate resource composition, and so forth. This is probably the source of the self-reinforcing nature of the concept and the unfalsifiable status of the theory. (p. 231, emphasis added)

It could be that one route to evaluating this model would be studies in which performance was compared between "depleted" and "non-depleted" subjects, with motivation held constant. However, because "depleting" tasks, we would argue, can affect motivation, this design represents a methodological challenge in the absence of good tools to measure motivation and the putative resource accurately.

Finally, a third model is that the amount of the resource that is available directly limits performance, but that motivation can (in some way) causally influence the amount of the resource. On this model, motivation is an antecedent variable that influences self-control performance indirectly – that is, the order of the two causal variables is reversed as compared with the strict husbanding model. For instance, Tice et al. (2007) showed that when subjects performed an initial self-control task, there were no adverse effects on a subsequent self-control task when they experienced positive affect in the intervening time period – either from watching a funny video, or receiving an unexpected gift. Tyler and Burns (2008) found similar effects with relaxation interventions, and Schmeichel and Vohs (2009) found similar effects with self-affirmation interventions. Tice et al. (2007) argued that positive affect might be able to "effectively replenish the depleted resource" (p. 380). We are uncertain what sort of mechanism might literally have this effect. We also note that this view is inconsistent with the view that the resource is something physical (e.g., glucose; see below).

3.2.2. Empirics of resource models. In addition to the concerns in the previous section, there are empirical results which seem hard for resource views to accommodate. Martijn et al. (2002) had subjects watch a brief video and had some subjects suppress their emotional expression, a task previously shown to yield performance reductions (Muraven et al. 1998). Martijn et al. then manipulated beliefs about self-control, suggesting to some subjects that the intuitive theory that exerting self-control relies on a limited resource is incorrect. The resource model predicts no effect of such beliefs. The dependent measure was the difference in performance on a hand grip task before and after watching the video. People who were given the emotion suppression manipulation but also told that the intuitive resource model of self-control was false showed an *increase* in performance on the hand-grip task. Along similar lines, Job et al. (2010) recently showed that "depletion" effects depend on individuals' beliefs. People who did not indicate agreement with the idea that energy is depleted by a taxing mental task did not show the reduction in performance frequently observed in a two-task design.

In addition, Converse and DeShon (2009), drawing on research on "learned industriousness" (Eisenberger 1992), had subjects complete a perceptual task – finding differences between two images – then a math task (for which subjects were financially incentivized to answer correctly), and then an anagram task. One group of subjects was given perceptual and math tasks that were more taxing than for the other group, which should lead to performance reductions in these subjects. However, the reverse occurred: those in the more difficult condition persisted longer on the anagram task. This effect was replicated when different "depleting" tasks were used (and incentives in the second task omitted).

Similarly, Dewitte et al. (2009) had subjects perform a "response reversal" task, performing one action when they saw particular stimuli, but reversing the response for those same stimuli under particular conditions. Subjects who suppressed thoughts of a white bear subsequently performed worse on this task compared to controls, as predicted by resource models. However, consistent with their predictions derived from "control theory" (Miller & Cohen 2001), Dewitte et al. found that subjects who did one response reversal task subsequently performed *better* than both the controls and those who had engaged in thought suppression. Similarly, subjects who did task reversal twice performed better the second time than the first time. (For similar results, see Eisenberger & Masterson 1983; Hickman et al. 1998.) Such improvements are difficult for resource models to explain, though they could perhaps be accommodated to the extent that these results could be attributed to practice effects.

Likewise, framing a laboratory task such as squeezing a handgrip as long as possible as a test of a subject's "willpower" improves performance compared to a neutral framing (Laran & Janiszewski 2011; Magen & Gross 2007). Finally, Ackerman et al. (2009) found that participants asked to mentally simulate the perspective of another person exerting self-control subsequently showed less self-control themselves.

In short, the theoretical and empirical difficulties for resource accounts suggest that alternatives, such as our proposal here, might be of value in accounting for the array of effects in this literature.

3.3. Comparison of models and predictions

In the foregoing, we have discussed evidence from prior empirical studies that in our view support an opportunity cost model of mental effort. Here, we summarize how our model's predictions diverge from alternative accounts of mental effort, some of which are supported by prior studies but most of which have yet to be directly tested.

First and foremost, while both our model and the resource account posit limits to mental activity, the nature of the limitations is different. In the resource account, mental resources are *depletable*: finite and destroyed with use. In our proposal, computational processes are *dynamic*: finite but not destroyed with use. The resource view holds that performance reductions result because some physical substrate in the brain (e.g., glucose) is literally depleted during self-control tasks. In contrast, our model suggests that performance reductions reflect the operation of a system designed to motivate disengagement with the present task when the opportunity costs are sufficiently high. Because computational processes are dynamically allocated rather than irreversibly (over short time spans) depleted, our model predicts that performance in self-control tasks might under specific circumstances *improve* over time, even in the absence of practice effects.

A second distinction concerns phenomenology. We suggest that the estimation of opportunity costs gives rise to the phenomenology of mental effort. These feelings (e.g., fatigue, boredom) in turn motivate the reallocation of computational processes away from a task to alternative, higher-utility activities. The phenomenology of mental effort in our view is generally adaptive, encouraging changes in behavior that are, in most circumstances, beneficial to the individual. The resource account, in contrast, suggests that the (perception of the) literal depletion of some substance gives rise to the phenomenology of mental effort. Whereas subjective experience in the resource account is, thus, both veridical and epiphenomenal, our view holds that subjective experience of effort is a representation that is neither always veridical (insofar as estimates can be wrong) nor epiphenomenal (insofar as feelings motivate behavior).

Third, our model specifically locates the costs of mental effort in opportunity costs. Several prior models have suggested that the mental effort precipitates an aversive subjective experience, which people seek to avoid. However, our model is distinct insofar as we specify what, in particular, makes mental tasks feel effortful – namely, the expected value of the next-best alternative use of the same computational processes. Importantly, it is not only the costs and benefits of performing the task at hand that give rise to the phenomenology of mental effort, but also the costs and benefits of rival activities to which the same computational processes might otherwise be directed. Crucially, and in line with existing data, *tasks that recruit mechanisms that can be flexibly deployed should feel more effortful and demonstrate the most precipitous declines in performance*, whereas mechanisms that are singular in their function should not. Solving four-digit multiplication problems feels "hard" in this view, because the required computational processes could be deployed to an alternative, profitable use (including prospection, daydreaming, and other "off-task" varieties of mentation). Vision, which also entails substantially complex computational processing, doesn't feel like anything at all, because the required computational processes are specialized for a particular purpose and cannot be flexibly deployed to alternate tasks unrelated to vision.

We have suggested that within-individual changes in the performance of mental tasks depend on estimates of their expected utility. Thus, one class of experiments useful in distinguishing accounts might replicate the two-task experimental paradigm from the resource model literature with one important modification: parametric variation of the expected utility of the second task. Our model predicts either declines or improvements in performance on the second task depending on the experienced costs and benefits of the first task. In contrast, only declines in performance – not improvements – are predicted by the resource model. Already, several published studies have shown that input to a variety of reward systems (in the form of calories, positive feedback, a gift) directly following the first task indeed improves performance during the second task (e.g., Eisenberger 1992; Gailliot et al. 2007; Tice et al. 2007). Additional studies might test whether other forms of reward produce the same pattern of findings, whether associating rewards more explicitly with performance in the first task strengthens these effects, and whether parametrically varying rewards produces systematic dose-response improvements in performance.

A second class of predictions to which our view is committed is that alternate activities one might be able to do should influence performance. Parametrically varying the appeal of an alternative – a more- versus less-rewarding alternative activity to the one that is being performed – should lead to systematic differences in performance. In the limiting case, participants performing self-control tasks without any alternative activity are predicted to perform better than participants performing the same tasks with an appealing alternative (e.g., their smartphone) available. Likewise, the well-documented decrement in performance in the single-task vigilance paradigm should be potentiated or attenuated using the same manipulations. Performance in the target task should also be influenced by the expected utility of less obvious alternatives, such as daydreaming. The expected utility of, say, prospection and scenario planning might be increased or decreased by manipulating people's beliefs about these activities. Our model predicts that making the benefits of off-task mental activity salient should decrease performance on the target task, whereas making the costs of off-task mental activity salient should increase performance on the target task.

Our model makes similar commitments in terms of predictions regarding phenomenology, although research in this area has been limited. Indeed, in a recent review, Ackerman (2011) noted that "(f)ew studies have involved explicit measurement of changes in subjective fatigue in the context of higher order cognitive task performance" (p. 25); we agree with his prediction that "it can be expected that most task situations that result in mean decrements in performance with additional time on task will also show a marked increase in subjective fatigue" (p. 27). (Though we recognize that performance and phenomenology might be dissociated in rare pathological cases; see Naccache et al. 2005.) For instance, manipulations that change performance should also change the corresponding subjective experience of mental effort (e.g., reduce feelings of boredom, stress, etc.).

Because we claim phenomenology drives behavior, we also expect changing phenomenology to change performance. Positive mood inductions before the second task should improve performance (Tice et al. 2007); in contrast, inducing feelings of boredom (e.g., perhaps by having the participant do an easy but extremely repetitious task) before the second task should impair performance. Blunting the phenomenology itself, for instance, by suggesting to participants that their mood will be stabilized by a (placebo) pill (Cialdini et al. 1987), should improve performance on self-control tasks; suggesting to participants that they pay careful attention to their feelings might have the opposite effect. Manipulating attributions of boredom or effort should also have an effect. Indeed, framing a task as a test of willpower, as Magen and Gross (2007) did, might have improved performance because it changed attributions of mental effort.

We recognize that a serious challenge for our model is that many effects in the experimental literature are found in studies with two different tasks, both of which require "self-control," but are quite different from one another. The variety of effects from one task to another is a key feature of this literature, and might seem at odds with a cost-benefit account. As indicated above, however, *any* use of the relevant systems might be represented as a cost. In such a case, carryover effects are possible, just as in the resource case, because related mechanisms are used across tasks. To the extent that the mechanism (or mechanisms) that computes costs takes as input only the fact that (some subset of) executive systems are being used, rather than which ones in particular are being deployed and/or what they are being used for, such carryover effects are possible. Further, as indicated above in section 3.1, persisting in tasks steadily reduces the debt owed for experimental credit, perhaps explaining reductions in effort.

Disentangling these accounts might be difficult. We predict that similarity across tasks – in the sense of which executive function systems are engaged – will lead to greater decrements in performance, but similar tasks also might show learning effects. The more similar the tasks, the lower the expected value of the second task given a poor experience (i.e., low perceived benefits) on the first task. Research on tasks in which subjects are at ceiling might be of use to limit learning effects while allowing the use of similar tasks at time 1 and time 2.

Our model also makes an important prediction regarding interventions aimed at increasing self-control. Specifically, we suggest that self-controlled behavior is reinforced over extended periods of time only when it is practiced and rewarded, whereas proponents of the resource account posit that repeated exertion of self-control followed by rest should improve performance regardless of whether behavior is rewarded. In other words, we believe that individuals will improve in self-control through a learning process, whereas a resource account suggests a mindless process akin to muscle building in which performance-contingent rewards are irrelevant.

Some data from the field are interesting in this respect. O'Connell et al. (2008) found in a prospective, longitudinal study of individuals who were trying to quit smoking that resisting urges to smoke predicted fewer – not more – subsequent lapses in the immediately ensuing 4-hour period. That is, exerting self-control increased, rather than reduced, subsequent self-control efforts, "providing a direct challenge to a resource depletion model of self-control" (p. 492). We suggest that smokers who are trying to quit might construe a period of sustained abstinence to be a victory and, thus, a reward that motivates further abstinence. More generally, we predict that interventions that provide performance-contingent feedback and/or external rewards should be more effective than those that do not.

Finally, our model entails certain requirements for its neural implementation that differ from those entailed by a resource account. A resource account predicts that there should be some physical resource that is depleted by mental tasks, and that there is a link between the level of this resource and task performance. In contrast, our model predicts that there should be neural systems that can be used flexibly for different tasks, thus creating a simultaneity problem; that tasks that feel effortful engage these neural systems; and that there are neural representations of costs and benefits appropriate for guiding decisions about continued task engagement. We now turn to the neuroscience evidence bearing on these issues.

4. The neuroscience of resources and motivation

A wealth of evidence from neuroscience is relevant to debates regarding subjective effort and task performance. This section considers resource accounts and the proposed opportunity cost account in this context.

4.1. The neuroscience of resources: The role of glucose in mental tasks

One proposal is that glucose is the putative resource depleted when effortful tasks are executed (Gailliot & Baumeister 2007; Gailliot et al. 2007; for the related view that the issue is the allocation of glucose, see Beedie & Lane 2012). There are, however, reasons to doubt this account.

Indeed, Hockey (2011) recently suggested that the reason that fatigue has remained mysterious despite intense study is "the irresistible tendency to think of it in terms of a loss of energy resources." Hockey argues that there is "no evidence" for the claim that "fatigue is the result of glucose depletion," and concludes that "there is little doubt that the energy-depletion perspective has been a source of distraction in the search for a theory of fatigue" (p. 167). However, because of the prominence of the idea, we address it very briefly here. (See also Kurzban 2010b.)

Although there is some evidence that cognitively taxing tasks reduce blood glucose levels (Fairclough & Houston 2004; Scholey et al. 2001), such results are inconsistent (Gibson & Green 2002) and leave open the possibility that reductions are due to activity in the peripheral systems, such as the heart, rather than the brain. Recent reviews of the relevant empirical work in this area have generally converged on the view that any changes in blood glucose are unlikely to be due to increased uptake in the brain (Clarke & Sokoloff 1998; Gibson 2007; Messier 2004). Further, recent research using sensitive measuring devices has confirmed that blood glucose levels do not go down when participants perform a "self-control" task (Molden et al. 2012); and reanalysis of Gailliot et al.'s (2007) data has shown that their inferences were statistically unsound, rendering their conclusions "incredible" (Schimmack 2012).

This conclusion resonates with quantitative analyses of brain metabolism. Local changes in cerebral metabolism due to engaging in an experimental task are very small relative to the rate of metabolism at rest (Raichle & Gusnard 2002). The largest local changes in glucose consumption (~25%) are observed in visual cortex in response to opening one's eyes (Newberg et al. 2005). So, if blood glucose were the resource, the visual system would be most sensitive to performance decrements; and if nutrient consumption caused sensations of effort, seeing would feel effortful. Further, under reasonable assumptions, the overall difference between self-control tasks and control tasks – the inconsistent Stroop versus the consistent Stroop, for instance – is miniscule in terms of calories consumed (Kurzban 2010a). In addition, exercise, which consumes orders of magnitude more glucose, improves, rather than impairs, subsequent performance on tasks such as the Stroop (Tomporowski 2003; see also Hillman et al. 2008; 2009).

The effects of glucose administration on task performance are often cited as support for blood glucose acting as a resource (see Gibson [2007] for a review). However, another possibility is that glucose is a *signal* rather than a *resource*. Consider that glucose is known to act on the brain's reward circuitry, both through receptors on dopamine neurons (Hommel et al. 2006) and indirectly (i.e., with delivery of glucose into the mouth; McClure et al. 2003; O'Doherty et al. 2003). Further, glucose can have behavioral effects similar to those of drugs of abuse that target the same circuitry (Avena et al. 2008). Glucose can therefore invigorate subsequent behavior in the same manner as other rewards, and quite independent from the calories provided (Hagger et al. 2009). Consistent with this, in the context of physical performance, improvements can occur when glucose is only swished around the mouth, rather than digested (Chambers et al. 2009; Jeukendrup & Chambers 2010). Indeed, recent work shows that swishing alone without swallowing the glucose solution eliminates the "depletion" effect (Molden et al. 2012).

In sum, the empirical evidence weighs heavily against the claim that glucose is the resource upon which performance on self-control tasks draws.

We know of no other explicit proposals identifying the putative resource, but acknowledge that there are many possibilities beyond glucose. Any such theory, however, will need to explain (1) what the resource is, (2) how that resource is depleted by effortful tasks, (3) how depletion of the resource is sensed and leads to subsequent decrements in task performance, and (4) why some kinds of mental/neural activity, but not others, lead to resource depletion. This fourth point could turn on differences in architecture across brain regions, but we know of no proposal that has identified the specific resource and the important architectural differences.

4.2. The neuroscience of costs and benefits

Abundant evidence exists for neural signals related to the costs and benefits of engaging in different tasks (Kable & Glimcher 2009; Lee et al. 2007; Rangel et al. 2008; Rangel & Hare 2010). Signals of exactly this type would be required by any computational mechanism that adjusts performance in accordance with cost/benefit trade-offs.

These signals are most prominent in an interconnected network that involves the prefrontal cortex and basal ganglia (Haber 2003; Haber & Knutson 2009). One part of this network involves the prefrontal cortex and a part of the basal ganglia called the striatum: The prefrontal cortex directly projects to the striatum, which sends indirect projections back through the globus pallidus (another part of the basal ganglia) and thalamus. Another part of this network involves dopaminergic neurons, which are located in other nuclei of the basal ganglia and send and receive prominent connections to both the prefrontal cortex and striatum. Further, these prefrontal-striatal-dopaminergic loops are partially segregated. Cost-benefit signals are most prominent in the orbital and medial sectors of the prefrontal cortex and the corresponding ventral sectors of the striatum (Kable & Glimcher 2009; Lee et al. 2007; Rangel et al. 2008; Rangel & Hare 2010). Lateral prefrontal cortex and associated striatal regions appear to have a different function, as discussed further below.

One prominent hypothesis is that the dopaminergic neurons encode a *reward prediction error* signal, equal to the difference between the reward expected and the reward obtained (Montague et al. 1996; Schultz et al. 1997). This kind of signal is used in computational algorithms for reinforcement learning. These algorithms learn from experience the overall values of states and actions, integrated over the various costs and benefits associated with those states and actions (Sutton & Barto 1998). Although the initial evidence for this hypothesis came from animal models (Schultz et al. 1997), evidence consistent with it has recently been obtained with pharmacological (Pessiglione et al. 2006; Rutledge et al. 2009), functional imaging (D'Ardenne et al. 2008), and neural recording (Zaghloul et al. 2009) techniques in humans.

An extension of this hypothesis is that the prefrontal and striatal neurons receiving dopaminergic input encode the overall integrated value of different states and actions

(Kable & Glimcher 2009). In other words, they encode the quantities that can be learned from reward prediction errors. Evidence consistent with this hypothesis has been gleaned from single neuron recording (Lau & Glimcher 2008; Padoa-Schioppa & Assad 2006; 2008; Samejima et al. 2005), functional imaging (Kable & Glimcher 2007; Plassmann et al. 2007; Tom et al. 2007), and lesion studies (Camille et al. 2011; Fellows & Farah 2007; Rudebeck et al. 2008).

Though there are alternative views regarding the prefrontal-basal ganglia network (e.g., Berridge 2007), the debates concern the precise nature of the signals carried in different regions. All theories share the core notion that this network plays a critical role in motivation and reward.

Importantly, orbital/medial prefrontal and ventral striatal regions respond to multiple categories of rewards and integrate multiple factors to encode reward value. These properties, which allow for the incorporation of diverse kinds of benefits, from food to social approval, are required for computing the overall benefits of task performance. Increased activity in ventral striatum has been observed in response to primary rewards such as food (McClure et al. 2003; O'Doherty et al. 2003), secondary rewards such as money (Kuhnen & Knutson 2005), and social rewards such as positive social comparison or one's rivals experiencing pain (Fliessbach et al. 2007; Hein et al. 2010; Singer et al. 2006). During decision making, prefrontal and striatal activity reflects the perceived value of potential outcomes, integrating over diverse factors such as the taste and health value of foods (Hare et al. 2009); the magnitude, delay, and risk of monetary rewards (Kable & Glimcher 2007; Tom et al. 2007); or the benefit to others and costs to oneself of social exchange (Harbaugh et al. 2007; Hare et al. 2010).

4.2.1. Neural systems for effort trade-offs. Much evidence illustrates the importance of this prefrontal-basal ganglia network in regulating the performance of tasks that require physical effort (for review, see Kurniawan et al. 2011; we discuss mental effort further on in sect. 4.4.2). For example, in one well-studied paradigm, animals choose between climbing a small barrier to obtain a less desirable food reward and climbing a large barrier to obtain a more desirable one. In this paradigm, depletion of dopamine in the ventral striatum shifts animals' preferences away from the high effort–high reward option (Salamone et al. 2009).

A computational account of this result and others begins with the proposal that, if dopamine neurons phasically respond to reward prediction errors, then the tonic baseline level of dopamine in the ventral striatum would be proportional to the average reward rate in a given environment (Niv et al. 2007). This quantity is important, because if animals are deciding how fast to work (one measure of effort), then the average reward rate is exactly the opportunity cost of working more slowly.

Other evidence suggests an important role for the anterior cingulate cortex (a specific region on the medial prefrontal surface) in making effort trade-offs. Lesions to the anterior cingulate also shift animals' preferences away from high effort–high reward options (Rudebeck et al. 2006; Walton et al. 2003), and the costs of physical effort are robustly encoded in this region (Croxson et al. 2009; Kennerley et al. 2009; Kurniawan et al. 2010; Prévost et al. 2010). Further, the anterior cingulate is well positioned to compute the overall costs of task performance because it responds to diverse kinds of costs, ranging from physical pain (Botvinick et al. 2005; Singer et al. 2004) to decrements in reward (Bush et al. 2002) to social disapproval (Klucharev et al. 2009). The anterior cingulate also responds to opportunity costs, such as what one would have received if choosing differently (Hayden et al. 2009).

4.3. The neuroscience of executive function

4.3.1. Effortful tasks engage a prefrontal executive network. The preceding section outlined evidence for a brain network that computes costs and benefits, and the involvement of this network in calibrating performance of tasks that require physical effort. Here we turn to what is known about the brain networks engaged by effortful *mental* tasks.

Put briefly, *the effortful tasks that show decrements in performance all engage prefrontal regions associated with executive function*. Different "executive function" tasks all reliably engage a network of brain regions that includes the lateral prefrontal cortex (inferior and middle frontal gyrus), dorsomedial prefrontal cortex (superior frontal gyrus and anterior cingulate), and posterior parietal cortex (typically intraparietal sulcus) (Buchsbaum et al. 2005; Derrfuss et al. 2005; Laird et al. 2005; Nee et al. 2007; Neumann et al. 2005; Wager & Smith 2003). Although different executive function tasks more strongly engage different parts of this network, the pattern of activation in executive function tasks as a class is distinguishable from patterns observed in perception, language, and semantic or episodic memory tasks (Cabeza & Nyberg 2000; Wager & Smith 2003).

Many of the tasks used to study mental effort or performance decrements are identical to those used in cognitive neuroscience to study executive function. This includes the sustained attention tasks used in vigilance experiments (Coull et al. 1998; Lim et al. 2010; Paus et al. 1997) and the Stroop and working memory tasks used in "depletion" experiments (Derrfuss et al. 2005; Laird et al. 2005; Neumann et al. 2005; Schmeichel 2007; Wager & Smith 2003; Wright et al. 2007). In other cases, the tasks used in the two literatures are not identical but are quite similar. For instance, two of the more widely used tasks to elicit decrements in performance – a crossing out letters task ("Cross out all *e*'s except for those adjacent to a vowel") and a focus-of-attention task ("Attend to the person in the video and ignore the words") – are similar to widely studied response inhibition and attentional control tasks such as the "go/no-go" (Buchsbaum et al. 2005; Nee et al. 2007) and attention networks test (Fan et al. 2002).

Other tasks used to study mental effort or performance decrements also engage the prefrontal regions associated with executive functions. This includes tasks used to elicit subsequent decrements in performance, including regulating emotional responses (Ochsner & Gross 2005), suppressing a specific unwanted thought (Mitchell et al. 2007; Wyland et al. 2003), and turning down unhealthy but "tempting" foods (Hare et al. 2009). This also includes tasks used to measure decrements in performance, such as solving anagrams (Schneider et al. 1996), solving mathematical problems (Dehaene et al. 1999; Nieder & Dehaene 2009), or logical reasoning (Goel 2007).

4.3.2. Engaging the prefrontal executive network entails opportunity costs. The lateral prefrontal cortex regions engaged by effortful tasks play an important role in "controlled" aspects of cognition. The prefrontal cortex receives input from all modalities, and, in addition to reciprocal connections to posterior regions, also sends output to the motor system. It is therefore anatomically well situated to influence how sensory and internal regulatory signals affect motor behavior. Miller and Cohen (2001) proposed that by actively maintaining information such as task goals and rules, the prefrontal cortex biases the flow of neural activity in other brain regions so that actions are affected by the behavioral context. This general idea, that the prefrontal cortex exerts a modulatory influence over information processing in other brain regions, forms the basis of more specific proposals regarding prefrontal function in attention (Desimone & Duncan 1995) and language (Thompson-Schill et al. 2005).

Consistent with this role in "controlled" cognition, the lateral prefrontal cortex is engaged by an array of different tasks, spanning different cognitive domains. This is apparent at the region level in the neuroimaging studies cited in the previous section. It is also apparent at the level of single neurons: The same lateral prefrontal neurons have been shown to respond to very different stimuli under different task conditions (Freedman et al. 2001; Rainer et al. 1998; Rao et al. 1997). Duncan (2001) argues that such "adaptive coding" in response to task demands is a special characteristic of the prefrontal cortex.

The prefrontal cortex is also subject to simultaneity constraints, in that there is a capacity limitation to the number of computational operations that the prefrontal cortex can engage in at any given time (Miller & Cohen 2001). While the precise nature of the capacity limitation is unknown, our view echoes Miller and Cohen's: "[N]o theory has provided an explanation of the capacity limitation itself. This could reflect an inherent physiological constraint, such as the energetic requirements of actively maintaining representations in the PFC. *More likely, it reflects fundamental computational properties of the system*" (2001, p. 192, emphasis added).

These factors imply that there will be large opportunity costs to performing tasks that recruit the prefrontal cortex, given all of the tasks that cannot be performed simultaneously because they require the same prefrontal processes. To the extent that engaging these processes at all also requires disengaging others, such as the "default mode network" (Raichle et al. 2001), the functions achieved by these other processes would also contribute to the opportunity costs.

4.3.3. Other constraints: Specialization in the prefrontal cortex. A potentially important set of observations that any theory of effort must account for is that there is anatomical specialization within lateral prefrontal regions. While there is significant debate about how to best synthesize existing data, evidence exists for specialization based on the kind of processing and on the nature of the information being processed, as well along the anatomical dimensions of left-right, dorsal-ventral, and anterior-posterior (Badre & D'Esposito 2009; Botvinick 2008; Courtney 2004; D'Esposito et al. 2000; Fuster 1997; Koechlin & Hyafil 2007; Petrides 2000; Smith & Jonides 1998; Wager & Smith 2003). Neuroanatomical specialization is broadly consistent with the behavioral evidence for separable components of executive control (Friedman & Miyake 2004; Friedman et al. 2006; Miyake et al. 2000). Such specialization implies that the degree to which engaging in a difficult task affects performance on a subsequent one might depend on the degree to which the two tasks tap similar executive functions and engage similar prefrontal regions. This idea, which has not been systematically explored (though see Persson et al. 2007), contrasts sharply with the notion that carry-over effects are uniform across diverse tasks that all tap a unitary "self-control" mechanism (Muraven & Baumeister 2000).

Specialization could also contribute to increasing opportunity costs as more prefrontal neurons are recruited to a given task. Suppose prefrontal neurons can be used for several processes but are best suited for specific processes (by virtue of their connectivity, for example), and the "best-suited" neurons are recruited to a task first. Then the marginal opportunity costs will increase as more neurons are recruited to a task, because the neurons recruited "at the margin" are less and less effective at the current task and more and more effective at other tasks (Just et al. 1999).

4.3.4. Links between executive and motivational circuits. Because tasks that are associated with mental effort all engage a prefrontal executive network, a cost-benefit account requires some mechanism by which neural signals regarding costs and benefits can modulate the performance of this executive network. Although this question has not been widely studied, there are two potential links between prefrontal executive circuits and the motivational circuits discussed above. These links mirror the two mechanisms discussed above for making trade-offs regarding physical effort.

One possibility is that dopamine levels in the prefrontal cortex reflect opportunity costs, similar to proposals regarding dopamine levels in the striatum (Niv et al. 2007). There are direct projections from dopaminergic neurons to the lateral prefrontal cortex, and classic studies from Goldman-Rakic and colleagues (Goldman-Rakic 1996; Goldman-Rakic et al. 2000) demonstrate that the stability of prefrontal activity is a function of local dopamine levels. Given other evidence linking the stability of prefrontal activity to performance (Funahashi et al. 1989), this provides one possible mechanism through which signals about recent reward history could strengthen or weaken prefrontal engagement on the current task (Braver et al. 1999). Aston-Jones and Cohen (2005) proposed a similar idea, arguing that norepinephrine rather than dopamine provides the critical signal regarding the benefit of continued engagement.

Another possibility is that the anterior cingulate cortex functions to link executive and motivational circuits. As discussed above, the anterior cingulate carries signals regarding various costs, such as physical effort, during reward-based decision-making tasks. The anterior cingulate is also part of the prefrontal executive network. In executive function tasks, the anterior cingulate has been associated with monitoring information-processing conflicts. Botvinick (2007) has proposed that these two roles share the same general performance-monitoring function: Information-processing conflicts serve as a negative feedback signal that promotes more efficient task performance in the same way that various other costs serve as signals that promote changes in task performance.

4.4. Neural changes accompanying changes in mental effort and performance

4.4.1. Neural signals related to the subjective cost of mental effort. There have been a limited number of functional imaging studies that have explicitly focused on the phenomenology of mental effort. McGuire and Botvinick (2010) used a paradigm in which subjects had to switch between two tasks, judging the magnitude or parity (odd/even) of single digits. Behaviorally, the frequency of task-switches was associated with a greater self-reported sense of cognitive demand, and people avoided high-demand in favor of low-demand versions of the task when given the opportunity (Kool et al. 2010; McGuire & Botvinick 2010). Rewards after high-demand blocks were also associated with decreased activity in the ventral striatum, consistent with the notion that cognitive demand is costly (Botvinick et al. 2009). Across two further fMRI experiments using this task, bilateral activity in the lateral prefrontal cortex was correlated across blocks with subjective ratings of demand (controlling for objective differences, such as reaction times and errors), and across subjects with the behavioral tendency to avoid high-demand versions of the task. These results suggest that activity in lateral prefrontal regions during demanding cognitive tasks is associated with a subjective cost, and that this cost can motivate subsequent task avoidance.

4.4.2. Neural changes accompanying performance decrements. Other functional imaging studies are of interest because they examine the neural changes that accompany performance decrements. Though small in number, there is a consistent picture that emerges from these studies: *Decrements in performance are associated with decreased engagement of prefrontal regions associated with executive function*.

Three published studies have examined neural activity with functional imaging during prolonged (>20 min) sustained attention tasks (Coull et al. 1998; Lim et al. 2010; Paus et al. 1997). All three studies found a vigilance decrement (i.e., increase in reaction times with time-on-task), and an associated decrease in right lateral prefrontal activity over the course of the task. This region has previously been implicated in sustained attention processes (Posner & Petersen 1990).

Two studies have used fMRI to examine neural activity associated with performance decrements in two-task carryover paradigms (Hedgcock et al. 2012; Persson & Reuter-Lorenz 2010). Although the tasks used in these studies differed greatly, both reported that activity in a lateral prefrontal region was greater when the first task was more difficult, and that this same lateral prefrontal region exhibited less activity during the second task when this was preceded by the more difficult initial task. Interestingly, the region of the lateral prefrontal cortex showing this effect was different in the two studies (left inferior frontal gyrus vs. right middle frontal gyrus), consistent with neuroanatomical specialization within the lateral prefrontal cortex.

Several additional studies have examined the neural correlates of performance decrements using event-related potentials. These studies have focused on the error-related negativity (ERN), which is believed to index anterior cingulate activity related to task monitoring. Inzlicht and Gutsell (2007) found that the ERN in a Stroop task was smaller after suppressing emotional responses to a sad movie clip, compared to freely expressing emotion. A similar decrease in the ERN has been observed with sustained (2-hr) performance of an effortful cognitive task (Boksem et al. 2006; Lorist et al. 2005). Importantly, these changes in anterior cingulate activity, like the concomitant behavioral decrements, can be reversed by providing additional incentives for performance (Boksem et al. 2006). Such responsiveness to incentives is consistent with the proposal that the anterior cingulate tracks costs and benefits; it also shows that brain activity, like performance, does not decrease in an obligatory manner with sustained effort.

4.4.3. Distinguishing resource and cost-benefit accounts. The findings in the preceding two sections do not, in themselves, distinguish between resource versus cost-benefit accounts of mental effort and performance. Decreased activity in lateral and dorsomedial prefrontal regions could be due to the depletion of a physical resource necessary for continued high levels of activity, or it could reflect a decision to engage these regions to a lesser degree given the costs and benefits of performance. Lateral prefrontal activity might be associated with a subjective cost because it expends a physical resource, or because it comes with a substantial opportunity cost – precluding any other task that would require the same neural processes.

However, a computational account seems more likely to explain both these results and others regarding these brain regions within a common framework. Previous studies have demonstrated that these regions exhibit changes in neural activity linked to changes in performance on a much faster timescale. For example, in the Stroop task, subjects are generally faster to respond to incongruent trials when the previous trial was also incongruent. Kerns and colleagues (Kerns 2006; Kerns et al. 2004) demonstrated that the size of this sequential adjustment effect was associated with trial-to-trial changes in anterior cingulate and lateral prefrontal activity, specifically (1) greater anterior cingulate activity on the *previous* trial and (2) greater dorsolateral prefrontal activity on the *current* trial. These results are consistent with the hypothesis (Botvinick et al. 2001) that the anterior cingulate monitors for information-processing conflicts, which then triggers the subsequent recruitment of lateral prefrontal regions in order to reduce these conflicts.

Note that this hypothesis has the same structure as the one we propose. The anterior cingulate cortex encodes a cost (here, the information-processing conflicts that result from low cognitive control), and lateral prefrontal activity and associated performance adjust accordingly (here, activity increases and performance improves). The direction of the changes in prefrontal activity and performance differ from our proposal, though Botvinick (2007) has already taken the first steps to incorporate both kinds of adjustments in one computational model. Trial-to-trial changes also present a difficulty for resource accounts in that they demonstrate *increased* lateral prefrontal activity and *better* performance subsequent to a difficult trial. If performance were determined only by the level of a resource, and this resource can only go down during the task, then such trial-to-trial improvements in task performance should not be possible.

4.5. Summary of neurophysiology

There is little neurophysiological evidence consistent with a resource account of mental effort and performance. Existing evidence does not support the claim that glucose is the physical resource. Effortful tasks do not reliably reduce glucose; things that do reliably reduce glucose, such as exercise, improve performance on cognitive tasks; and the beneficial effects of glucose on cognitive performance are due to its rewarding properties rather than its caloric content (Kurzban 2010b). While there could be other potential candidate resources besides glucose, there is no other mature theory of the resource; in particular, there is no theory of the resource that can explain why some kinds of mental activity but not others are effortful.

In contrast, there is abundant neurophysiological evidence consistent with a cost-benefit account of mental effort and performance. A cost-benefit model first requires that the brain encode costs and benefits in a way that integrates across very different kinds of costs and very different kinds of benefits. A ventromedial prefrontal-ventral striatal network encodes such signals (Kable & Glimcher 2009; Lee et al. 2007; Rangel et al. 2008; Rangel & Hare 2010). A cost-benefit model also requires that there be neural processes that (1) can be used for a variety of different tasks, and (2) have a limited capacity at any one point in time. A lateral prefrontal "executive" network fulfills these two criteria and is engaged by effortful mental tasks (Duncan 2001; Miller & Cohen 2001). Finally, a cost-benefit model requires a way for cost-benefit signals to influence the engagement of the limited capacity network, and we point to recent proposals describing how feedback signals in the anterior cingulate cortex, or dopamine levels in the prefrontal cortex, could achieve this (Botvinick 2007; Niv et al. 2007). This integrated proposal is consistent with the available evidence regarding neural activity during effortful tasks and performance reductions. Lateral prefrontal regions are engaged by effortful tasks, their engagement is accompanied by the sensation of mental effort, reductions in lateral prefrontal activity accompany reductions in task performance, and changes in lateral prefrontal activity are preceded by feedback signals about costs and benefits in the anterior cingulate.

The above proposal leans heavily on existing computational models describing how these same neural mechanisms calibrate the expenditure of physical effort (Niv et al. 2007) or modulate lateral prefrontal performance in response to information-processing costs (Botvinick et al. 2001), as well as on recent efforts to extend these models to the domain of mental effort (Botvinick 2007; Botvinick et al. 2009; Kool et al. 2010; McGuire & Botvinick 2010). While these models are well known in cognitive psychology and cognitive neuroscience, they appear to have had little influence on theorizing regarding some of the paradigms we focus on here, such as the vigilance decrement in sustained attention and the reduction in task performance in the dual-task paradigm. Clearly, extending these models to these domains is possible, and likely to be a fruitful enterprise.

5. Conclusion

Some, perhaps even many or most, phenomenological experiences are reasonably easy to understand from a functional perspective. The positive, rewarding sensations of behaviors ranging from sexual activity (Diamond 1997) to coming to be valued by others (Leary et al. 1995) can be understood as the output of motivational systems designed to bring about adaptive behavior. These positive sensations correspond in a reasonably straightforward way to behaviors related to fitness gains. To the extent that phenomenology is understood as part of the motivational system, driving organisms toward good fitness outcomes, many experiences – especially the valence of these experiences – make a great deal of sense.

In this context, the phenomenology of effort presents something of a puzzle. Many of the real-world tasks that evoke a sensation of effort lead to favorable outcomes in the long run – persisting on difficult tasks such as writing, doing math problems, and so on – yet the phenomenology is unpleasant rather than pleasant. Further, these sensations seem to be systematically related to performance reductions. Why do these "good" things feel "bad"?

We have tried to sketch one sort of solution to this puzzle. The central element of our argument is that the sensation of effort is designed around a particular adaptive problem and its solution, *simultaneity* and *prioritization.* Because some systems, especially those associated with executive function, have multiple uses to which they can be put, the use of these systems carries opportunity costs. We propose that these costs are experienced as "effort," and have the effect of reducing task performance. This connects the sensation of effort to other qualia, explaining the valence of the experience as a cost of persisting.

We also want to emphasize that our explanation is, of course, not wholly novel. Dodge (1917), for example, suggested that the subjective experience of fatigue had to do with subjects' desire to attend to something other than the task before them, and the general idea of fatigue as a problem of choosing what one ought to do can be traced back perhaps still further (Thorndike 1904). We have similarly tried to acknowledge throughout areas where our view overlaps, sometimes in substantial part, those of others (Boksem et al. 2005; 2006; Boksem & Tops 2008; Botvinick 2007; Hockey 2011; Kool et al. 2010; Lorist et al. 2005; McGuire & Botvinick 2010; van der Linden 2011).

Finally, we wish to point out that to some extent, the literatures on "self-control" in psychology and "executive function" in cognitive psychology and neuroscience have not been as tightly integrated as they could be, and part of our agenda in writing this piece was to highlight that these streams of research should be in closer contact with one another. Whether or not our particular computational explanation for these effects turns out to be correct, some computational explanation will eventually be required, and our hope is that this paper moves closer to that goal.

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Open Peer Commentary

Monotonous tasks require self-control because they interfere with endogenous reward

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Abstract: Self-control is a necessary component of subjective effort, but it depends only on farsighted motivation, with no additional, depletable resource. The aversiveness of boring tasks probably comes from their interference with endogenous reward, a new and potentially controversial concept. The self-control needed to stick with any kind of aversive experience increases as the values of the competing motives draw closer together.

Kurzban et al. have ably demonstrated that mental fatigue from doing repetitive tasks is a motivational phenomenon, rather than a matter of resource depletion. In doing so they propose an alternative answer to the basic question of why boredom is aversive: To be adaptive in the evolutionary sense, boredom is said to be a sort of meter that warns us about wasting our attention. But this could be said about non-reward in general. Hard evidence is sparse for their hypothesis about calculating cost-effectiveness, as it is for an alternative possibility that I propose: Monotonous tasks interfere with a baseline level of reward that does not depend on external contingencies, and these tasks require increasing amounts of self-control as this interference continues. I would argue that the latter model offers a more general account of the mental effort required for unrewarding activities.

The remarkable feature of monotonous tasks is that they seem to be worth less than nothing – that is, less than we would get by sitting idle. The authors assign the latter option (daydreaming) a utility of 2 units (see Figs. 2, 3, and 4 in the target article) – but what generates those 2 units of reward? Examination of this question can tell us something about our basic mental economies. People do not normally experience aversively low levels of reward in the absence of external sources. During idleness, in what is being called the "default mode" (Spreng et al. 2009) – for example, in daydreaming – we seem to generate our own reward. Challenging tasks facilitate this process regardless of the external incentives for them, as in Csikszentmihalyi's "flow" (Csikszentmihalyi 1990), whereas boring tasks are characterized by a structured attention that restricts it. When even dull experimental tasks are made more challenging, they become less depleting, as in the authors' example of Converse and DeShon (2009; sect. 3.2.2). Conversely, the extent to which external incentives can reduce fatigue in monotonous tasks is limited; even an awareness of watching for enemy warplanes does not prevent it (Mackworth 1948).

The phenomenology of this reward is familiar, but its causal properties are theoretically problematic. The defining feature of reward is that it selects for behaviors. In conventional utility theory a person cannot generate her own reward, as that would short-circuit the process that constrains her to behave adaptively. On the other hand, the model that all motivation comes from the expectation of some event-constrained reward is hard to fit to human experience. For one thing, activities that do not perceptibly lead to primary rewards should get extinguished – not only doing math problems in experiments, but playing with smartphones and daydreaming as well (sect. 2.4.1). For another, the rewarding effect of the outcomes of many tasks (in the extreme, puzzles or solitaire) is related more to the nature of the tasks themselves than to whatever events they might predict. Early hypotheses that such examples are based on long chains of secondary reward and broad generalizations (e.g., Dollard & Miller 1950) have not been subjected to later scrutiny, perhaps because they have seemed to be the only possible way that a behavioral economy could be designed. Even precise modern models of reward, such as temporal difference theory (e.g., Daw & Doya 2006), depict a process constrained to seek external events.

And yet it is possible that the great imaginative power that allows people to out-think our evolutionary predecessors has an inseparable, non-adaptive side feature: the ability to coin reward. I have argued elsewhere (Ainslie 2013) that the utility-based decision sciences (e.g., economics and behavioral and evolutionary psychology) should no longer assume all mental reward to be secondary to some innately determined primary. They should at least allow for the possibility that people can generate reward arbitrarily, limited only by our appetites for the processes involved (variously, an emotion, or curiosity, interest, suspense…). In this approach, the short-circuiting of the selection process is prevented, but only partially, by the incentive not to waste appetite. The hyperbolically based urge for premature gratification of appetites creates a countervailing incentive to link this gratification to external events that are singular and surprising – to bet on them, as it were – as limited *occasions* for this endogenous reward. Accordingly, someone who invests interest in a game of solitaire must protect this interest by not cheating, and someone who uses a novel to occasion reward must avoid reading ahead. The experience of daydreaming suggests that to some extent we can do without current occasions for reward; but the pathologies of sensory deprivation (Zubeck 1973) demonstrate that even endogenous reward deteriorates without some external occasions. Monotonous tasks accelerate this deterioration. Their defining feature is that they require the person to attend to bad (profuse, unsurprising) occasions for endogenous reward.

The ability to coin endogenous reward may interfere with adaptive goal-seeking less than might be expected, because optimal occasioning of reward overlaps extensively with the realistic performance of instrumental tasks: Benchmarks of accomplishments also make excellent occasions, in addition to their (predictive, extinguishable) secondary rewarding effects. By the same token, however, people have an incentive to believe in the instrumental effectiveness of tasks that offer good occasions, a possible explanation for the stubborn inefficiency of many ostensibly productive activities, from "X-inefficiency" (March 1978) to pathological gambling. The short span of human evolution should only have required the endogenously rewarding side-effect of imagination to be not too maladaptive.

Kurzban et al. do without a concept of self-control, positing only prioritization of tasks (sect. 2.3); but low-priority tasks should demand mental effort only to the extent that they elicit self-control, and even then only when the self-control requires attention. Despite the concreteness of resource-depletion theories, they are correct on that point. And these theories extend to mental effort in activities that are directly aversive, such as cold pressor endurance or prolonged handgrip, as well as those that are unrewarding because vigilance for performance errors feels like wasting resources (in the present authors' proposal) or prevents endogenous reward (as I hypothesize). In all these cases adherence to a less immediately rewarding policy should be felt as mental effort only to the extent that it demands ongoing executive function. Forgoing even a strongly motivated activity such as smoking is not experienced as effortful when the person has no doubt that she will succeed (Dar et al. 2005). The closer the value of the forgone opportunities comes to the motivational basis for the unrewarding activity, the more executive function must be devoted to forestalling contrary urges and weighing whether to continue. (See Ainslie [2012] for my model of self-control. Behavioral economists have recently made related proposals: Fudenberg & Levine 2006; Gul & Pesendorfer 2004.) The aversiveness of sensing inadequate motivation for self-control is therefore an example of a familiar phenomenon, cognitive dissonance (Brehm & Cohen 1962). This mechanism can indeed produce the appearance that "the estimation of opportunity costs gives rise to the phenomenology of mental effort" (target article, sect. 3.3, para. 3), where "opportunity costs [are] equal to the value of the next-best use of … mental processes" (sect. 2.3.1, para. 2). However, the authors' model implies that subjective effort should be a linear function of forgone opportunity; it is more apt to be an accelerating function up to the point where choice reverses. In either case, mental effort can be accounted for entirely within a motivational model, which I take to be Kurzban et al.'s main point.

NOTE

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Difficulty matters: Unspecific attentional demands as a major determinant of performance highlighted by clinical studies

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Abstract: The cognitive impairments shown by brain-damaged patients emphasize the role of task difficulty as a major determinant for performance. We discuss the proposal of Kurzban et al. in light of our findings on right-hemisphere–damaged patients, who show increasing awareness deficits for the contralesional hemispace when engaged with resource-consuming dual tasks. This phenomenon is readily explained by the assumption of unspecific depletable resources.

Task difficulty is a major determinant of human performance. This statement might be considered as little more than a truism, but in fact it is a crucial issue when heterogeneous tasks and populations are considered. Unfortunately, it is all but a rare event to come across studies in which the mere difficulty imbalance between tasks or conditions can account for the observed differences in performance, without resorting to fine-grained explanations, which are instead often preferred. This problem is exacerbated in studies on brain-damaged patients, in which it might constitute a very serious flaw when groups are formed on the basis of performance in a given diagnostic task that is not matched for difficulty to the experimental task. This happens, for example, when two completely different tasks are used, one to select the patient group (or to rule out potential confounds) and one to collect the data of the study. The mere selection of patients for the presence of a given disorder often results in the selection of cases who are more cognitively impaired (the experimental group) versus cases who are less (the control group) (see Bonato et al. 2012b).

For these reasons, we are very sympathetic with the proposal of Kurzban et al., which aims at a better understanding of the relation between task difficulty and performance. We also strongly agree with their claim that the literatures on "self-control" (task difficulty, sustained attention, willingness to engage) and "executive functions" in cognitive neuropsychology/neuroscience are not sufficiently integrated. Several tasks classically described as loading executive functions can simply be construed as very difficult tasks; and it therefore seems reasonable to maintain that cognitive effort and executive functioning are largely overlapping concepts (Bonato et al. 2012a), and do not depend on independent mechanisms, as strictly modularistic views would maintain. However, the opportunity cost model of Kurzban et al. appears too simple to account for the complex issue of the link between task difficulty and performance. Our skepticism revolves around two different lines.

First, the notion of a close relation between perceived effort and performance seems to take for granted that all cognitive processes are conscious. This is at odds with the widely accepted view that a large portion of our cognitive processes is not conscious (Bargh & Morsella 2008; Sergent & Naccache 2012), even in the case of very complex and apparently controlled tasks (e.g., for complex arithmetic, see Sklar et al. 2012). The mere notion that task performance can be driven by stimuli which are not consciously perceived suggests that performance and phenomenology might dissociate more often than in "rare pathological cases" (cf. target article, sect. 3.3, para. 7).

Second, several theoretical proposals show that task performance is closely dependent on the quantity and quality of the attentional load implied by the task. For instance, the load theory of attention (Lavie 1995; 2005) provides a comprehensive explanation of the influence of visual distractors, maintaining that their early or late filtering depends on the "load" of a concurrent attentional task, with reduced processing efficiency in the peripheral field (and hence less interference from distractors) when more attentional capacity is demanded by the central task. Higher perceptual load for central stimuli leads to exclusion of irrelevant peripheral inputs at an earlier stage, whereas under higher working memory load this exclusion occurs at a later stage. In other words, the processing efficiency seems to be related to the quantity and type of load, rather than to perceived subjective effort. Increased attentional load also reduces the will to spontaneously engage in internal, task-unrelated thoughts (Forster & Lavie 2009).

Stemming from this perspective, there is also robust evidence that, in right-hemisphere–damaged patients, the efficiency in contralesional hemispace processing is a function of the availability of attentional resources that can be engaged for monitoring visual space (Bonato 2012). In particular, patients show striking awareness deficits for the contralesional hemispace under multitasking in comparison to their baseline performance in a spatial monitoring task: The request to pay attention to an auditorily presented number or to a visual letter presented at fixation turns into inability to perceive targets appearing in the left hemispace (Bonato et al. 2010). Thus, increasing task-difficulty caused by multi-tasking results in severe awareness deficits for the contralesional hemispace, regardless of the nature of the concurrent task (i.e., the "depleting task"; target article, sect. 3.1, para. 5). Indeed, patients showed the same severity of spatial awareness deficit regardless of whether they had to pay attention to visual or auditory channels while monitoring the visual space for target appearance (Bonato et al. 2013). We maintain that the inability to perceive contralesional targets revealed with such an experimental procedure is the consequence of the impossibility to efficiently allocate attentional resources, which, in easier tasks, are allocated contralesionally and compensate for the patient's spatial deficits. Therefore, it seems that the classic view (Kahneman 1973), according to which resources are not only dynamically allocated among tasks but also strictly depletable, constitutes the most economic explanation for these findings. This contrasts with the position of Navon (1984), who argued that the concept of resources is "unnecessary," as well as with the view of Kurzban et al., who consider drops in performance as a consequence of individual trade-off between costs and opportunity.

More generally, the authors seem to maintain that the main reason for drops in performance can be traced back to a voluntary decision by the participant, which is hardly tenable in the case of our brain-damaged patients. Also, the idea that simultaneity and prioritization result in effective deployment of resources seems questionable in light of the patients' data. In summary, our results are in agreement with Kurzban et al.'s view that "task performance varies with the degree to which computational processes are allocated" and that resources can be "divided among multiple tasks" and "allocated in different portions to different tasks" (sect. 2.4.2, para. 1). Nevertheless, they also demonstrate that the "redistribution" (or "reallocation") of resources can be severely biased (spatially biased, in our case), and that it is not supported (at least in patients) by effective feedback mechanisms allowing the increase of attentional engagement when performance is unsatisfactory.

An addition to Kurzban et al.'s model: Thoroughness of cost-benefit analyses depends on the executive tasks at hand

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Abstract: Though Kurzban et al.'s model explains a considerable set of empirical findings, it cannot accommodate other results without relying on extra assumptions. We offer an addition to the model, and suggest that cost-benefit analyses themselves depend on executive function, and therefore can be biased. The adapted model allows for explaining depletion effects, as well as their reversals, documented in the literature.

Kurzban et al. run a fruitful attempt to explain why engaging in certain tasks (e.g., self-regulatory tasks) causes aversive experiences of mental effort and drops in task performance. Though Kurzban et al.'s model offers a potentially powerful explanation for a considerable set of empirical findings, at the same time it seems unable to accommodate other empirical results without relying on extra assumptions. We offer an addition to Kurzban et al.'s model in an attempt to explain these seemingly inconsistent findings in a more parsimonious way.

The gist of Kurzban et al.'s argument is that usage of executive function (inevitably related to self-regulatory exertion; cf. Schmeichel 2007) carries an opportunity cost, resulting in the subjective experience of effort and, ultimately, task switching. Opportunity costs are derived from comparing benefits linked to engaging in a given executive task with costs associated with not engaging in other tasks requiring the very executive functions already occupied by the initial task. Though Kurzban et al.'s model assumes independence between cost-benefit algorithms and the behavior it attempts to explain, we propose that cost-benefit analyses depend on executive function as well. Indeed, a link between complex thinking and executive function has been demonstrated empirically for tasks involving logic and reasoning or cognitive extrapolation (Schmeichel et al. 2003). Those tasks seem quite similar to the cost-benefit analyses described by Kurzban et al. This potentially poses a problem, as it implies that the quality of the cost-benefit analysis could depend on how much executive function is available for the cost-benefit calculation itself, which ultimately relies on the demandingness of the initial executive task. Indeed, Kurzban et al. argue rather convincingly that decision makers cannot successfully engage simultaneously in multiple executive tasks competing for executive resources. Research on cognitive load effects supports this claim: When the brain simultaneously engages in two tasks, both requiring executive function (or some minimal level of cognitive involvement), executive function mainly gets devoted to one of the tasks, while the other task gets attended to more automatically (cf. Hinson et al. 2003). This has implications for the task outcomes: The literature suggests that whether a task or a decision problem is attended to in a relatively more cognitive and effortful way, or a relatively more automatic and effortless way, may substantially change behavior or decisions (e.g., Lee et al. 2009).

We want to apply this insight to one particular type of setting studied by Kurzban et al., namely, a so-called depletion setting, in which two different self-regulatory tasks are performed in sequence (Baumeister et al. 1998; Muraven et al. 1998). Specifically, "depletion" studies typically use a two-task paradigm requiring participants to either engage in self-regulation (i.e., depletion condition) or in a neutral control task (i.e., neutral condition) first. Then, all participants engage in a seemingly unrelated task requiring self-regulation. "Neutral" participants typically obtain higher self-regulation scores in this second phase than do "depleted" participants (cf. Hagger et al. 2010a, for a recent meta-analysis). If our reasoning with respect to the cost-benefit analysis proposed by Kurzban et al. holds, there are two theoretical possibilities when using cost-benefit algorithms to explain depletion effects: Relying on the assumption that executive function faces simultaneity problems (cf. Kurzban et al.) and cost-benefit analyses depend on executive function (our proposition), *either* the executive task will be attended to in a relatively more effortless way and the cost-benefit calculation in a relatively more effortful way, *or* the executive task will be attended to in a relatively more effortful way and the cost-benefit calculation in a relatively more effortless way. Depletion conditions typically are relatively more challenging than neutral conditions (i.e., depleted participants engage in self-regulation in the first phase of the experiment already, whereas neutral participants do not), implying that depleted participants will invest relatively more executive resources in the experimental task at hand, and thus will have less to spare for cost-benefit trade-offs compared to neutral participants. Behaviorally, these less thorough cost-benefit analyses in depletion, compared to neutral conditions, translate into reduced self-regulatory performance in the second phase of the study.

Less thorough cost-benefit analyses might cause self-regulatory performance reductions for various reasons. One theoretical possibility could be that, akin to ease-of-retrieval effects (e.g., Winkielman et al. 1998), engaging in less thorough cost-benefit analyses and presumably coming up with fewer alternative uses of executive function makes these alternative uses subjectively more obvious and hence more pressing, causing one to cease engagement in the ongoing task sooner. Such a mechanism would also be in line with research on goal dilution, showing that increasing the number of goals that can be fulfilled by a single means (e.g., investing executive function) reduces perceived instrumentality with respect to each goal (Zhang et al. 2007). This also seemingly suggests that switching to alternative tasks will be more likely when fewer goals are activated. The potential mechanism through which thoroughness of cost-benefit analyses impacts ongoing task performance, however, remains to be tested empirically.

An example of behavioral findings that our adapted model can explain without relying on additional assumptions like practice effects (cf. Kurzban et al.) is: increasing self-regulation in sequential self-regulation tasks that are similar in nature. Indeed, previous research found depletion effects only when regulatory response conflicts differed across sequential self-regulation tasks (e.g., restraining food intake in one task and anagram solving in another), but not when regulatory response conflicts were similar (e.g., restraining food intake in both tasks; Dewitte et al. 2009). Our adapted model can explain this pattern as task similarity frees up mental resources (i.e., engaging in two different self-regulatory tasks is more taxing than engaging in one self-regulatory task), causing cost-benefit analyses to be more thorough in high-similarity conditions. Behaviorally, these thorough analyses translate into better (compared to regular depletion conditions) self-regulation in the second phase of the study (cf. previously developed reasoning as to why less thorough cost-benefit analyses might cause self-regulatory performance reductions).

Until now, depletion literature mainly provided motivational (as opposed to cognitive) explanations for the effect, as reflected in Kurzban et al.'s article. However, the field needs a cognitive perspective on depletion also (cf. Inzlicht & Schmeichel 2012). It is our hope that our adapted model can support such initial cognitive steps.

Local resource depletion hypothesis as a mechanism for action selection in the brain

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Abstract: As a comment on Kurzban et al.'s opportunity cost model, we propose an alternative view of mental effort and the action selection mechanism in the brain. Our hypothesis utilizes *local resource depletion* within neuronal networks, which justifies from a neurophysiological perspective why mental fatigue diminishes after switching to a novel task and explains action selection by means of neural competition theory.

Revealing the process of action selection is crucial for understanding and predicting human behavior. Kurzban and colleagues put forward an interesting evolutionary and economically inspired description of the opportunity cost model as a putative mechanism for action selection by the human mind. However, the authors unexpectedly omit several experimentally supported models of the working memory system (e.g., Barrouillet et al. 2009; Logie 2011), which emphasize the existence of resource-sharing or distinct cognitive resources as a crucial aspect of the human mind. We propose an alternative view of mental limits, which explains the action selection mechanism from a neurophysiological perspective. Referring to neural underpinnings of their model, Kurzban et al. point out that prefronto-striatal dopaminergic pathways play an important role in the action selection mechanism, a thesis supported mostly by functional magnetic resonance imaging (fMRI) data. We think that results from human and animal electrophysiological experiments would add much to the understanding of both mental effort and action selection processes. Below we explain our proposal for understanding the physiological foundations of mental effort and posit their possible effect on the action selection mechanism.

While analyzing possible physiological correlates of mental effort, Kurzban et al. conclude that there is no good candidate for the explanation of both behavioral effects and fMRI data. They discuss glucose as such a potential source of energy for what we can call "mind work" but they reject this possibility, stating that no data show a relation between feeling of effort and glucose consumption (sect. 4.1). We propose to treat physiological resources more *locally*, as prone both to depletion and refill (which could take place at a slow or quick pace). From such a point of view one can propose a good candidate for a limitation of physiological resources underlying mental fatigue. It is known that periods of highly elevated neuronal activity lead to a decrease in synaptic efficacy (Zucker & Regehr 2002). This phenomenon reflects the depletion of a readily releasable pool of synaptic vesicles (Denker & Rizzoli 2010), which in turn might lead to decreased availability of "neural fuel." As a physiological "fuel" prone to depletion on a local (but not global) scale, we propose available pools of neurotransmitters (Denker & Rizzoli 2010) and/or locally released neuromodulators (Hasselmo 2006; Hasselmo & Stern 2006). This notion is supported by several studies showing that administration of acetylcholine diminishes fatigue resulting from task execution while simultaneously improving performance (e.g., Hasselmo & Stern 2006; Sarter & Parikh 2005).

It is therefore feasible that a highly activated neural circuit cannot work efficiently for long periods of time, due to a depletable pool of resources. The hypothesis of local resource depletion is supported by electrophysiological recordings from freely behaving rats that exhibited a phenomenon called "local-network sleep" (Krueger et al. 2008). With elongation of an awakened state, some of the studied cortical neural networks briefly went "offline" as in sleep, and were accompanied by slow waves in the local electroencephalogram (EEG). Such observations increased in frequency with the duration of the awakened state, and were accompanied by progressively impaired behavior despite the rats' continuous activity and a globally "awake" EEG (Vyazovskiy et al. 2011). With these data at hand we propose – instead of a "global" resource hypothesis such as Kurzban et al.'s – a *local resource depletion* hypothesis. Such a hypothesis simply explains why mental fatigue is diminished after switching to a novel task: In such a situation a new, not depleted, neural ensemble (or novel part of the same network) would be engaged.

The proposed phenomenon of local resource depletion could also affect action selection. Competition between neural ensembles has long been used as a convincing neurophysiological mechanism to explain selection of action in the brain, supported by many computational models and empirical data. Very important and seemingly relevant to Kurzban et al.'s model is the idea of selecting ongoing activity according to the result of competition between neural ensembles, proposed by Bullmore and Sporns (2012). This view of the action selection process not only posits a mechanism for flexible and fast-changing emergence of topographically and functionally distinct neuronal populations, but also allows for an economic and efficient method of information exchange and – what is crucial in this context – for trade-offs between neuronal ensembles and picking the "winner." Paul Cisek's "affordance competition hypothesis" represents a similar argument, proposing constant competition between currently available actions as a way of dealing with fast-changing sensory inputs from the environment and therefore constituting a neurophysiological mechanism for selection of action in the brain (Cisek 2007).

Crucial in our proposal is that a switch between active neuronal assemblies could be initiated by a decrease of long-lasting activity in the first assembly caused by resource depletion (see Fig. 1). This switch would shift the system towards different behavior by engaging new neuronal circuits, resulting in a diminished experience of fatigue. An advantage of our local resource depletion hypothesis is that, in contrast to Kurzban et al.'s proposal, it does not require assignment of control functions (i.e., opportunity costs calculation or action selection) to the particular brain structure.

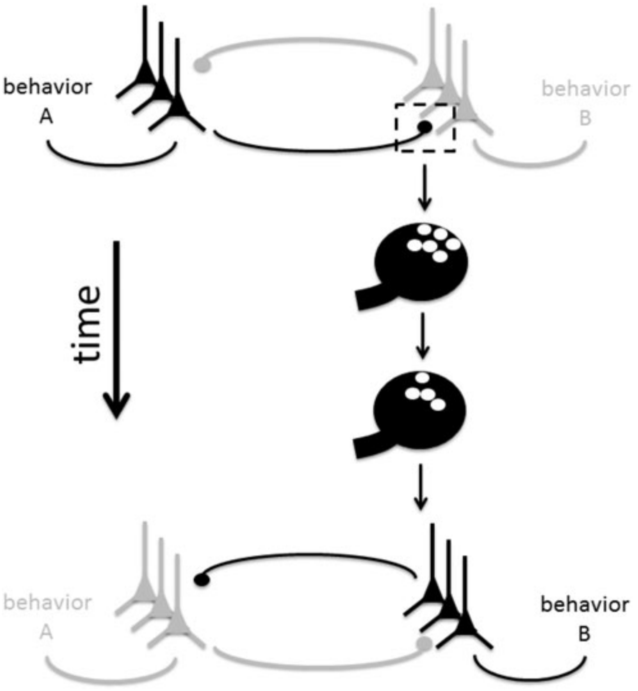

Figure 1 (Brzezicka et al.). A graphical representation of the local depletion hypothesis. In the upper scheme a neural ensemble underlying behavior A is a "winner," effectively inhibiting activity of the neural network underlying behavior B. After a certain period of time locally accessible resources of "neural fuel" (i.e., synaptic vesicles) in ensemble A would diminish, leading to a decrease of inhibition exerted on ensemble B and therefore allowing ensemble B to "win" a competition and inhibit the activity of ensemble A.

On a more general level, Kurzban and colleagues discuss cognitive limitations as a crucial feature of the human mind. We would like to enrich this view by recalling an existing hypothesis, which could help to understand this limitation at a physiological level. Lisman and Idiart (1995) proposed a model assuming that maximal capacity of working memory is determined by the number of individual gamma cycles that can fit within one theta cycle. Such a hypothesis is strongly supported by animal experiments (Pastoll et al. 2013), modeling work (Jensen & Lisman 1998), and human EEG observations (Kamiński et al 2011). These data allow a neuronal level to be taken into account when discussing any new model of cognitive brain processing limitations.

Is ego depletion too incredible? Evidence for the overestimation of the depletion effect

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Abstract: The depletion effect, a decreased capacity for self-control following previous acts of self-control, is thought to result from a lack of necessary psychological/physical resources (i.e., "ego depletion"). Kurzban et al. present an alternative explanation for depletion; but based on statistical techniques that evaluate and adjust for publication bias, we question whether depletion is a real phenomenon in need of explanation.

Much of Kurzban et al.'s discussion centers on the so-called depletion effect (i.e., the reduction of task performance between self-control tasks; Baumeister et al. 1998). For example, in sections 3.1 and 3.2 of the target article the authors argue that currently popular theoretical accounts of the depletion effect (i.e., that it is due to the depletion of some necessary resource) are inadequate and that an opportunity cost model is more appropriate. Assuming the depletion effect is a real phenomenon, we believe that the authors' account is indeed preferable to other explanations that have been proffered. However, based on the meta-analytic methods that Hagger et al. (2010a) used to evaluate the depletion effect, there is license for doubting that depletion really occurs. If one wishes to believe it is real (which may also be licensed), then it could be meaningfully weaker than Hagger et al. concluded.

Hagger et al. estimated that the overall size of the depletion effect was d = .62 (95% CI [confidence interval] = .57, .67). However, a meta-analytic estimate of an overall effect size is biased to the extent that the sample of experiments used to derive that estimate misrepresents the population of experiments that have been conducted on the effect. Samples of experiments can easily become unrepresentative if the probability that an experiment is included in a meta-analytic sample is influenced by the results of the experiment, a phenomenon known as *publication bias* (e.g., if findings confirming a particular idea are more easily published and, consequently, more easily identified and included in the meta-analysis). Importantly, Hagger et al.'s meta-analytic estimate resulted from a sample of experiments that was drawn exclusively from the published literature. Their neglect of the relevant unpublished results leaves open the possibility that the estimate is therefore inflated. Here, we summarize some results from our work that was prompted by this possibility (Carter & McCullough, submitted).

Based on Ioannidis and Trikalinos (2007), Schimmack (2012) proposed the "incredibility-index" (IC-index) as an estimate of the probability that a set of studies contains fewer statistically non-significant findings than would be credible under unbiased sampling (i.e., the number of significant findings is "incredible"). The IC-index, which takes values from 0 to 1 (where higher values suggest greater incredibility), is calculated through a binomial test on the observed number of significant results (151 of the 198 experiments analyzed by Hagger et al. were significant), given the probability that a single experiment will be significant (estimated as the average statistical power of the set of experiments). Based on post-hoc power calculations for each experiment in the Hagger et al. dataset, in which we assumed the true effect size was $d = .62$, average power was estimated to be .55, which resulted in an IC-index greater than .999 (for the binomial test, p = 3.72E-10). Therefore, it is extremely likely that more non-significant findings exist than are included in Hagger et al.'s meta-analysis, because the probability of drawing a set of 198 experiments in which only 47 or fewer were non-significant is roughly 3.7 in one billion.

Hagger et al. addressed the possibility of publication bias in their dataset by calculating the fail-safe N (Rosenberg 2005), but this method for assessing the robustness of a meta-analytic conclusion to publication bias is considered far from adequate (Sutton 2009). Alternatively, regression-based methods can both assess and correct for publication bias in a sample of experiments (Stanley 2008). In a weighted least squares regression model in which effect sizes are regressed on the standard errors (SEs) of those effect sizes, effect size and SE should be unrelated. However, if publication bias exists, SEs will be negatively associated with effect size (Egger et al. 1997). Additionally, one can think of the intercept in this model as an estimate of the effect size of a hypothetical, infinitely large study (i.e., one with zero sampling error variance: Moreno et al. 2011; Stanley 2008). Simulation studies suggest that such regression-based extrapolation yields accurate estimates of true effect sizes in the face of publication bias (Moreno et al. 2009; Stanley 2008).

We applied two regression models to Hagger et al.'s dataset: One in which the predictor was SE, and an alternative model in which the predictor was SE-squared (SE^2; Moreno et al. 2009). In both models, the regression coefficient for the predictor was significant ($t_{SE} = 11.87$; $t^2_{SE} = 11.99$; $ps < .001$), which is consistent with the presence of publication bias. The model-based estimates of the true underlying effect differed, however. Using SE-squared, the corrected effect size was $d = .25$ (95% CI [.18, .32]). Using SE as the predictor, the corrected effect size was a non-significant $d = -.10$ (95% CI [−.23, .02]). So, based on these methods, ego depletion could be a small effect – less than half the size of that estimated by Hagger et al.; but it could also be a non-existent effect for which belief has been kept alive through the neglect of null findings. If the true effect size is close to $d = .25$, then the set of experiments Hagger et al. analyzed was extremely underpowered (Mean power = .15, 95th percentile = .24). And even these less skeptical results counsel caution: Assuming the mean effect size is $d = .25$, researchers hoping to study depletion by comparing two means with 80% power should be prepared to collect a sample with $N > 460$, not $N = 84$ (as implied by Hagger et al.'s estimate of $d = .62$).

The great pity here is that editorial vigilance could have obviated these concerns: Editors and reviewers of meta-analyses should insist on rigorous efforts to track down the hard-to-find (i.e., unpublished) results. As things stand, we believe that the highest priority for research on the depletion effect should not be arriving at a better theoretical account, but rather, determining with greater certainty whether an effect to be explained exists at all.

Can tasks be inherently boring?

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Abstract: Kurzban et al. argue that the experiences of "effort," "boredom," and "fatigue" are indications that the costs of a task outweigh its benefits. Reducing the costs of tasks to "opportunity costs" has the effect of rendering tasks costless and of denying that they can be inherently boring or tedious, something that "vigilance tasks" were intentionally designed to be.

Kurzban et al. begin with the question as to why certain tasks cause an aversive experience of mental effort, with consequent deterioration in task performance. Although almost all of the examples they give are of "vigilance tasks" (to which I shall return below), their answer does not concern such tasks per se, nor does it address the special features of vigilance tasks (or why they are designated "vigilance" tasks in the first place). Rather, Kurzban et al. present a theory about the engagement of executive function in general, along with a general theory of the phenomenology of the conscious experience of "effort," "boredom," and "fatigue." According to the authors, these sensations are an indication of the opportunity costs of an activity – namely, that the costs of continued engagement in the present activity are outweighed by the "value of the next-best possible action" (sect. 2.4.1). What is unique about this account is the authors' claim that the costs of an activity simply are its opportunity costs, an assumption that has far-reaching implications.

If the costs of a task are equated with its opportunity costs, then the *task itself is costless.* Defined this way, tasks cannot be (or be perceived to be) inherently boring or tedious or fatiguing. But this assumption is certainly wrong. Before explaining why, consider the following question: Can tasks be (or be perceived to be) inherently rewarding (or exciting, engaging, invigorating)? The authors do not address this question directly, but it is telling that all of the examples they present of "rewards" or "benefits" associated with a task are *external* to the task itself – for example, payment given to a study participant for completion of a task. This implies that just as performing tasks is, in and of itself, without cost, so too, performing tasks is, in and of itself, without benefit. Or put another way, just as tasks cannot be inherently boring, they cannot be inherently exciting or rewarding or invigorating. But both of these assumptions (if *both* are in fact assumptions) are obviously incorrect.

Imagine that you are going to be a study participant. If you were given a choice of two tasks that involved an equal monetary reward and the same amount of time, which would you choose: To watch the second hand on a clock for three hours, indicating its position in response to an irregularly presented signal? Or to pilot a spacecraft simulator through a fantastic 3D virtual reality for three hours? We can safely assume that everyone would choose the latter (and many young persons would likely volunteer to perform the task for free). Why? The answer is not because the opportunity costs are higher for the latter than the former. Presumably, they are the same. Rather, it is because the former task is inherently boring, tedious, and effortful, whereas the latter task is interesting, exciting, and engaging. Can such a claim be made if we accept the authors' model? Whether or not they would accept that "benefits" can be internal to, or part of, a task, their model clearly cannot accommodate the claim that watching a clock on a wall is *inherently* boring. For what could such a claim mean if the costs of a task are reducible to its opportunity costs?

Let us move out of the highly artificial world of study participants being paid to perform tasks like the Macworth Clock for a moment. Let us also consider that "task" is too restrictive a term for what the authors are considering (although appropriate in the context of study participants and Macworth clocks). What they are considering is any kind of mental activity that entails a performance of some sort that can be measured.

Consider two friends, Amy and Peter. Amy is proficient at chess and loves the game. She can play for hours on end with no apparent fatigue and no diminishment in her performance. She is excited and engaged when she plays, and enjoys the experience. Peter is a mediocre chess player and hates the game. He finds it incredibly boring. When Amy insists that Peter play chess with her, Peter has aversive experiences of mental effort, boredom, and fatigue, with a concomitant rapid decline in performance, and he usually forfeits the game after 10 minutes. To be sure, part of Peter's boredom is an acute awareness of opportunity costs – he would rather be doing just about anything else (and is consciously aware of this fact). But the opportunity costs loom large precisely *because* he finds the activity of playing chess itself boring, tedious, and effortful. In other words, high opportunity costs do not make playing chess effortful and boring for Peter; rather, the fact that Peter finds playing chess boring and effortful makes the opportunity costs high to him. Boredom dictates opportunity costs, not vice versa.

To return to vigilance tasks: While to Peter, in the above example, playing chess may seem a vigilance task, vigilance tasks (unlike chess) are explicitly designed to give rise to aversive experiences of mental effort, boredom, and fatigue, with a concomitant deterioration in performance. That is why they are called *vigilance* tasks. Interest in vigilance or sustained attention arose during World War II, when British air force radar operators were required to spend lengthy periods of time monitoring screens for the radar return patterns of enemy surfaced submarines (Warm & Dember 1998). Although the job was considered not physically strenuous or mentally taxing, the maintenance of accurate performance turned out to be beyond human capability. Vigilance tasks were designed to generate the same mental effort, boredom, and fatigue that radar operators indicated that they had experienced.

Finally, concerning the enigma as to why revising a manuscript can be aversively effortful: Many a professor finds writing stimulating, engaging, and exhilarating, and can work for 15 hours without fatigue or boredom. But endless checking of typos, footnotes, and bibliographies bores many to tears, and after an hour or two, just about any activity seems preferable.

Maximising utility does not promote survival

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Abstract: We argue that maximising utility does not promote survival. Hence, there is no reason to expect people to modulate effort according to a task's opportunity costs. There is also no reason why our evaluation of the marginal opportunity costs of tasks should predictably rise with repetition. Thus, the opportunity cost model cannot explain why tasks typically become harder over time.

Kurzban et al. seek to explain two phenomena: (1) why cognitive tasks typically *feel* increasingly difficult with repetition, and (2) why *performance* in these tasks degrades with repetition. For instance, in a task involving the continuous multiplication of four-digit numbers over several days, subjects experienced the task as increasingly difficult, and at the same time became less proficient at the task (Arai 1912; Huxtable et al. 1946).

Kurzban et al. offer a common explanation of both target phenomena relying on three claims. They argue: (a) that the difficulty we experience in performing cognitive tasks reflects our subconscious evaluation of the next-best alternative task (this constitutes the *marginal opportunity cost* of the current task – it is the value we miss out on in virtue of performing that task); (b) that the difficulty we experience in performing cognitive tasks reduces our proficiency in performing those tasks; and (c) that when we repeatedly perform cognitive tasks, our evaluation of the opportunity costs of these tasks steadily increases. These three claims together imply that people who repeatedly perform cognitive tasks will experience increasing difficulty and, as a result, will manifest steadily degraded performance. In our commentary, we wish to challenge claims (a) and (c).

First, what reason is there to think that the difficulty we experience in performing cognitive tasks should reflect our evaluation of their marginal opportunity costs? Kurzban et al. offer an evolutionary answer, arguing that it makes good adaptive sense for an organism to modulate its expenditure of cognitive resources on a task according to the task's expected utility. (Kurzban et al. appear to take the utility of a task to be determined by its contribution to the organism's well-being.) But we question the presupposition that there is any relation between a task's expected utility and its survival value. For example, neither my judgement that rock-climbing is good for me nor the truth of that judgement (entailing that rock-climbing is indeed good for me) implies that this activity is conducive to my survival. It may or may not be the case that our most basic motivation is to maximise utility (our well-being). But even if we are, in fact, utility-maximisers, there seems no reason to think that being a utility-maximiser is adaptively optimal. This point is especially clear if we analyse well-being in terms of preference-satisfaction: There is no reason to assume that the actions that maximise my preference-satisfaction will also maximise my chances of survival.

But even if we grant the supposition that maximising utility is adaptive, it seems that an organism would benefit most from being disposed, not to *modulate* its commitment to a task according to the task's expected utility (as Kurzban et al.'s model entails), but rather to *fully* commit its resources to the cognitive task with the highest expected utility, and to *be prepared* to shift resources as soon as some other task becomes more beneficial. Thus, even if the value of an alternative task is increasing, it would make no sense for an organism to shift any resources to that task until the tipping point where the alternative task is, in fact, more valuable than the current task. By analogy, if I think Barack Obama is the best candidate, surely I should devote all my resources to his re-election, unless I come to think that Mitt Romney is the best candidate, all things considered. However, I may discover that Romney is a better candidate than I had thought he was – my evaluation of him may indeed be rising; still, this gives me no reason to allocate *any* resources towards his election until I think he is the *best* candidate.

Of course, as Kurzban et al. explain in section 2.4.2, it may sometimes be the case that the best task available to an individual involves a sharing of cognitive resources between two activities. In their example, a participant in an Arai-style math task might do best by dividing her "mental processors" between performing the math task and daydreaming. Kurzban et al. argue that as a result of experiencing the math task as effortful, the subject may well end up performing the optimal mixed task of math-plus-daydreaming. However, an optimal mixed task may not always be available. Often, the next-best alternative task will be entirely incompatible with the task at hand. In these cases, according to the model offered by Kurzban et al., people will nevertheless experience aversive effort corresponding to the opportunity costs of their behaviour. For instance, even the subject who performs an optimal math-daydreaming task will, according to the model, continue to experience this task as effortful, corresponding to the value of the next-best task available. But, as we have already argued, there is no benefit in having such a disposition.

Now, what reason is there to think that our evaluation of the marginal opportunity cost of a task will predictably *rise* when the task is repeated over a brief period of time? In section 2.4.3, Kurzban et al. argue that a bias towards exploring new tasks will protect organisms from over-investing in tasks whose value they overestimate. However, the authors provide no reason for thinking that we are in more danger of overestimating the value of our tasks at hand, rather than alternative tasks. Of course, a task will often *seem* to lose value with repetition simply in virtue of its increasing *sunk costs*. But sunk costs should not figure in our calculations about the rationality of a course of action. Ultimately, the account offered by Kurzban et al. in the target article explains one mystery (why cognitive tasks reliably feel harder over time) only by substituting another mystery (why one's evaluation of the marginal opportunity costs of a task should increase – reliably – over time).

An interoceptive neuroanatomical perspective on feelings, energy, and effort

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Abstract: A homeostatic energy model of awareness proposes that the anterior insular cortex engenders feelings that provide an amodal valuation of homeostatic energy utilization in an opponent, bivalent emotional control system. Feelings are the "common currency" which enable optimal utilization in the physical and mental behavior of a highly social primate. This model offers a different perspective.

As a functional neuroanatomist, I applaud Kurzban et al.'s efforts to integrate parallel literatures, despite the jargon barriers (oh, yes, phenomenology = *feelings*!). Of course, it's difficult even within our own fields. I'm certain that psychologists who adhere to "self-perception theory" (see Laird 2007) would have difficulty with the statement that "feelings motivate behavior," as do I.

I mapped an ascending neural pathway for affective feelings from the body and identified the cortical image of these elemental feelings in an interoceptive representation of the physiological condition of the body, which anchors the insular cortex of primates (Craig 2002). A convergence of evidence across disparate fields led me to suggest that the progression of interoceptive processing from posterior to anterior in the insula culminates in a moment-to-moment global representation of homeostatic salience in the anterior insula, which we experience as feelings. The model incorporates each finite momentary representation in a cinemascopic structure across present time built upon learned predictions. The comparators needed to use this structure for the optimization of moment-to-moment emotional behavior also substantialize reflective subjectivity (as a "spandrel"), which is always one moment behind and cannot "see" itself. It may or may not be veridical, and it can become functionally distorted (Craig 2009; 2010).

The key concept is that feelings are an amodal valuation of energy utilization constructed on the homeostatic sensori-motor template generated by the elemental interoceptive feelings from the body. This construct, which we experience as feelings, can represent any pattern of neural activity in the brain; for example, a neural activation pattern in a sensory system, in the cognitive network, or in one of the motor planning networks. Being able to feel every percept, thought, motivation, or potential behavior provides a powerful "common currency" for evaluation and comparison of energy costs and benefits.

In my view, the homeostatic principle of optimal energy utilization in an organism in which the brain consumes 25% of the entire energy budget compelled the evolutionary development of a common valuation system for energy cost-benefit analysis. That system had to be capable of representing not only the homeostatic significance of any behavior, but also the homeostatic significance of the potential behaviors inherent in any network pattern of neural activity (Craig 2011). I believe that feelings are the coinage of that valuation system, the interoceptive indicators of actual or potential homeostatic energy significance. Very recent evidence confirms that the bilateral insular cortex encodes action-specific valuation (Fitzgerald et al. 2012). I believe the precise control of emotional behavior is effected by the opponent processes of energy nourishment (positive affect, approach motivation) and expenditure (negative affect, avoidance motivation) that are engendered in the bivalent, bicameral brain of all vertebrates (Craig 2009; MacNeilage et al. 2009).

It is important to recall that emotional behaviors evolved as energy-efficient means of producing goal-directed actions that fulfill homeostatic and social needs, as Darwin and others taught. In other words, the emotional feelings of happiness, anger, and the like, can be viewed as the sensory complement of fundamental neural patterns that are genetically ingrained in our (limbic) emotional motor system. Like the pleasantness or unpleasantness of a cool stimulus on the hand, which is inverted in hyperthermia and hypothermia, an emotional feeling is the perceptual correlate of a behavioral motivation. Sometimes we are aware of the feeling that accompanies each motivated behavior, and sometimes we are not (Wegner 2002). All behavior is emotional (Dunn et al. 2012; Montague 2006a).

In this model, the limbic (emotional) motor cortex (the anterior cingulate and medial prefrontal cortex) works together with the limbic sensory cortex (anterior insula); that's why they are almost always co-active, and why they are the most commonly activated regions of the brain (Nelson et al. 2010; Sepulcre et al. 2012). The anterior insula is involved in thoughts, emotions, and bodily feelings, and it is the foundation for emotional awareness (Oosterwijk et al. 2012; Zaki et al. 2012). It is also the bottleneck in the attentional blink, the basis for inspection time, and a basic resource that underlies fluid intelligence (Britz et al. 2010; Cole et al. 2012; Craig 2009; Menon & Uddin 2010).

The homeostatic (Group III/IV) sensory input from muscles to the insular cortex is a primary generator of feelings of "fatigue" and "effort" (Amann et al. 2010; Hilty et al. 2011). Individuals who are more aware of their homeostatic condition self-regulate their energy consumption more efficiently, and highly trained athletes and warriors use interoceptive sensory activity to produce optimal performance (Herbert et al. 2007; Paulus et al. 2010; 2012).

And lastly, the anterior insula serves as the evidence accumulator for decision-making, the source of error negativity, and in my opinion, the basis for mental energy and effort (Gluth et al. 2012; Jansma et al. 2007; Wessel et al. 2012). Unfortunately, its activation is not registered in certain studies, probably because of its structural variability and the use of subtractive contrasts.

I enjoyed reading the authors' views of the literature they are familiar with. I hope they will enjoy reading another literature, and I hope they find these comments constructive. Our respective views are conceptually distinct, yet quite similar teleologically. I would very much enjoy an opportunity to discuss these ideas further with such knowledgeable scholars.

Opportunity cost calculations only determine *justified* effort – Or, What happened to the resource conservation principle?

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Abstract: We welcome the development of a new model on effort and performance and the critique on existing resource-based models. However, considering the vast evidence for the significant impact of experienced task demand on resource allocation, we conclude that Kurzban et al.'s opportunity cost model is only valid for one performance condition: if task demand is unknown or unspecified.

Identifying the processes that determine the mobilization and experience of effort is important for understanding human motivation and performance. Given that theoretical models on this topic are rare, we highly welcome the formulation of a new model on effort and task performance that challenges existing ideas. However, we think that the current version of Kurzban et al.'s opportunity cost model suffers from a major shortcoming: It does not consider that task choice and task execution are influenced by different variables, and it neglects the considerable amount of research that has examined and demonstrated the significant role of task demand in effort and resource allocation, respectively.

The core idea of the opportunity cost model is that mental effort is a function of the relative utility of action alternatives, determined in an opportunity cost analysis. Surprisingly, Kurzban and colleagues do not consider findings and models that draw on the idea that the motivation to conserve resources governs effort mobilization, as stated in the principles of "least effort" or "least work" (e.g., Hull 1943; Kool et al. 2010; Tolman 1932; Zipf 1949). More than a hundred years ago, William R. B. Gibson highlighted the crucial role of task demand for resource investment. He discussed the role of the "principle of least action" in psychology (Gibson 1900), postulating that individuals invest only the effort that is minimally required to perform a task. Likewise, it was postulated in the "difficulty law of motivation" that effort is mobilized proportionally to the magnitude of obstacles in goal pursuit, once a goal is set (e.g., Ach 1935; Hillgruber 1912). Consequently, the allocation of computational resources should be primarily driven by task demand, and not by the relative utility of task alternatives as suggested by Kurzban et al. We agree that utility may play a major role for *task choice*. But effort refers to *task execution,* and for this process other variables are relevant than the ones for task choice, as identified in research on action phases of goal pursuit (e.g., Gollwitzer 1990; Heckhausen & Gollwitzer 1987). Kurzban et al. make no explicit distinction between *task choice* and *task execution*, which may explain why they neglect the role of task demand in their analysis.

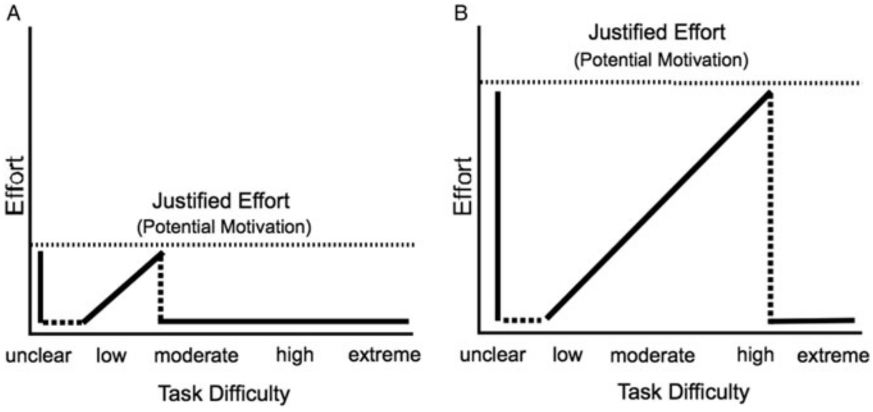

Figure 1 (Gendolla & Richter). Effort mobilization according to motivational intensity theory (Brehm & Self 1989). Panel A shows predictions for effort mobilization when only low effort is justified (i.e., low potential motivation). Panel B shows predictions for the condition when high effort is justified (i.e., high potential motivation). (Adapted from Gendolla & Wright 2009, p. 134. Copyright: Oxford University Press, 2012)

Focusing exclusively on task execution, particularly motivational intensity theory (Brehm et al. 1983; Brehm & Self 1989) has elaborated the resource conservation principle by considering the role of utility, or success importance, and by specifying when and how utility determines effort in interaction with task demand. This theory posits that effort is mobilized proportionally to experienced task demand as long as (1) success is possible and (2) the amount of effort that is necessary to succeed is justified. If one of these limits is reached, people disengage, because effort investment would not bring return, meaning a waste of resources. Thus, effort should vary non-monotonically with the perceived difficulty of instrumental behavior, as depicted in Figure 1.

The theory posits that utility – which may be the result of an opportunity cost analysis – has only an indirect impact on effort in most situations: It defines the maximal effort people are *willing* to invest (i.e., potential motivation; see Wright 2008 for a discussion). Most relevant for the model of Kurzban et al., unclear difficulty is the only condition under which justified effort directly determines actual effort. Only if people have no idea about the extent of task demand, can they not calibrate effort to the level of task demand (e.g., Richter & Gendolla 2006; 2009). Consequently, referring to task execution, we regard the opportunity cost model as valid only for this one performance condition: If task demand is unknown.

Nevertheless, we think that the opportunity cost model may be compatible with the resource conservation principle if one considers that organisms seem to prefer low opportunity costs, especially in task choice situations (as already identified by the behaviorists in the principles of least effort and least work: Hull 1943; Tolman 1932). However, the logic consequence of the energy conservation principle is that organisms do not invest more resources than *necessary* for an action. Consequently, motivational intensity theory posits that effort rises with subjective demand as long as success is possible and justified. We agree that *justified* effort can be determined by an opportunity cost analysis, making this a central variable for task choice. However, in contrast to Kurzban et al.'s analysis, it is task demand that should primarily determine mobilized and experienced effort. Supporting this idea, numerous studies have shown that effort is low when demand is low, even when justified effort (i.e., task utility) is high (for overviews, see Gendolla & Richter 2010; Gendolla et al. 2012; Wright & Kirby 2001). Only if subjective demand is unclear does justified effort directly determine actual effort (e.g., Richter & Gendolla 2006; 2009).

In summary, we regard Kurzban et al.'s analysis as suitable for predicting task choices. However, concerning effort mobilization and experience, which refers to task execution, their arguments are valid only for one specific condition – if task demand is unclear. If demand is known, effort is determined by experienced difficulty up to the level of maximally justified effort, which may be the outcome of a cost-benefit analysis in terms of the opportunity cost model.

The opportunity cost model: Automaticity, individual differences, and self-control resources

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Abstract: I contend that Kurzban et al.'s model is silent on three issues. First, the extent to which opportunity-cost computations are automatic or deliberative is unclear. Second, the role of individual differences in biasing opportunity-cost computations needs elucidating. Third, in the absence of "next-best" tasks, task persistence will be indefinite, which seems unfeasible, so perhaps integration with a limited-resource account is necessary.

The scope and ambition of Kurzban et al.'s model is commendable. I believe it advances understanding of mental fatigue and task performance and integrates hitherto disparate literatures on mental fatigue, self-control, and vigilance. My comments focus on areas that remain to be elucidated in the model, which I hope will further the debate on the link between mental fatigue and task performance. I will confine my comments to three main areas: (1) automaticity and conscious awareness, (2) the role of individual differences, and (3) resource depletion models of self-control.

First, I felt it was unclear as to the extent to which the processes outlined in the model were automatic and outside the subjective experience of the individual, or whether they were, at least in part, driven by deliberative decision-making. This opens the question as to which kind of cognitive system(s) controls the opportunity-cost computations. The implication is that the computations occur outside conscious awareness and the phenomenology of subjective fatigue is a by-product signalling the effort involved and regulating task performance accordingly. However, the worked example involving "next-best" alternatives to the task at hand (e.g., daydreaming, using a smartphone) implies some conscious awareness of these as viable alternatives. The problem here is the extent to which individuals will have a clear representation of these alternatives if we were, for example, to apply the model to understand persistence and fatigue on tasks presented in laboratory environments where other alternatives are relatively limited (other than the "background" alternative of daydreaming). I found Kurzban et al.'s account relatively silent on this matter, and there were occasions where the authors' narrative implied deliberative decision-making processes (e.g., "We can think of this participant as having a *choice* [emphasis added] between performing those calculations or, alternately, daydreaming"; sect. 2.4.1, para. 1).

Another illustration lies in the use of the Stroop task as an analogy for the proposed opportunity-cost computations. The performance decrements experienced on incongruent Stroop tasks are due to competition between the visual and word-naming systems leading to a response-inhibiting processing "bottleneck." This is an automatic process; individuals have no subjective awareness of the interference or control over whether or not their visual system reads the presented words. So, while this competition in processing systems may be the cause of subjective fatigue, it is independent of, and different from, the opportunity cost decision-making process involved in whether to persist with the task or select an alternative. So I think this analogy is problematic, in that it does not elucidate the extent to which the individual consciously deliberates over decisions to persist with the "best" task or allocate resources elsewhere (or not at all), or whether decisions on the devotion of processing capacity are automatic and outside the individual's awareness. Perhaps Kurzban et al.'s account needs to identify the extent to which the computational processes are accessible to the individual. Dual-systems models of social cognition describing the relative contribution of deliberative (reflective) and automatic (impulsive) processing may provide a possible framework (Strack & Deutsch 2004).

Second, Kurzban et al.'s account also does not incorporate individual differences. A hallmark of social-cognitive models is the assumption that individuals process information in identical ways. This is not the case if one takes into account individual differences that affect cognitive processing. For example, there is research demonstrating that individual differences in trait self-control moderate effects of mental effort on computationally-demanding tasks (Hagger et al. 2010a). How could the opportunity cost model explain individuals differences in processing bias brought about by such traits? Could it be that traits bias individuals' tendency to interpret the opportunity costs of their responses relative to the next most desirable action, similar to the way experimenter presence is outlined in the model (cf. Figure 3 of the target article)? It would be interesting to incorporate this into the model.

Finally, despite an array of examples in support of the model, including alternative explanations of limited-resource models of self-control, a question remains as to whether all experiences of mental fatigue can be attributed to changes in opportunity cost over time. Kurzban et al. state that "mental 'resources' are finite, *dynamic*, and *divisible,* … rather than finite and *depletable over time*" (sect. 2.4.2, para. 1, emphasis theirs). Does this mean that in the absence of "next-best" alternate tasks for which perceived opportunity costs do not exceed those of the "best" task, performance on tasks will be consistent and indefinite? In such cases the marginal utility of the current task would consistently exceed that of the marginal value of the "next-best" task, leading to a decision not to divide processing capacity across the tasks. This seems implausible given research on vigilance tasks that consistently demonstrates fatigue and performance decrements over time. Kurzban et al. concede that "to the extent that there are no offsetting benefits . . . the relationship between perceived costs and benefits can become less favorable over time" (sect. 2.3.2, para. 4), suggesting that, given sufficient time, processing resources will inevitably be allocated elsewhere. However, no alternative explanation is provided in the model to explain fatigue in the absence of a competing alternative task that "wins out" in the decision-making process over the "best" task in opportunity-cost computations.

So is there still room for a "resource" account that provides additional limits on the extent to which processing capacity can be allocated over time? Kurzban et al. point out recent research that has challenged the limited-resource approach. These include studies demonstrating that beliefs (e.g., Job et al. 2010) and motivational incentives (e.g., Muraven & Slessareva 2003) mitigate ego-depletion, as well as conceptual (Kurzban 2010a) and empirical (Hagger & Chatzisarantis 2013) accounts that raise doubts over glucose as a physiological analog for the resource. These issues notwithstanding, recent evidence suggests that self-control performance is impaired in the presence of beliefs about resources and motivation, provided the level of depletion is sufficiently extensive (Vohs et al. 2012). Further, Kurzban et al. acknowledge that further candidate physiological analogs may exist for the limited resource, but conceptual and empirical verification are needed. The ego-depletion literature is problematic; but it seems that in light of new evidence, and the possibility that the opportunity costs model may not provide a comprehensive explanation for mental fatigue, future research should aim to reconcile these differences, perhaps through theoretical integration (Hagger 2009).

Give me strength or give me a reason: Self-control, religion, and the currency of reputation

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Abstract: We show that Kurzban et al.'s approach illuminates the relationship between religion and self-control. Whereas resource-depletion theorists suggest religion replenishes self-control resources ("strength"), we submit that religious cues make people feel observed, giving them "reason" to persevere, and we describe an experiment that supports our interpretation. Finally, we question the claim that subjective fatigue is a signal to redeploy resources.

> *"Dear Lord, give me strength to carry on"*
> — Eric Clapton (1974) "Give Me Strength"
>
> *"Just give me a reason to carry on"*
> — Sam Roberts (2008) "Words and Fire"

By situating the concept of "effort" in an adaptive context, Kurzban et al.'s target article represents a major advance toward a scientifically mature conception of self-control. We agree that perseverance depends less on reservoirs of a depletable resource than on favourable cost-benefit computations. In what follows we will show how this approach can illuminate recent findings concerning the relationship between religion and self-control. In doing so we highlight a central currency of cost-benefit computation – the currency of social approval or reputation. However, we also raise doubts about the claim that the phenomenology of effort is a signal that resources are better deployed elsewhere.

The notion that God can replenish one's "strength" to face hardships and resist temptations is common in scripture (e.g., Isaiah 40:31; Peter 5:10) and in popular culture (e.g., Clapton 1974). Consistent with this idea, Rounding et al. (2012) suggest that "invoking religious beliefs may provide important psychological 'nutrients'… to restore self-control resources … after their depletion" (pp. 640–41). These authors report that participants primed with religion endured more discomfort, delayed gratification longer, persisted longer in an "ego-depletion" test, and performed better on a Stroop task than did control participants. Although Rounding et al. (see also Baumeister et al. 1998; McCullough & Willoughby 2009; Preston et al. 2010) favour a resource-depletion explanation for these results, the cost-benefit approach of Kurzban et al. affords a more compelling interpretation.

Imagine a man who, approached by a beggar requesting spare change, demurs. He may be unable to donate, having no change on him, or he may be unmotivated to donate. Later, another beggar approaches the man as he passes a church. This time the man digs in his pocket and hands the beggar some coins. Whatever effect the religious context has had, it has not magicked money into the man's pocket, strengthening his financial reserves; more likely it has increased the salience of certain incentives (e.g., the approval of supernatural agents), giving him a *reason* to donate money he already possessed. Similarly, we contend that the effects Rounding et al. report reflect changes in the implicit incentive structure of relevant tasks, giving participants more reason to wait, persist, and endure – not greater reserves of the ability to do so.

Rounding and colleagues' delayed-gratification study particularly illustrates why we favour a cost-benefit explanation for such priming effects. After priming, participants chose between returning the next day to collect a $5 honorarium, or returning in seven days to collect $6. Participants primed with religion more frequently chose to wait. Rounding and colleagues' contention that religious priming replenished self-control resources suggests that control participants were unable (rather than unmotivated) to wait, implying that participants who waited *discounted* the value of the delayed $6 less than those who did not wait. However, applying Mazur's (1987) discounting formula to the choice indicates that participants who waited must have had miniscule temporal discounting rates ($k \leq .0286$). Such rates are generally observed in studies involving larger dollar amounts (Green et al. 1997); small amounts (<$10) generate much higher discounting ($k = .132$; Harrison & McKay 2012). If religious primes reduce discounting to approximately 20% of typically observed rates, this effect should be easily detected. We tested this possibility in a follow-up study (Harrison & McKay 2013), but reduced the possible influence of social desirability.

In Rounding and colleagues' study, it was obvious that electing to wait would make participants appear more patient. We used a discounting measure that was opaque in this respect – that is, it was difficult for participants to discern the socially desirable response. We randomly assigned 42 participants to a neutral or a religious prime group; participants completed temporal discounting tasks prior to and immediately following the priming task. Although experimentally induced changes to discounting rates have been detected using similar research designs, in our study religious priming had no effect on subsequent discounting.

So why would primed participants in Rounding et al. (2012) have elected to wait? We agree with Norenzayan and colleagues (Gervais & Norenzayan 2012; Shariff & Norenzayan 2007) that the religious primes probably activated the notion of surveillance (supernatural or otherwise), triggering cognitions that regulate behaviour in the service of reputation management (Haley & Fessler 2005). As a consequence, primed participants were implicitly motivated to signal their patience and persistence to potential observers. In Rounding et al.'s delayed-gratification study the relevant signal was the decision to wait the extra six days – their other studies involved other signals.

What is not clear is whether, in altering subjective incentives to exert "self-control," religious priming actually alters the *experience* of effort. Kurzban et al. argue that the phenomenology of effort reflects the opportunity cost of continuing the current course of action; so if perceived incentives to persist with current tasks are increased, those tasks should feel less aversive. However, the recently described "martyrdom effect" suggests that in certain contexts people will deliberately seek out effortful experiences (Olivola & Shafir 2013). Such situations (e.g., self-imposed penance) may simply reflect cultural distortions of biological function – exceptions that prove the "effort as deterrent" rule. However, there are other reasons to doubt that the feeling of effort constitutes a signal to pursue alternative goals (Hockey 2011). For one thing, this claim entails the prediction that if there were absolutely no other useful tasks one could engage in (imagine a person in solitary confinement whose only option is to figure out how to escape), the current course could be pursued indefinitely without fatigue. However, the necessity of sleep suggests that resources cannot be endlessly deployed.

This issue notwithstanding, we find Kurzban et al.'s approach extremely compelling, and view their cost-benefit analysis as providing a parsimonious explanation for recent findings regarding the effect of religion on self-control. With apologies to Eric Clapton, our view is that religion affects not the strength "to carry on" but the expected utility of doing so.

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Depletable resources: Necessary, in need of fair treatment, and multi-functional

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Abstract: I make three points. First, processors and depletable resources should not be regarded as alternative means of processing information: they are both necessary. Second, comparing a processor account with a rational allocation mechanism to a depletable-resources account without one is not a fair comparison. Third, depletable resources can act as signals as well as fuels.

Were the mind any other sort of system that processes information, there would be few objections to the statement that mechanisms (processors) fuelled by resources carry out processes in order to perform tasks. Poor performance may arise because the mechanisms are overloaded, because resources are being depleted faster than they can be renewed, or for both of these reasons.

We can also think of processors as a type of resource; however, they are occupiable rather than depletable. (Both my car and the fuel it uses are travel resources – but the car is an occupiable resource, whereas the fuel is a depletable one.) If we use this sort of terminology, we still need to recognize that both types of resource (depletable and occupiable) are needed to carry out processes to perform tasks. (Having just fuel or just a car will not enable me to give my friend a lift to the airport.)

Kurzban et al. refer to occupiable resources as finite, dynamic, and divisible, and to depletable resources as finite and depletable over time. They say that "mental 'resources' are finite, *dynamic,* and *divisible* at any given point in time, rather than finite and *depletable over time*" (sect. 2.4.2, para. 1, emphasis in the original). Here their use of the term "rather than" indicates that they consider occupiable and depletable resources as alternative means for processing information, when, in fact, they are both essential. A system that could process information using mechanisms alone without any energy input would provide us with an example of perpetual motion.

To make their point, the authors do not need to deny the existence of depletable resources. They can accept the existence of such resources but then attribute the effects they discuss to the rational allocation of *mechanisms* to higher priority tasks.

I turn now to the main substance of the target article. The authors argue that, by adding a mechanism that rationally allocates processors (occupiable resources) to tasks, they can render their processor account superior to the depletable-resources account. Their argument is convincing. However, it is not fair or balanced. They have shown that an occupiable-resource account that incorporates a rational allocation mechanism is superior to a depletable-resources account that does not incorporate such a mechanism. It is perfectly possible to rationally allocate depletable resources – electricity suppliers do it when faced with a large unexpected loss of generating capacity. A mechanism precisely analogous to the one that the authors describe could be added to the depletable-resources account.

If this were done, it is unlikely that the resulting model would be inferior to the one proposed by Kurzban et al. There is no reason to suppose that prioritization of resources using opportunity costs would be any less effective than prioritization of processors using opportunity costs in explaining all the phenomena that the authors discuss. For example, effects of incentives and availability of alternative tasks, such as using a smartphone, could be handled equally well. Furthermore, one could still argue, as the authors do, that *"the sensation of 'mental effort' is the output of mechanisms designed to measure the opportunity cost of engaging in the current mental task"* (sect. 2.3.2, para. 2, italics original).

It might prove difficult to design experiments to distinguish the occupiable-resources account and the depletable-resources account of performance decrements if a rational resource allocation mechanism were added to both types of model. Recovery rates after demanding performance may provide one line of attack.

Unfortunately, there is a third possibility. Both processors and depletable resources may be rationally allocated to tasks. Distinguishing this alternative from the other two is likely to pose further difficulties.

Finally, I consider the authors' argument that there are no proposals that identify an explicit neural resource beyond Gaillot and Baumeister's (2007) argument in favour of glucose. Kurzban et al. say that any such proposals would need to explain: "(1) what the resource is, (2) how that resource is depleted by effortful tasks, (3) how depletion of the resource is sensed and leads to subsequent decrements in task performance, and (4) why some kinds of mental/neural activity, but not others, lead to resource depletion" (sect. 4.1, para. 6).

These seem very stringent conditions for classifying something as a depletable neural resource. There are many neurological problems, such as Parkinsonism, where performance decrements can be attributed to some neural resource (e.g., a neurotransmitter or neurohormone) that cannot be renewed at the rate at which it is depleted. In such cases, the resource has been primarily depleted not by an effortful task but by disease. Effective drug treatments replace the resource. In cases such as this, the depletable resource is not fuelling the processor but acting as a means of signalling for it. However, its depletion still causes performance impairment.

Kurzban et al. appear to exclude depletable resources that serve as signals rather than as fuels from their definition of a depletable resource. For example, though they say they know of no proposals for an explicit neural resource beyond glucose, they still suggest that information about opportunity costs needed for rational allocation may be provided by levels of a neurotransmitter, such as dopamine. This looks like a depletable-resource account: It predicts that chronic depletion of dopamine via disease or experimental manipulation will lead to an inability to regulate its levels in the prefrontal cortex for signalling purposes, and that, as a result, rational allocation would be impaired.

Distinguishing occupiable and depletable resources at the neural level is open to the criticism that all brain constituents are subject to chemical turnover. Ultimately, it is the rate of this turnover that should allow us to distinguish resource types. Occasionally, I need to replace parts of my car when they are broken or worn out. This does not mean that my car is a depletable rather than an occupiable resource: I have to replace parts of my car much less frequently than I have to re-fill it with fuel.

Competing goals draw attention to effort, which then enters cost-benefit computations as input

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Abstract: Different to Kurzban et al., we conceptualize the experience of mental effort as the subjective costs of goal pursuit (i.e., the amount of invested resources relative to the amount of available resources). Rather than being an *output* of computations that compare costs and benefits of the target and competing goals, effort enters these computations as an *input*.

Kurzban et al. argue that mental effort experienced during task engagement is a function of opportunity costs – that is, the degree to which the mental processes allocated to a target task or goal are not available for other tasks or goals. We consider this idea intriguing and concur that feelings of effort, like other sensations, are most likely the outputs of mechanisms designed to produce inputs to decision-making systems (Bloom 2010; Thornhill 1998). We doubt, however, an additional assumption of the model, namely, that the experience of effort itself changes as a function of the presence of competing goals. We propose a potential alternative account of subjective feelings of effort and their adaptive value. Accordingly, subjective effort emerges from cost computations associated exclusively with the currently pursued goal and is a function of the means invested into the goal at hand and the means available for pursuing it. In our conceptualization, alternative goals do not enter this computation through opportunity costs. The presence of competing goals may, however, draw more *attention* to the resources and, in turn, the effort invested into pursuing the target goal.

Our account of mental effort differs from Kurzban et al.'s account regarding the effect of competing outcomes. Kurzban et al. predict that competing goals increase mental effort through opportunity costs, that is, the degree to which resources invested into the target goal are not available for achieving competing goals. In our view, subjective effort is a function of the resources a person perceives to invest into the pursuit of the target goal in relation to the subjectively available goal-relevant resources (e.g., when time is crucial for pursuing the target goal, perceived effort is mainly based on how much of one's available time is spent for its pursuit). Based on the definition of goals as cognitive representations linking means to desired outcomes (e.g., Freund et al. 2012; Kruglanski et al. 2002), the subjective perception of effort should be related to the *means* of goal pursuit (i.e., how many resources does one have to invest to attain the outcome?). Kurzban et al. posit that mental effort is related to potential *outcomes* or alternative goals, but it remains unclear how people gauge the effort if they do not do so on the basis of how many resources they invest relative to the resources they have available for the pursuit of a target goal. By reflecting these relative costs, subjective feelings of effort provide an informational basis for further cost-benefit computations that determine whether an individual decides to continue investments into the goal at hand or turn away from it and towards other goals. As costs during task engagement accumulate over time, the feeling of mental effort during task engagement increases simultaneously (cf. Boksem & Tops 2008). In agreement with Kurzban et al., and contra to previous accounts of mental effort (Kahneman 1973), we consider mental effort not a finite capacity but a metacognitive phenomenon that signals the ratio of the finite amount of available resources to the subjectively invested ones.

How, then, is the subjective experience of effort influenced by potential alternative goals? We posit that perceiving alternative desired outcomes draws *attention* to the means of goal pursuit to determine whether such outcomes require the same means. The presence of competing outcomes should make people become more aware that their resources are finite and have to be spent carefully, that is, that they are best invested in means that yield the most valuable outcome (e.g., Ebner et al. 2006).

Each alternative goal has an (expected) cost/benefit ratio. In order to compare multiple goals, a person needs to make a rough overall estimate as to how many resources will be needed and are available to attain the goals. Hence, a person should compare the experienced cost/benefit ratio of the ongoing goal against the expected cost/benefit ratio of additional or alternative goals. In this way, the mental effort invested into goal A enters cost-benefit computations that compare target goal A to the alternative goal B (note that goal B might also be to pause the pursuit of a target goal in order to conserve resources; Boksem & Tops 2008; Hennecke & Freund, in press). The presence of alternative goals creates a reference against which the cost/benefit ratio of the ongoing goal-pursuit is compared. By triggering this comparison, alternative goals draw attention to the effort – as a subjective representation of the costs – invested into the ongoing goal. Without changing subjective effort directly, alternative goals might thus change the *perception* of effort by putting it into the center of attention (Kool et al. 2010). By providing information about the means/resources a person currently invests into the pursuit of a goal, subjective effort allows a rough estimate of how many resources are available for the pursuit of additional or alternative goals. It may thereby serve as an important metacognitive cue as to whether to continue with the current goal or to switch to an alternative goal. This function would be undermined if subjective effort were affected by the presence of alternative goals. Note that this conceptualization of subjective effort does not imply that it is a veridical reflection of the actual costs and resources a goal requires. A person might very well underestimate goal requirements and/or available resources, which might then lead to such phenomena as the planning fallacy (Buehler et al. 1994).

Important in the current context, however, is that our conceptualization of subjective effort should be unaffected by the presence of competing outcomes. Rather than being an output of computations that consider (potential) costs and benefits of the current and the competing goal, effort enters these computations as a subjective representation of the costs of the current goal. As proposed by Kurzban et al., experiments that assess and compare perceived mental effort under different concurrent task conditions are needed to compare both accounts.

Persisting through subjective effort: A key role for the anterior cingulate cortex?

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Abstract: One shortcoming of Kurzban et al.'s model is that it is not clear how animals persist through subjectively effortful tasks, particularly over a long time course. We suggest that the anterior cingulate cortex plays a critical role by encoding the utility of an action, and signalling where efforts should be best directed based on previous and prospected experience.

Kurzban et al.'s model aligns well with emerging metacognitive proposals of fatigue and effort, and provides a useful account of why task switching occurs. However, under many circumstances individuals continue to persist in a primary task where the immediate costs are considerable and where alternative options present significant benefits. As an example, in academia the tangible rewards of funding, publication, and tenure are far removed from the months of executive-function–demanding writing, research, and teaching required to reach these goals. The level of persistence needed in such scenarios is not well accounted for in the proposed model, which predicts that the large opportunity costs associated with long-term goals should prompt a high mental-effort signal and subsequent re-prioritization of behavior. So how do we sometimes "stay the course" in the face of subjective effort?

Several potential mechanisms could be involved in persistence. While the fatigue signal could be directly attenuated, say, by reward receipt, other mechanisms could operate upstream of this point. For example, the discounting of the primary goal that normally occurs under conditions of temporal distance, uncertainty, or exertion, could be attenuated during the cost/benefit evaluation. Alternatively, the degree of discounting of competing tasks could be increased. Kurzban et al. suggest that the key to task persistence involves attenuating the effort signal through reward, although they are not specific about the underlying brain mechanisms. Here we propose that activity in the anterior cingulate cortex (ACC) is critical, functioning to integrate cost/benefit ratios to provide a relative utility signal that may work directly to suppress subjective effort.

As the target article notes, as ACC activity decreases, so does task performance. One interpretation of this effect is that as long as activity in this region of the prefrontal cortex (PFC) remains high, vigilance and persistence are maintained. We and others have examined single-unit ACC activity during decision tasks and found that heightened firing appears to indicate a worthwhile course of action; however, a sufficiently strong signal may be required to drive pursuit and persistence (Amiez et al. 2005; Hillman & Bilkey 2010; Quilodran et al. 2008; Sallet et al. 2007; Shidara & Richmond 2002). Importantly, this ACC signal appears only when significant cost/benefit analysis is required; furthermore, heightened firing does not always correspond to the most costly action, but rather seems to indicate the most worthwhile choice in terms of relative cost/benefit computed utility (Hillman & Bilkey 2010; Kennerley et al. 2006; Rudebeck et al. 2008). Moreover, the ACC is recruited regardless of the actual type of effort involved – be it physical exertion, competitive fighting, or mental taxation – suggesting that the region may be responding to generalized opportunity cost calculations inherent in cost/benefit decision tasks.

These encoding characteristics of ACC match the descriptions of several of the opportunity cost model components illustrated in Figure 1 of the target article: The ACC's experience-based encoding of cost/benefit computations provides an output signal that drives allocation of cognitive processes towards completion of tasks with optimal utility. Viewing the ACC in this way – as a dynamic utility encoder versus a cost encoder – represents a minor but important shift in thinking, one that could account for the persistence signal missing from the current model. Strong ACC signals could drive task persistence; however, as the ACC output signal wavers ("utility decreasing"), the phenomenology of effort begins, leading to reductions in persistence. Hence, the subjective experience of effort is, we propose, neither the result of the initial ACC recruitment nor the result of low levels of ACC activity, but rather, it results from a *decrement* in ACC activity from some prior, higher level. When tasks require cost/benefit computations, the ACC is recruited but subjective effort is usually not immediately reported. As a course of action is pursued, the expectation of high or imminent reward – which behaviorally serves to promote motivation and task engagement – also keeps ACC activity high (Croxson et al. 2009; Shidara & Richmond 2002). However, if rewards are not anticipated (e.g., in randomized tasks or repetitive practice conditions), then ACC activity decreases (Raichle et al. 1994; Shidara & Richmond 2002), cingulate motor area activity increases (Shima & Tanji 1998) and task switching is likely to occur in response to the subjective effort experienced.

In our adaptation of the model, maintaining ACC activity at a high level is the key to persisting. We know that extrinsic incentives help ameliorate decrements in ACC activity over time; however, frequent tangible rewards are not always present in day-to-day life. What other mechanisms might work to maintain heightened ACC activity? We propose that experience also modifies ACC functionality over time such that in future tasks, higher ACC activity (and subsequent lateral PFC engagement) can be sustained in the absence of immediate rewards. This might be due to one of the mechanisms mentioned earlier – for example, reduced discounting of potential rewards available through the primary task or increased discounting of rewards associated with alternative actions – and ties into the learning process highlighted in the target article (sect. 3.3, para. 9). As one example of how this might occur, recent work has shown that individuals who are better able to visualize the future rewarded outcome of a choice tend to pursue long-term, over short-term, goals (Berns et al. 2007; Boyer 2008). Thus, the discounting of reward value that normally occurs for temporally distant rewards is attenuated. Interestingly, scanning data indicate that that when this effect occurs, the hippocampus and PFC, including the ACC, co-activate in a coordinated manner (Benoit et al. 2011; Peters & Buchel 2010). The exact nature of any communication that occurs between these regions is unclear, but it is possible that "future thinking" mediated through the hippocampus has a critical role. Future studies will help determine exactly how such systems enable us to persist in the face of subjective effort, further clarifying the neurophysiological framework that underlies the opportunity cost model.

On treating effort as a dynamically varying cost input

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Abstract: Kurzban et al.'s framework may be extended in fruitful ways by treating effort also as a cost input that affects the utility computation of a given option (rather than only as the output of a utility comparison between options). The weight people assign to effort as a cost may vary dynamically as a function of situational and dispositional factors.

The target article by Kurzban and colleagues is an intriguing and impressive attempt to integrate vast amounts of the cognitive, self-control, and neuroscience literature into an opportunity cost model of subjective effort. Here, we would like to propose that the explanatory power of the opportunity cost model could be further increased in two interrelated ways. First, rather than treating subjective mental effort solely as the *output* of a relative utility comparison among possible activities as proposed by Kurzban et al., subjective task effort may also enter as a cost *input* into the cost/benefit analysis that underlies the utility calculation of each activity involved. Second, and building on the first extension, the model might benefit from an inclusion of the idea that the judgment *weights* assigned to task effort as a cost may vary dynamically as a function of (a) temporary state reductions in executive functioning due to prolonged use of these capacities, (b) dispositional differences in executive functioning and related traits, and (c) meta-level theories about mental effort (e.g., theories of willpower).

In its current version, the model may have difficulties dealing with the following problems: First, because effort is treated as the result of a relative utility comparison of opportunity costs, people should go on almost infinitely (experiencing virtually no effort) pursuing a cognitively demanding option A when the value of this option is very high and no alternative option B comes close in utility. We argue, instead, that people may not only compare salient alternatives against each other in relative terms; rather, the net utility of each option, by itself, may already be the outcome of a benefit/cost consideration, with effort expenditure factoring in as a cost (see Table 1). We further assume that options with negative net utility are typically not enacted. The more demanding a given option – based on the relation between cognitive demand of the task and skill/cognitive executive capacity – the higher its perceived costs (in terms of task effort) and therefore the lower its net utility.

Most important, assuming that certain executive functions cannot be exerted infinitely without a state reduction in executive capacity and that people are motivated to monitor and conserve capacity (Muraven & Slessareva 2003), the *weight* (i.e., importance) assigned to task effort as a cost entering the utility computation may increase up to the point where the net utility of performing the task becomes negative (see Table 1, Case B). Such an extended version of the computational model would predict that people may value a given effortful activity more or less depending on the degree to which they perceive resource scarcity, even when all available alternatives are kept constant. In other words, it would account for why people may stop or choose to not engage in a demanding activity such as doing math problems in the absence of large opportunity costs associated with salient attractive alternatives. The current model tries to solve this problem by suggesting that there are more attractive alternatives (e.g., "daydreaming") that are seen as opportunity costs in relation to the present activity, thus producing subjective feelings of effort that lead to disengagement from the present activity. A version that treats effort as a cost parameter with a dynamically varying judgment weight does not necessarily have to invoke such an alternative, because the cost-benefit ratio for the task itself may become negative (see Table 1, Case B).

The present model may also have difficulties explaining why people, in their daily lives or in lab studies, may deliberately choose alternative options at times that help to restore cognitive capacity, such as "taking a break" before returning to the focal activity at hand. In the current formulation of the model, such self-imposed periods of rest would constitute an irrational waste of processing time. We argue, instead, that, as state executive capacity is decreased over prolonged periods of task engagement, the weight assigned to effort as a cost increases. This change in the importance of effort dynamically influences the utility calculation process in a way such that the net utility of effortful activities decreases, whereas the net utility of activities instrumental for restoring capacity increases. By treating effort solely as the outcome of a relative utility comparison (rather than also as a possible input that affects computed utilities), Kurzban et al.'s model may have difficulties explaining why people would ever want to engage in an activity that has the sole purpose of restoring attentional and other capacities. For instance, drivers covering long distances should never feel motivated to take a break.

We believe that additional findings in the self-control literature can be explained (and that further predictions can be made) by considering the idea that the judgment weights assigned to

Table 1 (Hofmann & Kotabe). *Illustration of task effort as a cost input variable**

	Benefits (+) / Costs (−)	Judgment Weights (importance)
Case A: Conditions of resource plentifulness (e.g., no prior engagement in effortful activity; high dispositional executive functioning; belief in unlimited willpower)		
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)		
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.

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; Hyafil 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 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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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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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

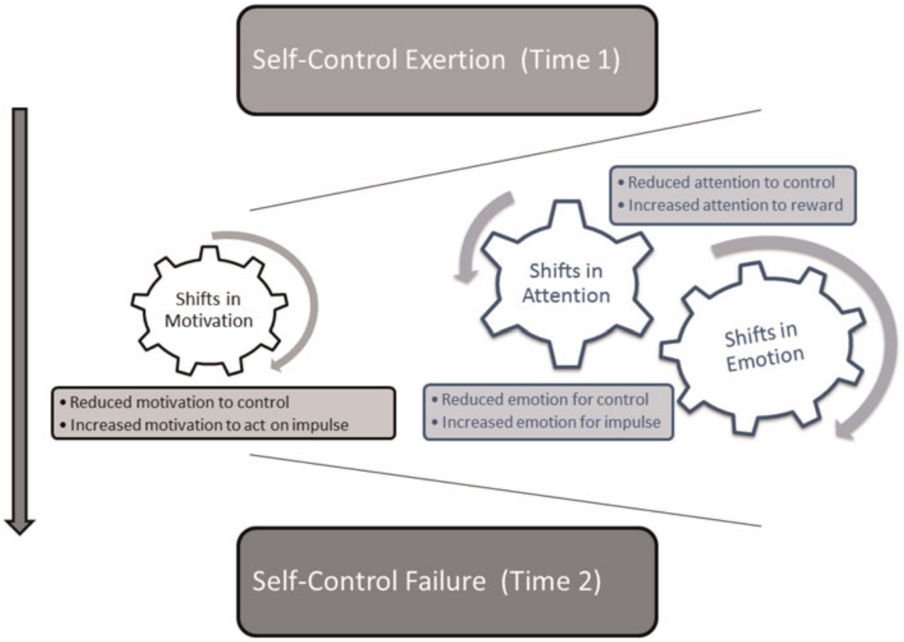

Figure 1 (Inzlicht & Schmeichel). The process model of self-control fatigue. Self-control failure tends to occur after initial self-control exertions because of shifts in motivation away from control and toward impulses and gratification. This shift in motivation consists of shifts in attention and shifts in emotional responding.

overrides the impulse. In this view, self-control fails after initial task exertions when impulses are relatively strong, when control is relatively weak, or through some combination of both of these factors. According to our process model (Fig. 1), self-control at Time 1 leads to shifts in motivation away from restraint and toward gratification, such that people become less motivated to control themselves and more motivated to self-gratify at Time 2. As part of this motivational shift, people pay less attention to self-control cues and more attention to reward cues. We also suspect as part of this motivational shift that people become less aroused by the prospect of goal failure or success and more aroused by the prospect of reward and immediate gratification.

Our model is still preliminary, but it can accommodate data that give the resource model fits (e.g., Job et al. 2010; Muraven & Slessareva 2003); it can also accommodate data that are left unexplained by the current opportunity cost model (e.g., Schmeichel et al. 2010). Whereas Kurzban et al.'s model is vague about how the calculation of utility changes over time, our model better specifies directions in the dynamics of "processing allocations," by suggesting that it moves toward reward/gratification and away from conflict and further control. Most important, our model makes novel and testable predictions that run counter to the current model. Our model predicts, for example, that self-control at Time 2 can be maintained when people are given veridical negative feedback on their performance; it also predicts that increases in emotional acuity will increase, not decrease, control at Time 2.

More generally, we worry that the opportunity cost model makes a fundamental error: It assumes that people calculate costs and benefits in an objective, dispassionate manner. This hyper-rational view discounts seminal work in psychology on the follies of human decision-making (Kahneman & Tversky 1979) and modern economic takes on utility theory that allow for non-rational, hyperbolic discounting of the future (Ainslie 1991).

We admire the authors' ultimate explanation for self-control fatigue, but we find that their proximate explanation falls short of accounting for observed patterns of data and is based on an outdated view of human rationality.

Opportunity prioritization, biofunctional simultaneity, and psychological mutual exclusion

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Abstract: We argue that prioritization, simultaneity, and mutual exclusion are mind-body integration functions that can't be addressed meaningfully at the psychological (computational) level alone. We describe the outlook for an integration between Kurzban et al.'s profound discussion of opportunity cost/benefit prioritization and decades of related development in biofunctional science.

The central argument of this target article – that *opportunity cost/benefit prioritization* (OC/BP) is why human behavior consumes mental effort – is supported by two compelling themes. One is intuitive, has to do with the phenomenology of mental effort, and enables reflective psychological engagement/disengagement. The other is utilitarian and pertains to the idea that "phenomenological experiences are reasonably easy to understand from a [bio]functional perspective" (sect. 5, para. 1; cf. Iran-Nejad et al. 1984). Kurzban et al. use these and related ideas skillfully to dislodge the standard resource theory of human endeavor in favor of their promising OC/BP alternative, a feat long overdue. In this commentary, we assume that the computation metaphor, if used for other than a mathematical tool of science, is an Achilles heel; it confines the OC/BP theory to the psychological level; and the theory can survive without it. The purpose of this commentary is to show how OC/BP theory relates to the biofunctional theory of human understanding, including consideration given to the role of biological and computational metaphors in prioritizing opportunities, simultaneity, and mutual exclusion as used in the target article.

The assumption in the target article that cognition is, by nature, computational, adds distance between biology and psychology, in general, and OC/BP and biofunctional theories, specifically (Satyadas et al. 1993). Without this assumption, the two realms of study have much in common. The trolley dilemmas used in moral research offer an illustration (Greene & Haidt 2002). In one scenario, participants face the dilemma of either letting a stampeding trolley, about to kill five people on its tracks, roll on, or hitting a re-route switch to send the trolley to a set of side tracks, killing one person instead. In agreement with a computational perspective, most participants are okay with solving the OC/BP dilemma by hitting the switch to save the five and kill only the one (5−1=4). Consider, however, a closely-related variation where no side tracks exist: instead, there happens to be a fat person standing by the tracks. The participant can choose to push and let the trolley run over this person, crushing the unfortunate soul, but, thereby, stopping the trolley and saving the five. Most participants say no to this option. Cognition-as-computation theories leave us in a quandary with the second scenario. Biofunctional science implies that two different kinds of human understanding – biofunctional and psychological (Iran-Nejad & Bordbar 2013) – interact in a body-mind cycle of adaptation-reflection to explain both scenarios without resorting to the metaphor of cognition as computation (Iran-Nejad 2012; Iran-Nejad & Gregg 2001), even though there is no argument that computation is an indispensable tool of science.

It is common practice in science to use metaphor; and OC/BP and biofunctional theories rely on computational and biological metaphors, respectively. The computational metaphor builds on the foundation of cognition as computational knowledge (software) – and implies that the minds of organisms contain mathematically exact counters that prioritize, literally speaking, by computing rates of cost/benefit returns. Biofunctional metaphors suggest that OC/BP theory can be understood without risking the reification fallacy inherent in the computational metaphor. Instead, biofunctional science embraces almost literally true biological metaphors, thereby supporting the cycle of mind-body interaction between the complementary types of biofunctional and psychological understanding (Iran-Nejad & Bordbar 2013). Like in computational theory, in biofunctional science psychological understanding is knowledge-driven, albeit by the fundamentally different kind of non-computational (or intuitive) knowledge. Unlike computational theory, biofunctional science is, first and foremost, based on the foundation of biofunctional understanding. If so, OC/BP theorizing can benefit by disavowing the Achilles heel of computationalism and embracing the more natural ground of biofunctional science. Human understanding is, by evolutionary design, the special *biological* function of the nervous system, both literally and metaphorically (Iran-Nejad & Gregg 2011; Iran-Nejad & Ortony 1984) – just as breathing is the special function of the respiratory system, and fighting germs is the special function of the immune system.

As is, the OC/BP theory strives to solve the problem of simultaneity at the psychological level. Additionally, claims to the contrary notwithstanding, genuine simultaneity is an anomaly in computationalism, at least as we understand it today (Iran-Nejad 1989). In biofunctional science, simultaneity is a mutual-inclusion function of *ongoing biofunctional activity* (OBA) in the nervous and bodily systems (Iran-Nejad & Gregg 2011). The need for prioritization arises when the same systems must engage in *momentary constellation firing* (MCF) to perform multiple mutually exclusive tasks (Iran-Nejad et al. 1992). For example, a smile and a frown are mutually exclusive behaviors, to the extent that the same lips, eyebrows, muscles, and the like, must be engaged in performing each of them (Diener & Iran-Nejad 1986). Similarly, as the target article illustrates, "foveating one part of the world necessarily precludes foveating other parts of the visual scene" (sect. 2.3, para. 2). Thus, it is in the realm of psychological or behavioral mutual exclusion that the OC/BP and biofunctional theories unite. They part ways in the realm of biology.

In biofunctional science, some of the key ideas of the OC/BP theory apply with renewed vigor. For example, the target article states that prioritization is the general solution to the problem of simultaneity. However, if prioritization means mutual exclusion, what is simultaneity? In biofunctional science, the answer is clear: Prioritization is psychological (i.e., mental or behavioral) mutual *exclusion* and simultaneity is biofunctional mutual *inclusion*. This enables a restatement of the foregoing claim in the target article, to saying that prioritization is evolution's psychological, as opposed to general, solution to the problem of biofunctional simultaneity (Iran-Nejad & Bordbar 2013). Specifically, simultaneity in biofunctional science is auto-regulated (or effortless) mutual inclusion in ongoing biofunctional activity in the nervous and bodily systems, and priority is (effortful) mutual exclusion caused by momentary constellation firing in the neurons of the nervous system. Moreover, OBA and MCF work together complementarily in the body-mind cycle of adaptation/reflection (Iran-Nejad 2000; Iran-Nejad & Gregg 2001; 2011; Prawat 2000). The mutual inclusion/exclusion theory started as an explanation for the quantitative and qualitative shifts in simultaneity and separation between affective valences when understanding surprise-ending stories, and soon became one of the leading theories in affective science (Brehm & Miron 2007; Diener & Iran-Nejad 1986; Iran-Nejad 1980; 1989; Iran-Nejad et al. 1984; Iran-Nejad & Ortony 1984; 1985; Schimmack 2001).

The intrinsic cost of cognitive control

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Abstract: Kurzban and colleagues carry forward an important contemporary movement in cognitive control research, tending away from resource-based models and toward a framework focusing on motivation or value. However, their specific proposal, centering on opportunity costs, appears problematic. We favor a simpler view, according to which the exertion of cognitive control carries intrinsic subjective costs.

Research on the dynamics of cognitive effort have been dominated, over recent decades, by accounts centering on the notion of a limited and depletable "resource" (Baumeister et al. 1998; Baumeister et al. 2007). Quite recently, however, a trend has emerged, away from resource-based theories and toward accounts centering instead on motivation or value (Hagger et al. 2010a; Inzlicht & Schmeichel 2012; Job et al. 2010). To paraphrase recent work by Inzlicht and Schmeichel (2012), the question of interest has begun to shift from whether an individual is *capable* of exerting cognitive effort to whether the individual will *choose* to do so.

The target article by Kurzban et al. contributes robustly to this motivational turn. To start, the article offers a penetrating and authoritative critique of the resource model, convincingly asserting both its theoretical and empirical liabilities, and clearing the way for a fresh value-based perspective. Of course, to be satisfying, such a perspective must be specific, indicating precisely how value or motivation constrains cognitive effort. Kurzban and colleagues come through on this front as well, offering a formally explicit, testable theory, framed in terms that place it in continuity with a wealth of recent work on value-based decision making.

We agree with Kurzban et al. that it may be fruitful to view cognitive effort as carrying subjective costs. Having said this, however, we also see at least two problems with the specific proposal the authors put forward, which identifies the costs involved with *opportunity* costs.

The first problem involves the question of sufficiency: One can think of many situations that feature salient opportunity costs, but that seem unlikely to involve any sense of subjective effort. Imagine, for example, sitting in a restaurant with a friend who is enjoying a dish you wish you had ordered. This scenario involves an awareness of opportunity costs, and perhaps an experience of regret, but no obvious role for effort.

A second problem arises from the theory's explanation for so-called resource-depletion effects: the finding that voluntary effort exertion is diminished following bouts of obligatory exertion. According to the opportunity cost model, such declines occur because, over time, the expected utilities of alternative mental activities rise through learning, ultimately triggering a shift in focus. This account relies on the unfounded assumption that initial value estimates for alternative activities will generally display a negative bias, and implausibly predicts that depletion effects should be isolated to novel task circumstances.

In contrast to the opportunity cost model, we favor a simpler hypothesis: Subjective effort reflects an *intrinsic* cost attaching directly to the exertion of cognitive control.

The idea that cognitive control carries inherent disutility has arisen as a background assumption in numerous literatures over the years. In recent work, we have been able to undergird this idea with some direct empirical support. Using a variety of choice tasks, we have provided evidence that, when all else is held equal, decision-making displays an avoidance of cognitive control demands, and that people will avoid such demands even at the price of delaying the accomplishment of task goals (Kool et al. 2010). Using functional magnetic resonance imaging (fMRI) we have shown that neural responses to monetary rewards are reduced when such rewards are framed as payment for a cognitively demanding task, consistent with the view that cognitive demand registers as costly (Botvinick et al. 2009). Further fMRI results show that task-induced activity in cortical regions associated with cognitive control predicts later avoidance of the same task (McGuire & Botvinick 2010).

In very recent work, we have provided behavioral evidence that the cost of control is context sensitive: The more control is exercised, the more costly it becomes (Kool & Botvinick, in press). Rather than arising from resource depletion or fatigue, the data suggest that this effect arises from a set of preferences that favor a balance, over time, between cognitive exertion and cognitive disengagement or rest, an idea that originates in labor economics and which has been fruitfully applied to physical effort.

A view of effort based on the intrinsic cost of cognitive control appears to avoid some of the difficulties of the opportunity cost model. The restaurant scenario introduced above is no longer problematic, since it features no demand for cognitive control, and therefore predicts no sense of effort. (However, effort may arise when the dessert menu arrives, as recent findings suggest that the intrinsic cost of control extends to the exertion of self-control; Kool et al. 2013.) The intrinsic-cost perspective also fares better with depletion effects, as the context-sensitivity of control costs predicts that the sustained exertion of control will trigger eventual cost-driven disengagement, even in contexts involving no learning (see Kool & Botvinick, in press).

It is worth noting that the predictions of the intrinsic-cost approach may, in certain cases, mimic those of the opportunity cost model. In particular, the availability of appealing alternative activities may increase demands for cognitive control, in order to maintain focus on the central task. In such situations, effort could be defensibly attributed either to intrinsic control costs or to the registration of opportunity costs. Such considerations indicate that some care will be necessary in designing experiments to test between the relevant theories. However, whatever the empirical challenges, it is encouraging to see specific competing motivational accounts for cognitive effort now emerging.

Beyond dopamine: The noradrenergic system and mental effort

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Abstract: An opportunity cost model of effort requires flexible integration of valuation and self-control systems. Reciprocal connections between these networks and brainstem neuromodulatory systems are likely to provide the signals that affect subsequent persistence or failure when faced with effort challenges. The interaction of these systems should be taken into account to strengthen a normative neural model of effort.

Understanding how individuals respond to mental challenges and why mental effort evokes fatigue and aversion remains a challenge for cognitive science. In the 1960s, attentional resource theories were proposed to account for dual-task interference and linked resources to physiology through the use of measures such as pupillometry (Kahneman & Beatty 1966). These theories fell into disfavor in the 1980s when recognized as largely circular and unable to provide testable hypotheses (Navon 1984). Although resource theories continued to play a role in applied psychology (e.g., Wickens 1984), cognitive researchers focused on structural explanations for dual-task interference (e.g., Pashler 1994) and largely ignored the subjective aspects of mental effort. At the same time, social psychologists began to develop resource theories to describe "ego depletion" effects on self-control, which ultimately led to the notion that glucose serves as a physical resource for mental effort (Baumeister et al. 1998). However, the physical-resource theory has also turned out to be problematic (Kurzban 2010a).

Kurzban et al.'s account of subjective effort as an adaptive signal of the opportunity cost of using limited executive control mechanisms offers a new way forward for understanding the psychological and neural mechanisms underlying mental effort. Importantly, the framework proposed in their account does not require depletion of a single resource (physical or attentional) to explain performance declines and subjective effort. The conflicting evidence for a single physical resource, most notably glucose, and consistent neurophysiological evidence for estimation of value and cost in prefrontal networks makes an opportunity cost model of effort particularly compelling. A critical challenge for this account of effort is to formally express how signals for value and cost interact, particularly in choosing to adaptively persist or withdraw effortful behavior. While Kurzban et al. focus on the role of dopamine, we propose that a successful normative account of effort persistence and aversion will require consideration of other brainstem neurotransmitter systems.

Recent proposals of the function of brainstem neurotransmitter systems advocate for their role in signaling useful decision variables. Leading examples include Niv's (2007) proposal that tonic dopamine in the striatum signals average reward rate and Yu and Dayan's (2005) proposal that norepinephrine and acetylcholine signal different estimates of uncertainty. Behavioral and neural evidence supports the ability of interconnected brainstem nuclei and executive structures to influence decision-making processes (Aston-Jones & Cohen 2005; Kurniawan et al. 2011). In particular, the pattern of activity and connections of the locus coeruleus-norepinephrine (LC-NE) system suggests a causal role in effortful behavior (Aston-Jones & Cohen 2005).

An organism that utilizes an opportunity cost model of effort expenditure requires the ability to rapidly adjust task engagement in response to information from the environment and internal homeostasis monitors. The locus coeruleus (LC) receives input from the anterior cingulate cortex and orbital frontal cortex, structures implicated in the evaluation of cost/benefit trade-offs and valuation, as well as arousal-related inputs from the autonomic nervous system (Aston-Jones & Cohen 2005). Additionally, human and animal studies demonstrate that prefrontal networks are sensitive to norepinephrine concentration (Robbins & Arnsten 2009), with optimal levels necessary for successful task performance. This literature advocates for continuous feedback between the LC and cortical structures estimating the utility of maintaining the current effort-allocation policy. Critically, top-down cortical signals and peripheral autonomic input may shift the activity of the LC-NE system in a temporally relevant manner (Aston-Jones & Cohen 2005). For example, projections from the anterior cingulate cortex may shift the firing rate of the noradrenergic neuron population, in turn altering the level of norepinephrine in the cortex, which decreases stability of the current effort policy and promotes disengagement and selection of a new action plan (Aston-Jones & Cohen 2005; Sara & Bouret 2012).

A system that adaptively shifts among action contingencies, as proposed in prominent theories of LC-NE system function, is central to an opportunity cost model of effort. Theories of LC-NE function broadly conceptualize its activity as shifting the balance of exploratory versus exploitative behavior or mediating a global signal to reset brain networks involved in action selection (Aston-Jones & Cohen; Sara & Bouret 2012). Examining LC-NE system activity in humans is difficult, due to the small size of the nucleus, its brainstem location and the feasibility of assessing cortical levels of norepinephrine in vivo. However, several functional neuroimaging studies have described patterns of activity in LC. An early study described patterns of activation in a putative LC region and right lateralized prefrontal regions that appear to respond parametrically to task difficulty (Raizada & Poldrack, 2007). Although consistent with a connection between LC and lateral prefrontal self-control networks, the study lacked the spatial specificity necessary to attribute a specific role to the LC. A subsequent study claimed to pharmacologically modulate LC activity (Minzenberg et al. 2008) but faced similar scrutiny about the precision of LC localization (Astafiev et al. 2010). Recently, a group applied improved brainstem spatial alignment to conclude that activity in LC correlates with unexpected uncertainty in a decision-making task (Payzan-LeNestour et al. 2013), consistent with a theoretical model (Yu & Dayan 2005).

Assessing the LC-NE system in humans remains a challenge, but recent studies point to a possible alternative solution. Several groups have demonstrated the utility of peripheral neurophysiological measurements, notably changes in pupil diameter, as an index of LC-NE system activity. As classically described by Kahneman (1973) and revived by Jepma and Nieuwenhuis (2011), Nassar et al. (2012), Eldar et al. (2013) and others, changes in pupil size appear linked to the noradrenergic arousal system and related to decision variables such as novelty and uncertainty that are useful for a system estimating opportunity costs to control effort-allocation policy. As Kurzban and colleagues note, a normative account of effort will benefit from unification of executive and self-control literature. We propose that validation of peripheral measurements of LC-NE activity and their integration with effortful tasks constitutes a worthwhile approach to test Kurzban et al.'s opportunity cost model. Evaluation of LC-NE activity in effort contingency, trade-off, and performance tasks will provide key evidence to support or refute particular mechanisms by which valuation and control systems interact to shift behavior in accordance with an opportunity cost model. Together with parallel investigations of other neuromodulatory systems, this work will provide the quantitative framework that a normative model of effort requires.

An expanded perspective on the role of effort phenomenology in motivation and performance

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Abstract: Kurzban and colleagues propose that experiences of effort alter motivations to persist during goal pursuit by highlighting costs of persistence. I expand this proposal by discussing how effort experiences (a) not only influence, but can be influenced by motivations to persist on a goal; and (b) not only highlight costs that undermine persistence, but can also signal progress and increase persistence.

Declines in effort and performance following sustained goal pursuit are frequently explained in terms of people's limited resources for engaging in self-regulation (Muraven & Baumeister 2000). Although many findings support such limited-resource explanations (see Hagger et al. 2010a), emerging evidence has produced a growing consensus that changes in people's motivation, rather than their capacity for self-regulation, may be responsible for decreases in performance over time (Beedie & Lane 2012; Inzlicht & Schmeichel 2012; Molden et al. 2012). The target article by Kurzban and colleagues not only adds to this consensus, but also provides a more detailed account of how such changes in motivation and performance arise.

Perhaps the most novel and intriguing aspects of Kurzban et al.'s account of self-regulation is the proposed role of people's experiences of effort and fatigue on their motivations to persist with a current task or goal. In this account, such experiences alter the perceived opportunity costs involved in maintaining this goal versus pursuing an alternative goal, and thus shift motivations away from the present task and toward different endeavors. This opportunity cost mechanism helps to explain and integrate many findings from a variety of literatures. However, the phenomenology of effort is also connected to additional motivational processes that influence self-regulation and performance. Below, I review research that illustrates these additional processes and extends Kurzban et al.'s motivational analysis.

Determining the perceived costs and benefits of particular outcomes is certainly one of the primary routes through which motivations affect goal pursuit and performance (see Molden & Higgins 2012). However, another influence of motivation on goal pursuit is how it alters the experiences people have during this pursuit (Higgins 2006). That is, many motivational interventions that boost performance do not merely influence evaluations of the costs and benefits of different goals or outcomes, but instead change people's experiences of effort and engagement while pursuing these outcomes.

For example, much research has shown that goals involving feelings of autonomy and self-direction, rather than feelings of control and coercion, create greater engagement and enjoyment (Deci & Ryan 2000). Consistent with these general findings, people who perceive that they have autonomously chosen to perform vigilance-related self-control tasks (e.g., monitoring for the appearance of a particular stimulus) experience less fatigue and more energy, which then increases how long they can successfully perform these tasks (Muraven et al. 2008; see also Moller et al. 2006; Muraven 2008). Moreover, additional research has shown that when the strategies people employ during goal pursuit are motivationally compatible with their broader self-regulatory preferences, this creates experiences of *regulatory fit* (Higgins 2008). Such fit also increases engagement in and enjoyment of goal pursuit, which subsequently improves performance on self-control tasks involving vigilance (e.g., avoiding distraction) and resistance to tempting alternatives (e.g., choosing fruit over chocolate as a snack; Freitas et al. 2002; Hong & Lee 2008).

The effects on self-regulation of experiences of engagement arising from autonomy or regulatory fit are broadly consistent with the central role that Kurzban and colleagues give to feelings of effort and fatigue in goal pursuit. However, these findings also demonstrate that, just as experiences of effort can affect motivations to sustain performance on current goals, so, too, can the broader motivational context in which a goal is pursued affect performance by influencing experiences of effort.

Beyond directly altering experiences of effort during goal pursuit, various motivational processes can also affect self-regulation and performance by influencing how people interpret these experiences (see Molden & Dweck 2006). That is, although people may often attribute feelings of effort and fatigue to diminishing returns for the continued pursuit of a current goal, and thus shift attention to other alternatives, research has also shown that other attributions for these feelings with different implications for self-regulation and performance are possible. Indeed, some studies have even shown that, in particular contexts, experiences of effort are interpreted as signs of progress and sustain goal pursuit.

One clear demonstration of how varying interpretations of effort experiences can dramatically influence the effect these experiences have on subsequent self-regulation and performance was provided by Clarkson et al. (2010). When people were led to attribute feelings of effort to a superficial source unrelated to the pursuit of their primary goal (e.g., the color of the paper on which their task instructions were printed), they no longer showed subsequent declines in persistence or performance. Furthermore, when they view effort as an instrumental part of achieving their desired goals, people then interpret experiences of effort as signaling progress toward goal completion, and these experiences help sustain rather than undermine self-regulation and performance (Labroo & Kim 2009; Miele et al. 2011; Miele & Molden 2010). Thus, instead of highlighting growing opportunity costs, effort experiences can also at times indicate that continued goal pursuit is likely to yield benefits.

The effects on self-regulation of attributions for effort experiences are also broadly consistent with the important role that Kurzban and colleagues give to effort phenomenology in explaining the maintenance of or disengagement from goal pursuit. However, these findings also demonstrate that effects of such phenomenology are not limited to static considerations of opportunity costs but are instead altered by people's dynamic interpretations of their experiences of effort, engagement, or fatigue during self-regulation.

To summarize, Kurzban et al. have made a substantial contribution to the literature on self-regulation and performance with their analysis of how people's experiences of effort during goal pursuit affect their likelihood of sustaining this pursuit. Here, I expand this contribution by noting that: (1) Experiences of effort are not simply determined by bottom-up evaluations of goal progress, but can also be influenced by top-down orientations that determine the broader motivational context within which the goal is pursued. (2) Effort experiences can afford many other attributions beyond the rising opportunity costs associated with continued pursuit of the same goal, and, within mindsets where effort is directly linked to progress, such experiences can even increase goal commitment. These expansions broaden the scope of the model proposed by Kurzban et al. and make it applicable to an even wider range of phenomena.

Willpower is not synonymous with "executive function"

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Abstract: Kurzban et al. make a convincing case against the idea that willpower is a depleting resource. However, they do not advance a positive account of willpower. Rather than treating "willpower" as a synonym of "executive function," we argue that the term *willpower* should be designated for mechanisms individuals deploy to reduce dynamic inconsistency in their behavior.

The typical effect-size of depletion experiments (~d = .6; Hagger et al. 2010a) is not the right order of magnitude to go with the idea that there is a literal store of willpower that is being "used up." Nor is the fact that post-depletion, self-control can be restored by receipt of a gift, or by a self-affirmation (Schmeichel & Vohs 2009). Compare self-control depletion effects with the actual muscle fatigue from repeatedly lifting a heavy weight – here total muscle failure can easily and reliably be produced, and any effect of self-affirmation is likely to be modest. Although it remains to be seen whether Kurzban et al.'s model has it just right, it is on its face a more plausible account.

However, we think neither Baumeister et al. (2008) nor Kurzban and colleagues characterize *willpower* usefully (although in fairness, only Baumeister and colleagues seem to want to use this term). The phenomenon that both deal with is variously referred to as "executive function," "conscious processing," and as the output of "System 2" (Baumeister et al. 2008). The incongruent condition of the Stroop fits well, and is a standard depletion paradigm. The task requires color naming, which competes with the automatic tendency to read lexical items. There is no question that the Stroop Task is an interesting example of an important category of mental functioning. But the term "willpower" has a more specific meaning – it is *not* a synonym for "executive function". In particular, we believe that the mechanisms of willpower are directed at reducing the otherwise marked tendency most people have to systematically change their preferences over time.

The case of addiction is illustrative. The criteria used in the United States for "substance dependence" and for "substance use disorder" include (paraphrasing from the *Diagnostic and Statistical Manual of Mental Disorders IV-R*) "failed attempts to quit or moderate use" and "repeated episodes in which the individual uses more than she originally planned." In everyday use of the terms, these central features of addiction are considered struggles of "willpower" and of "self-control."

What does the self-control struggle of the addict have in common with an executive function task such as the Stroop? This is a point of some disagreement, but we suspect that the answer is *not very much*. First, peak performance on executive control tasks is observed in early adulthood; performance declines dramatically with aging. If this type of functioning were synonymous with "willpower," one would have reason to expect addiction to be a rare problem among young adults, but to increase in prevalence as people age. But the opposite is observed, with prevalence highest in early adulthood, and with a large percentage of addicts "aging out" in mid to late life (Anglin et al. 1986). Second, there is a mismatch between the timescale of failures on the incongruent Stroop and the self-control failures of an addict. When a person makes a mistake on the Stroop, she is succumbing to a reflexive tendency to read lexical items. If she is given an opportunity to slow down, she will fix her error. By contrast, when the cocaine addict who has been clean for a month "falls off the wagon," she may have to go to some lengths to get cocaine. It is not a momentary "oops" that is reliably corrected if she is given a moment to collect her thoughts. Unlike the participant performing the Stroop, the individual looking for cocaine is engaged in sustained goal-directed action, and even complex problem solving.

Of course, the situation of the addict falling off the wagon is so interesting because it is goal-directed action she previously dismissed as undesirable, and which she likely will later regret. Indeed, she may even believe she will regret it, even as she currently devotes herself to obtaining the drug. And these are the critical features that define the domain of willpower/self-control struggle – they involve the recognition of systematic changes in preference over time, and responses to the anticipated inconsistency. The "resolutions" people make are central. The "resolution" is more than a plan; it anticipates a future in which some alternative to that current plan might be more attractive. Moreover, the resolution seems to preemptively apply some force to oppose the foreseen reversal. The nature of that force is not completely understood, but Ainslie (1975; 1992; 2001) productively suggested that when remembered, a past resolution makes the otherwise appealing plan – for example, to binge today but diet tomorrow – less plausible. I could say, "Just this last one, and then I will be good." But if I made a similar resolution yesterday, I have reason to believe I cannot both binge today and be confident my resolution about tomorrow will fare any better than yesterday's. In other words, an interest in a particular future behavior, and uncertainty that the interest will be realized, indirectly gives force to resolutions, since they cause current behavior to have added importance beyond what is literally at stake (Monterosso & Ainslie 1999).

This sort of internal dialog – the resolution, transgression, regret, and back around again to another resolution – is, we think, familiar to most people. To the extent that this process yields regularity in outcomes, the regularities diverge from the patterns highlighted in the will-as-muscle literature. Most notably, a single failure appears to often turn into a protracted run of failures (known as the "abstinence violation effect"; Shiffman et al. 1996). There is nothing within the depletion account that predicts this phenomenon, but it follows naturally as a collapse of confidence, if the force of a resolution rests in part on the belief that continued resolve is possible if the resolution is kept.

The willpower-as-muscle metaphor has brought attention within the behavioral sciences to willpower struggle. If Kurzban and colleagues are successful in casting doubt on the metaphor's usefulness, then it will be a good time to consider alternative positive accounts of willpower. Intrapersonal bargaining provides, we think, a promising framework.

Effort aversiveness may be functional, but does it reflect opportunity cost?

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Abstract: Though the aversiveness of effort may indeed serve in selecting tasks for executive attention, the notion that it reflects opportunity costs is questionable: The potency of distractions in real-life situations is not regularly related with the potential benefit from attending to them.

The argument from which Kurzban et al. set out in their theoretical discussion is that resource scarcity does not satisfactorily explain two well-known phenomena: (1) Performance of volitionally selected tasks often feels like it requires mental effort. (2) That feeling is aversive.

I concur. Subjective effort may have nothing to do with the amount of processing resources expended on an executed task (and it is, furthermore, yet unclear to what extent, if at all, variance in task performance is due to the amount of available resources, since it may as well be due to cross-talk or some other sort of outcome conflict; see Hirst & Kalmar 1987; Navon 1984; Navon & Miller 1987). In my view, effort is the typical corollary of attentional selection per se: "Effort is not any scarce commodity. It is the aversive valence of the operation of decoupling. The more sustained decoupling is, the more aversive it is" (Navon 1989, p. 203).

The term *decoupling* denotes an inhibitory operation (mediated by selectively attenuating some communication channels) meant for attaining effective attentional emphasis sufficient for withstanding distractions. That operation seems useful for actuating any task that is not habitual enough to benefit from being served by a dedicated, special-purpose communication channel, and hence must resort to gaining temporary high visibility, subjectively felt as awareness, within an internal communication network accessible by numerous processing modules (for more detail, cf. Navon 1989, pp. 200–201).

Furthermore, as stated in Navon (1989): "because effort is aversive, motivation is needed to override the aversion" (p. 203). Therefore, to the extent that aversion is functional, the function of aversion may be to set a high enough hurdle that would most often select for focal attention the best-fitting candidate – that task which the subject is at the time most motivated for. Tasks for which the subject is only mildly motivated are unlikely to be selected, as motivation in this case would often not outweigh effort aversion. Further on, a selected task whose momentary appeal has decreased with time may not be maintained in focal attention, or at least may be less immune to distraction, once the motivation does not suffice anymore to outweigh the aversiveness of effort.

Aversiveness is a particularly good guide, because it is a sort of sentience. Just like the effect of suffering muscle aches on the determination of a marathon runner to keep running must be greater than whatever effect the mere cognitive feedback about physiological measures could have, the felt aversion to keeping the execution of a mental assignment must predict persistence more than would a mental act of merely deliberating how the time could have been alternatively spent.

So far, I suppose, my stance does not appear significantly discordant with the thesis proposed in the target article. Yet, I do have some reservations about the notion that aversion is borne by computing opportunity costs.

Though people clearly prefer to engage in rewarding activities, it seems a bit hard to believe that our information-processing system as a rule manages to gauge and rank on-line, albeit implicitly, the costs/benefits of all alternatives (or even only the most salient ones) sufficiently for estimating opportunity costs. Is it a closed set at all? How large, for example, is the set of all alternatives for what I am doing right now to generate this written sentence?

Furthermore, some of the most powerful triggers of distraction, that naturally require much effort to withstand, are transient stimuli or associations that, in spite of their high capturing potential, would not much benefit a subject's functioning in the short run or well-being in the longer run. To illustrate, my concentration over conceiving and phrasing this sentence would clearly have been much harmed if a flying bird presently had found its way into my office, worse yet if some obsessive image or thought had popped up in my mind. I doubt that I would have been as much distracted by a potential reflection about the next-best objective that I could have otherwise engaged myself with. In passing, is it just incidental that I am now failing to find anything like that in my short term memory (STM)?

Hence, it seems debatable that effort aversiveness is nothing but the felt output of the computation of opportunity costs. Anyhow, that sort of aversion need not reflect opportunity cost to be functional. If its inherent function is to constitute a hurdle high enough for selecting the task that the subject is most motivated for (and later, for maintaining focused attention there), aversion could simply be the experienced output of the extent of decoupling required for doing that.

Finally, performance may deteriorate with time neither because processing resources deplete, as often believed (e.g., Gailliot & Baumeister 2007), nor because the priority of the attended-to task somewhat declines, as Kurzban et al. suggest. Possibly, the effectiveness of the inhibitory operation termed "decoupling" here, may tend to slowly decay for some reason.

Alternatively, the products of pre-attentive processing of unattended objects, perhaps occasionally exercising some failed attempts to invoke attention to themselves, pile up over time in some push-down stack which might bear a gradual increase of outcome conflict, in turn causing distractions to become progressively harder and harder to withstand. To date, there seems to be no sufficient evidence to substantiate any one of these conjectures.

The costs of giving up: Action versus inaction asymmetries in regret

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Abstract: Kurzban et al.'s opportunity cost model of mental effort relies heavily on counterfactual thinking. We suggest that a closer inspection of the role of counterfactual emotions, and particularly of action/inaction asymmetries in anticipated regret, may be important in understanding the role of opportunity costs in decisions to persist with a current task.

Kurzban et al.'s opportunity cost model of mental effort relies heavily on counterfactual thinking – that is, consideration of opportunities missed while the individual performs a task. Missed opportunities are commonly associated with aversive feelings of regret, induced by the knowledge that something might have been better had we chosen to act differently. Furthermore, when multiple possible alternatives are available to us and when we have control over our actions, the anticipation of possible future regret has a strong influence on our choice behaviour (Mellers et al. 1999). A regret-averse individual will select behaviours with the aim of minimizing future regret (Savage 1951). Such decisions include whether to persist with a current task, or to devote a portion of our computational resources towards alternative mental activities (such as daydreaming or future planning), or even to abandon the task altogether.

The magnitude of anticipated regret is commonly quantified as the difference between the received outcomes of our actual choice and the best possible outcome that might have been received from a different choice (Bell 1982; Loomes & Sugden 1982). This formalisation is also supported by the neuroimaging evidence that, in brain regions commonly associated with reward and decision-making, activity changes with the magnitude of this measure of regret (Coricelli et al. 2005; Nicolle et al. 2011a). Accordingly, the anticipated regret associated with performing a given a task can be computed as the expected reward of doing well in the task, minus the best possible reward that might be achieved from devoting some (or all) of our efforts towards an alternative task.

We suggest that Kurzban et al.'s model may be complicated by the commonly observed finding that regret is stronger when arising from decisions to act (or switch task) than from decisions to refrain from acting (or stick with a current task) (e.g., Kahneman & Tversky 1982). Proposed explanations for this action/inaction asymmetry in regret include suggestions that active decisions are perceived as more directly causal of their consequences, and that passive decisions are perceived as more easily justified than are active decisions. A learned action/inaction asymmetry in the anticipation of regret is also thought to promote a bias towards more passive decisions, such as decision delay, inaction, or sticking with the norm or status quo (e.g., Baron & Ritov 1994). In further support of this regret-induced status quo bias, neuroimaging data show that activity in the anterior insula (a region commonly involved in error processing and its impact on behaviour) is stronger for action regrets than for inaction regrets, and that this activity is associated with enhanced subsequent inaction bias (Nicolle et al. 2011b).

On the surface, this action/inaction asymmetry in regret appears to present a problem for Kurzban et al.'s opportunity cost model of mental effort. Their model presents the attractiveness of performing alternative tasks as critical to feelings of mental effort and as a key motivator for withdrawing processing capacity away from the current task. In stark contrast, action/inaction asymmetries in regret predict that anticipated regret is greater for switching away from the current task than for sticking with it, and that this would motivate persistence in the task (*if* the individual anticipates any regret associated with switching). If we consider a decision to switch computational resources towards an alternative task as an active process, and the decision to persist with the task at hand as a more passive process, then the former *should*, according to the above findings, be associated with higher anticipated regret. In other words, whereas missed opportunities may present a cost to the individual while performing a given task, decisions to give up and switch to an alternative task may result in greater, regret-based costs. A regret-induced status quo bias would then predict a reduced tendency to switch task.

Although these two costs (i.e., missed opportunities from alternative tasks and the anticipated regret of switching) might be predicted to motivate opposite behavioural tendencies, it seems likely that both types of costs enter into calculations of the benefits of persisting with a given task. The relative influence of each of these costs on our behaviour, however, may depend upon several factors. For example, the possibility for the individual to receive performance-related rewards in the current task may increase the anticipated regret associated with quitting the task, while opportunity costs (associated with the value of alternative tasks) would be unaffected. Therefore, if the individual is offered financial incentive for successfully completing the task, the anticipated regret of missing that reward would be a strong motivator, even if there is a possibility for greater reward from switching to an alternative task. Another important factor may be the individual's uncertainty about the likelihood of reward from the alternative tasks. If uncertainty is high, the anticipated regret of switching task may be enhanced compared to the relative safety of continuing. Finally, the role of anticipated regret in the decision likely depends upon the responsibility the individual has for the consequences of their actions (since personal responsibility is critical for the experience of regret).

In sum, we suggest that some consideration of regret (and particularly of action/inaction asymmetries in anticipated regret) may be necessary for development of an opportunity cost model of subjective mental effort.

Mental effort and fatigue as consequences of monotony

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Abstract: Kurzban et al. associate mental effort and fatigue with a hypothetical mechanism able to estimate the utilities of possible actions and then select the action with a maximal utility. However, this approach faces fundamental problems. In my opinion, mental effort and fatigue are results of a conflict between the monotony of long-term activities and the novelty-processing systems.

In the target article, Kurzban et al. attempt to explain phenomena such as mental effort, fatigue, and boredom. They derive these phenomena from the functioning of a hypothetical mechanism which mechanically estimates the utilities of different possible actions and then selects the action that has a maximal expected utility. The idea seems interesting but its implementation in the article has fundamental problems. The article contains no formal description of possible actions. Kurzban et al. arbitrarily select possible actions for each situation considered in the article. However, such an approach is wrong, because the number of possible actions is potentially infinite in any situation (Russell & Norvig 2003). Because possible actions can be very different, the unconscious comparison of their utilities seems impossible. Kurzban et al. do not explain how the mind compares doing math calculations and mind wandering. The functioning of the hypothetical mechanism is described abstractly without pointing to the situations in which mental effort and boredom occur (see the target article's Figure 1). As a result, it is unclear why the output of this mechanism is mental effort and fatigue rather than, for example, fear and anxiety. Fear and anxiety can obviously be applied to optimize costs and benefits.

Another model can be sketched as an alternative to the authors' approach and the theories of depleting resources. Some details should be specified prior to the description of the model. Mental effort and fatigue occur in two sorts of situations. First, mental effort and fatigue usually occur when an individual attempts to acquire novel skills. However, this activity is typically not perceived as boring and negative. As an individual acquires a novel skill, the feeling of mental effort usually disappears (Logan 1985). It is reasonable to assume that in this case mental effort simply reflects the necessary restructuring of the mind. Second, mental effort and fatigue frequently occur when the mental activity of an individual is not difficult but is long-term. In this case, mental effort is perceived as aversive. Obviously, the experiments in the target article were simple but long-term mental activities. The proposed model deals with such situations.

The proposed alternative model is based on two assumptions. First, the mind is able to maintain several processes in parallel. One of the processes is a task which occupies the focus of consciousness while other processes function in a background mode. Second, pursuing a long-term goal is usually an execution of a limited number of actions; many of them should be performed over and over again. As a result, any long-term activity is a sequence of recurring actions and therefore it is monotonous.

The brain has two systems that process monotony and its antagonist, novelty. One system is associated with the hippocampus (Grossberg & Merrill 1992; Vinogradova 2001). This system has a representation of the ongoing situation and compares it with the input from other brain systems. A mismatch between the representation and the input means that the situation is changed, and then the brain is activated. If the representation matches the input, then habituation occurs and the brain activity is decreased (Vinogradova 2001). The second system is the novelty-seeking system, which is responsible for seeking novel and varied sensations and experiences (Roberti 2004; Zuckerman 1994). The functioning of this system is associated with the interaction between neurotransmitter systems that are concentrated in the limbic areas of the brain (Zuckerman 1996).

It can be hypothesized that the monotony of long-term activities leads to the engagement of both novelty-processing systems. The first system attempts to inhibit the ongoing task, and the second system tries to activate any parallel processes. The feeling of mental effort reflects the competition between the task, which suffers from inhibition, and other processes. Fatigue and boredom mirror the inhibition of the ongoing task and habituation. The reduction of performance in tasks such as vigilance tasks results from the inhibition of the task by the first system. Accordingly, changes in the situation may result in the improvement of performance owing to the activation of the brain by this system. The decrement in performance when participants perform sequentially several tasks can be explained on the basis that these tasks share the common experimental context (one experimenter, one room, etc.), and therefore the situation can be considered monotonous.

The relationship between reward and fatigue can be hypothesized as a consequence of the interaction between the novelty-processing systems and the reward system. Indeed, novelty seeking should be maximally intense in neutral situations, because seeking novel sensations in very dangerous or very pleasant situations is hardly a useful strategy. As a result, reward can inhibit the novelty-processing systems, thereby decreasing the feeling of fatigue.

The feelings of fatigue and boredom in long-term activities possibly reflect a conflict between various brain systems. In my opinion, the ability to pursue long-term goals having no innate basis is the main characteristic distinguishing humans from other animals (Prudkov 1999; 2005). The experiments described in the target article are obvious examples of pursuing such goals. Indeed, subjects participated in the vigilance tasks not because they were hungry, sexually unsatisfied, or frightened. The ability is maintained by the prefrontal lobes (Luria 1966; 1982). This is a young structure maximally advanced in humans (Luria 1966).

However, long-term activities often are monotonous. Monotony results in the activation of the novelty-processing systems. These systems are maintained by ancient limbic structures, which also maintain other biological goals (Kolb & Whishaw 2003). For the novelty-processing systems, pursuing social goals is a neutral situation because the limbic structures are weakly involved in processing social goals. Therefore, in this case the novelty-processing systems should be activated, thereby hindering social activities.

Kurzban et al. ask, "Why, if revising a manuscript contributes to the achievement of key long-term goals, does it feel aversively 'effortful'?" (sect. 2.1, para. 4). They attempt to respond to this question, but the target article does not contain a clear answer. The proposed model, however, offers a simple solution: because a mature scientist frequently revises manuscripts and this activity becomes monotonous.

Subjective effort derives from a neurological monitor of performance costs and physiological resources

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Abstract: Kurzban et al.'s expectancy-value mechanism of effort allocation seems relevant in situations when familiar tasks are initiated. However, we think additional mechanisms are important when people continue with a task for a prolonged time. These mechanisms, which are particularly relevant for performance of novel or urgent tasks, involve neural systems that track performance costs and resources.

Why are some tasks experienced as more effortful than others? To address this question, it is useful to distinguish between *reactive* action control in unpredictable environments and *predictive* control in predictable environments. These different types of action control are supported by different brain systems. Predictive control areas are associated with the dorsal prefrontal cortex, dorsal anterior cingulate cortex (dACC), and dorsal striatum, which sustain feedforward action control in tasks that are familiar and predictable (Luu et al. 2011; Tops & Boksem 2011; 2012). By contrast, reactive control areas include the inferior frontal gyrus

(IFG) and anterior insula (AI), which sustain momentary feedback-guided control when tasks are performed that are novel, urgent, or unpredictable. Reactive control thus represents a specialized mode of operation for detecting new information, encoding it in memory, and assimilating it into preexisting knowledge structures, and for changing earlier schemata, thereby facilitating future predictive control (Hasher & Zacks 1979; Tops & Boksem 2011). Because reactive control reduces predictive homeostatic regulation of the internal milieu (discussed below), such cognitive control requires the momentary tracking of physiological costs and resources and is experienced as effortful. The experience of effort is hence an adaptive motivational mechanism that limits the (re-)initiation and prolonged performance of tasks that demand reactive control, especially when there are insufficient perceived benefits, threats, or resources to compensate for the physiological costs of reactive control (Boksem & Tops 2008).

The notions of predictability and controllability are central to understanding which challenges trigger a physiological stress response (Sapolsky 2005). Physiological responses to challenge parallel the two forms of action control: *Reactive* homeostatic responses arise in relation to changes in physiological variables that have already occurred, and *predictive* homeostatic responses emerge in anticipation of predictably timed challenges (Moore-Ede 1986; Romero et al. 2009; cf. Landys et al. 2006). When a challenge or task is perceived as predictable and controllable, because resources are perceived to be sufficient for the task (e.g., enough muscle strength), predictive homeostasis is maintained and the task may not be experienced as effortful. By contrast, situational novelty (e.g., Hasher & Zacks 1979; Shiffrin & Schneider 1977) and unpredictability of cognitive operations (Ackerman 1987; Fisk & Schneider 1983) require effortful processing and can trigger reactive physiological responses that potentially incur health costs (Romero et al. 2009). Importantly, reactive homeostatic control may decrease less urgent predictive homeostatic regulation, causing "somatic neglect" of, for example, circadian variation in appetite (Koole et al., in press).

Neuroimaging evidence supports our thesis that reactive control systems translate information about action costs and resources into a motivational feeling of effort. Through its reciprocal connections with autonomic and visceral centers of the nervous system such as the hypothalamus (Carmichael & Price 1995), the AI may be involved in the monitoring and regulation of peripheral resources such as glucose levels (Allport et al. 2004), muscle condition (Craig 2003), autonomic activation (Critchley et al. 2004), and the processing of aversive bodily states (Paulus & Stein 2006). In addition, insula activation has been related to the subjective perception of physical effort and exertion (de Graaf et al. 2004; Williamson et al. 1999; 2003). The IFG/AI areas that are active when people experience subjective effort are also implicated in compensatory effort allocation with time on task. One study found the bilateral AI to be involved in assessing the level of energy expenditure required to reach a proposed effort (Prévost et al. 2010), while several other studies suggested that increased attentional effort during performance over extended periods of time or after sleep deprivation is associated with increased activation of right-hemisphere ventral cortical areas including IFG/AI, and sometimes in the context of activity declines in dACC and/or the dorsolateral prefrontal cortex (Bell-McGinty et al. 2004; Chuah et al. 2006; Coull et al. 1998; Paus et al. 1997; Walker et al. 2005). Moreover, momentary lapses in attention, which increase with time on task and fatigue, are associated with reduced activity in this right ventral attentional network, whereas its compensatory recruitment during subsequent trials is associated with recovery from lapses in attention (Weissman et al. 2006).

Thus, the AI may influence action-selection by monitoring the availability of resources and the physiological costs associated with actions. The readout of this monitor may be experienced as feelings of effort, resistance, and discomfort that influence choices to initiate or (dis)continue task performance (Tops & de Jong 2006). Unlike what Kurzban et al. propose, increased subjective effort does not *necessarily* shift engagement towards alternative, more rewarding options, but may also stimulate disengagement, inactivity, and recuperation when perceived resources (as signaled by the AI) are low (Boksem & Tops 2008). In our view, this is the most important role of subjective effort in decision-making. Indeed, effort may be considered as an adaptive signal that the present behavioral strategy is no longer appropriate, because it continues to demand reactive control that usurps costly physiological resources when substantial resources have already been invested and the goal evidently has not yet been achieved. Feelings of effort may provide the cognitive system with a signal that stimulates lowering of current goals and/or seeking of less demanding alternative strategies.

A major advantage of our account over Kurzban et al.'s is that ours more precisely explains which tasks trigger subjective effort and fatigue (i.e., those that require reactive control, such as tasks that are novel or urgent). Moreover, our account is able to address the transition of prolonged effortful demand into persistent forms of fatigue. When the situation is uncontrollable, individuals are forced to rely on reactive control, associated with feelings of effort, up-regulation of reactive homeostatic responses, and decreased predictive homeostatic regulation. Although adaptive in the short-term when dealing with important and urgent situations, prolonged reactive homeostatic control can lead to enduring physiological changes (Romero et al. 2009), which may give rise to chronic fatigue.

The economics of cognitive effort

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Abstract: If cognitive effort indexes opportunity costs, it should be investigated like other cost factors including risk and delay. We discuss recent methodological advances in behavioral economics and neuroeconomics, highlighting our own work in measuring the subjective (economic) value of cognitive effort. We discuss the implications of Kurzban et al.'s proposal and how some of its predictions may be untestable without behavioral economic formalisms.

Kurzban and colleagues posit phenomenal effort as a marker of opportunity cost, and thus as input to an economic decision about the subjective value of cognitive engagement. As such, cognitive effort is ripe for behavioral economic investigation. If effort represents a cost, formalisms developed in behavioral and neuroeconomic research can be used to quantify that cost. Moreover, many of the extensive implications of the authors' hypothesis may be untestable without objective cost measures. To distinguish their proposal from resource models, Kurzban et al. suggest indexing effort expenditure with performance. As we discuss below, however, performance has a complicated relationship with effort. Furthermore, humans can make effort-based decisions in an offline manner (i.e., during an unengaged period); this points to the need for offline indices of cognitive effort. The full potential of Kurzban et al.'s essentially economic theory will only be realized once variables of interest are formalized within a behavioral economic framework.

Broadly, behavioral economics is concerned with formal methods for probing the influence of choice dimensions on decision-making. The discipline has yielded a wealth of information about the extent to which cost factors, including delay

(Frederick et al. 2002), risk (Green & Myerson 2004), and physical effort (Salamone et al. 2012), impact decisions about goal pursuit. Cost measures combined with neurophysiological and imaging techniques have elucidated the neural systems responsible for economic decision-making (Huettel et al. 2006; Kable & Glimcher 2007; Kennerley et al. 2009; Padoa-Schioppa 2011; Peters & Büchel 2009; Rangel et al. 2008; Salamone et al. 2012). The result is an increasingly richly detailed account of normal and disordered decision-making with implications for understanding pathological gambling, addiction, and more (Alessi & Petry 2003; Bickel et al. 2007; Kollins 2003; Madden et al. 2009).

Recently, we adapted the formalism of discounting to measure cognitive effort (Westbrook et al. 2013). Discounting paradigms quantify costs by the extent to which a cost factor diminishes preference for a reward. In our paradigm, participants experience parametrically varied load in the N-back working memory task. Next, during a decision-making phase (offline) they choose which levels (N) they are willing to re-do for money. Their choices in a series of programmed offers are used to establish that subjective offer value is increasingly discounted as load increases (Fig. 1). We also found that subjective value is sensitive to a number of state and trait variables that should impact subjective effort.

Trait variables modulating subjective value include cognitive age (older adults find task engagement more costly, even controlling for differences in performance and response times) and personality (Fig. 1). Need for Cognition (Cacioppo & Petty 1982), a trait measure of an individual's likelihood to engage with and enjoy cognitively demanding activities, increases with lesser discounting. Such effects support the proposal that individuals vary considerably in their sensitivity to cognitive effort (Cocker et al. 2012; Kool et al. 2010; McGuire & Botvinick 2010; Westbrook et al. 2013). Hence, opportunity cost models should account for individual differences in sensitivity to opportunity costs.

State variables modulating subjective value include objective load (Fig. 1), but also performance and offer amount. Sensitivity to state variables implies that a behavioral economic approach could provide critical evidence against resource models. As Kurzban et al. argue, evidence that expected task utility affects participants' motivation to expend effort would support an opportunity cost account over a resource model. Accordingly, we found that larger offers ($5 vs. $1) resulted in reduced discounting of high-load tasks by participants (cf. Thaler 1981). Because participants make decisions about larger and smaller offers within a single, uninterrupted decision block (without intervening task engagement), increased motivation to expend effort on higher-utility, but equally demanding tasks, cannot be straightforwardly explained by resource depletion.

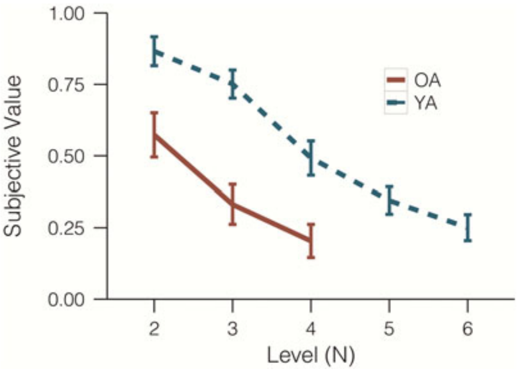

Figure 1 (Westbrook & Braver). Subjective value of a cash offer, or conversely, motivation to engage with a task, decreases with increasing working memory load for both young adults (YA) and older adults (OA).

Critically, performance (signal detection d') and load (N) independently influenced the subjective value of task engagement. This finding also has implications for testing Kurzban et al.'s proposal. While performance measures are bedrock evidence for resource models, task performance – the focus of Kurzban et al.'s opportunity cost model – was only indirectly linked with motivation. Performance is a function of motivation, but also capacity, both trait and state, including practice and fatigue effects. Hence, declining performance with increasing load does not necessarily indicate that motivation is diminished. Moreover, our findings support a more complicated reciprocal relationship whereby declining performance can produce feedback effects, increasing subjective effort (Venables & Fairclough 2009) and decreasing motivation. Without a third, independent measure of motivation – precisely what our behavioral economic measure provides – it is impossible to test whether load impacts expected utility and thereby motivation, as the opportunity cost model predicts.

Finally, experimental methods are needed to study effort-based decision-making in isolation. Unlike performance, which can only be measured during task engagement, discounting quantifies motivation offline, while participants are unengaged. Hence, discounting can be compared before and after extended task engagement to investigate what role fatigue plays in subjective effort, independent of opportunity costs. Similarly, offline measures can be used to study how cached estimates of subjective effort, for a task experienced when opportunity costs were high, carry over to when opportunity costs for the same task are low. Detailed predictions about carry-over effects are limited in Kurzban et al.'s proposal, but could be investigated thoroughly with offline behavioral economic measures.

The model of subjective effort proposed by Kurzban and colleagues is a promising theoretical advance that may ultimately unify well-studied ego-depletion effects with an emerging behavioral- and neuro-economics of cognitive effort (Botvinick et al. 2009; Cocker et al. 2012; Kool et al. 2010; McGuire & Botvinick 2010; Westbrook et al. 2013). The first step will require objective quantification of cognitive effort, which we believe may be accomplished with economic formalisms such as our novel cognitive effort discounting task described here.

Effort processes in achieving performance outcomes: Interrelations among and roles of core constructs

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Abstract: We address points of confusion pertaining to interrelations among and roles of core constructs involved in the production of performance outcomes. We do so informed by the body of work derived from Brehm's seminal motivation intensity theory – in particular an elaboration from the theory concerned with fatigue influence on effort and associated cardiovascular responses in people confronted with performance challenges.

Kurzban et al. offer a careful and clever analysis that contains truths, but also points of confusion pertaining to interrelations among and roles of core constructs of effort, subjective effort, fatigue, and performance. The points of confusion could be informed by consideration of the sizable and expanding body of work derived from Brehm's seminal motivation intensity theory (Brehm & Self 1989), which the authors somehow overlooked in their literature review. Particularly relevant is an elaboration from motivation intensity theory concerned with fatigue influence on effort and associated cardiovascular responses in people confronted with performance challenges (Wright & Stewart 2012; see also Wright & Kirby 2001).

The elaboration takes as a working "given" a venerable hypothesis in cardiovascular psychophysiology that beta-adrenergic influence on the heart and vasculature is proportional to effort ("active coping") in action circumstances (Obrist 1981). It also takes as a given the common understanding that difficulty appraisals increase with fatigue within relevant performance systems, that is, the depletion of resources in active performance structures (Fairclough 2001). With these givens in place, the elaboration applies motivation intensity theory to derive interactional implications regarding fatigue influence, assuming – like motivation intensity theory – that effort is a mechanism through which energy is mobilized and that effort processes are designed to maximize energy efficiency, that is, to make the best use of energy stores.

Core propositions of motivation intensity theory are that effort (motivation intensity) should be (1) proportional to the perceived difficulty of a performance challenge so long as success is viewed as possible and worthwhile, and (2) low when success is viewed as impossibly difficult or excessively difficult, given the importance of meeting the challenge (i.e., the value of the benefit that can be accrued). In combination with the elaboration givens, this implies that fatigue should augment, retard, or leave unaffected effort and associated cardiovascular responses, depending on the difficulty of the challenge at hand and the importance of meeting it. In theory, fatigue should augment effort and cardiovascular responsiveness when it leaves unchanged a perception that success is possible and worthwhile, generating compensatory striving (i.e., effort exertion: Fig. 1, sect. A). By contrast, fatigue should retard effort and cardiovascular responsiveness when it causes success to appear impossible or excessively difficult, leading performers to withhold effort (Fig. 1, sect. B). By further contrast, fatigue should have no effect on effort and cardiovascular responsiveness when it reinforces a perception that success is impossible or excessively difficult, confirming performers' intention not to try (Fig. 1, sect. C).

Cardiovascular implications above have been confirmed repeatedly in fatigue studies involving a range of procedures and conducted in different laboratories (e.g., Marcora et al. 2008; Schmidt et al. 2010; Wright et al. 2003; 2012). Moreover, they can be profitably brought to bear with respect to inhibition, a topic to which Kurzban et al. devote considerable attention. The implications can be brought to bear assuming (1) that behavioral restraint (a particular type of performance challenge) requires a degree of effort determined by the strength of the relevant behavioral impulse, and (2) that inhibitory performance systems can in fact become fatigued (weakened through the depletion of resources). Insofar as these assumptions are warranted, the suggestion is that inhibitory system fatigue should augment effort when it leaves unchanged a perception that inhibitory success is possible and worthwhile; retard effort when it causes inhibitory success to appear impossible or excessively difficult; and have no effect on effort when it reinforces a perception that inhibitory success is impossible or excessively difficult.

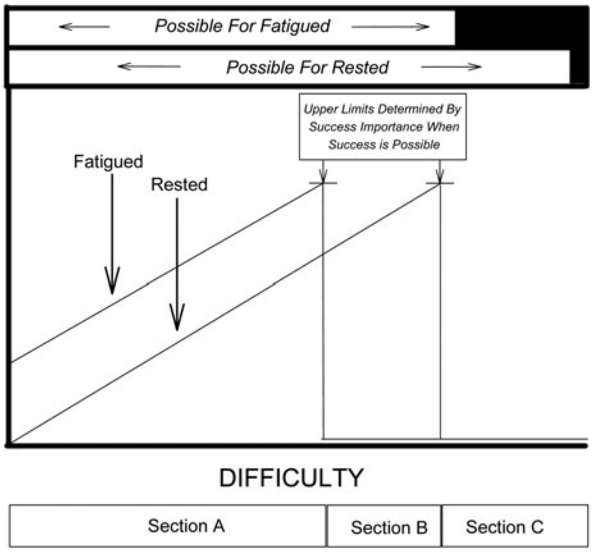

Figure 1 (Wright & Pantaleo). Relation between challenge difficulty and effort for fatigued and rested performers (from Figure 1 in Stewart et al. 2009).

Importantly, although relevant cardiovascular responses in fatigue studies referenced above have consistently comported with effort expectations based on the elaborated fatigue analysis, subjective effort and performance outcomes have not. Disparities between cardiovascular outcomes, on the one hand, and subjective effort and performance outcomes, on the other, might be taken as evidence contrary to an effort interpretation of the cardiovascular results. However, they should not be so taken, because effort reports and performance outcomes have long been recognized as highly fallible indices of actual engagement levels. Regarding effort reports, there is reason to believe that performers sometimes over-report effort in order to please (e.g., experimental) observers and sometimes under-report effort to protect self-esteem in the event of failure. Further, it is possible that performers are not always aware of how engaged they are in goal pursuits (e.g., in the midst of "flow") and that effort appraisals are sometimes impacted by outcomes other than effort itself, including opportunity costs (Kanfer 2011). Regarding performance outcomes, depending on a variety of considerations, improved effort might or might not result in their improvement. Indeed, improved effort has potential for producing performance decrements (Harkins 2006).

Potential lessons are multifold. Effort is a mechanism involved in energy mobilization, that is, the process of converting energy stores into energy. It arguably is multifaceted, with physical and phenomenological components that might or might not correspond with one another. Fatigue is distinct from – and bears an interactional relation to – effort. Fatigue can serve a "stop" function, but also a "go" function insofar as it produces compensatory striving in certain performance circumstances. Fatigue can leave effort unaffected as well, in which case one might say it serves a "stay the course" function. Improved effort can, but will not necessarily, improve performance outcomes, which calls into question the use of such outcomes in making effort inferences. The authors' thesis that opportunity costs might systematically influence effort appraisals is reasonable in some respects, and testable, and could account for some empirical (e.g., performance) outcomes. However, we struggle to see how the thesis can explain effort, fatigue, and performance processes in general. Considering the function of effort, it seems that effort qualia are more likely to index that which is being lost (expended), than that which might be gained by altering the direction of behavior.

Persistence: What does research on self-regulation and delay of gratification have to say?

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Abstract: Despite the simplicity of Kurzban et al.'s framework, we argue that important information is lost in their simplification. We discuss research on delay of gratification and self-regulation that identifies key situational and psychological factors affecting how people represent rewards and costs. These factors affect the expected utilities of behavioral options and thus dramatically influence whether individuals persist on a difficult task.

> *Make everything as simple as possible, but not simpler.*
> — Albert Einstein

When faced with either working on math problems to prepare for an upcoming test or texting with friends, why does one student (Mat) choose to work on the math problems, while another student (Tex) chooses to text with his friends? Kurzban et al.'s model provides a simple framework for these decisions: The expected utilities of the two activities as estimated by Mat and Tex differ. Mat chooses to study because he values doing the math problems more than texting. And Tex chooses to text because he associates higher value to texting than to studying. Moreover, according to the authors, if Tex were to work on math problems, he would experience fatigue because of the greater expected utility he assigns to texting, and this subjective experience is likely to disengage him from studying.

Despite the appeal of the simplicity of the Kurzban et al. framework, we argue that important information is lost in their simplification. One unifying theme in research on self-regulation and delay of gratification (e.g., Mischel et al. 2011; Zayas et al., in press), which is largely unaddressed by Kurzban et al., has implications for the factors that influence how people assign value to rewards and costs of various behavioral options. *Why* does Mat assign a higher utility to studying (vs. texting), compared to Tex? Below we summarize research that identifies key situational and psychological factors that affect how people represent rewards and costs in each behavioral option, and how these, in turn, naturally influence whether people persist on difficult tasks.

All situations are not equal: Situations involving immediate versus delayed outcomes. Does a person study now for a reward to-be-obtained in the future, or instead chat with friends on the phone? This situation reflects a typical delay of gratification dilemma, which involves forgoing an immediately available reward for the sake of a more desirable reward in the future. Surprisingly, Kurzban et al. provide little discussion of how inherent, structural differences in these competing situations affect how they are construed and ultimately which tasks individuals pursue. As we discuss next, situational and psychological factors likely influence the estimation of rewards and costs, and thus the activities to which one decides to allocate computational resources.

Immediate/concrete outcomes loom larger than distal/abstract outcomes. Differences in the temporal nature of the competing situations (delayed vs. immediate) affect a person's estimates of the costs and rewards. In situations discussed by Kurzban et al., the rewards of the current activity (doing math) are delayed but its costs are immediate. In contrast, in situations involving a tempting alternative (texting), the rewards are immediate but its costs are delayed. All things being equal, immediately available rewards weigh more than rewards accrued sometime in the future, and likewise, the costs in an immediate situation weigh more than costs in a delayed situation (e.g., Ainslie 1975). Hence, differences in the temporal nature of the competing situations affect the expected utilities of the current and alternative activities, thereby favoring the allocation of resources toward situations in which the rewards are immediately available.

Reflexively responding to the immediate and reflectively conjuring the future. The competing situations (immediate vs. delayed) in a delay of gratification dilemma also differ in their inherent difficulty. First, the activities themselves differ on the effortful versus automatic dimension. In situations involving immediately available rewards, obtaining the rewards is typically achieved relatively effortlessly. Mindlessly texting simply requires engaging in more reflexive and automatic processes (e.g., Hofmann et al. 2009). In contrast, in situations involving delayed rewards, obtaining the rewards is typically associated with greater effort. Working on math problems to earn good grades in the future presumably requires effortful and more reflective processes.

A second difference in the inherent difficulty of the two competing situations emerges in how the goals are represented. Whereas immediate outcomes are readily available and easily processed, delayed outcomes must be envisioned. Indeed, individuals must keep the delayed rewards in mind, albeit not necessarily consciously, to continue working toward the goal and simultaneously inhibit tempting, highly accessible alternative representations (e.g., Hofmann et al. 2012). The ability to control the content of working memory is a key ability in cognitive control and facilitates delay of gratification (Berman et al. 2013; Casey et al. 2011; Eigsti et al. 2006).

Thus, situations that differ in the immediacy (vs. delay) of the rewards and costs possess another inherent asymmetry: All things being equal, the computational costs in a situation involving delayed rewards are higher than those in which the rewards are immediately available.

Representations of future rewards affect expected utilities. Given the structural reasons why delaying gratification is difficult (as described above), not surprisingly considerable research has shown that being able to control mental representations of various behavioral options and associated outcomes is a key factor influencing whether one persists in working on a difficult task (for a review, see Zayas et al., in press). For example, being able to bring to mind goal-relevant representations, keep them active in working memory, and shield them from competing goals lessens tempting aspects of the situation and facilitates persistence on difficult tasks (Fujita 2011). In some situations, representing delayed goals may increase the salience of future rewards (in a sense it makes them more immediate), and increase motivation. However, in some cases, focusing on delayed rewards may be detrimental (see Metcalfe & Mischel 1999).

Moreover, keeping a delayed reward in mind may even affect the mental effort of pursuing the current mental activity. When the value of the future reward (obtaining a good grade) increases relative to the value of the alternative option (texting), pursuing the current activity may require less effort and less executive functions to inhibit the tempting alternative (in a sense, temptations are no longer as salient and alluring; Ferguson 2008).

In sum, why does Mat choose to study for his math test whereas Tex chooses to text with his friends instead? The fact that one values texting more than studying is fairly self-evident. The important question is *why* does one student value texting more than studying. To provide a comprehensive framework of self-regulation that accounts for these individual differences and situational factors, Kurzban et al.'s model should incorporate psychological processes that affect representations of costs and rewards.

Authors' Response

Cost-benefit models as the next, best option for understanding subjective effort

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Abstract: The commentaries on our target article are surprisingly sympathetic to our overall approach to explaining subjective effort, though disagreement with particulars inevitably emerged. Here, in our response, we first review the few disagreements concerning the basic structure of our proposal, highlighting areas in which little or no resistance was voiced. Opposition to the assumptions that underlie our opportunity cost model is noticeably limited. Areas of genuine disagreement, however, include: (1) the inputs to and outputs of the relevant decision-making systems; (2) how to interpret data regarding individual differences in performance; (3) how to explain persistence on tasks that give rise to the sensation of subjective effort; and (4) the details of the relevant neuropsychological systems. Throughout we point to empirical issues raised by the commentaries and suggest research that will be useful in arbitrating points of disagreement.

R1. Introduction

We could hardly be more pleased with the commentaries. To be sure, many scholars who offered responses found fault with some of our reasoning or ideas. Still, we were prepared for – indeed, expected – a thoroughly different flavor of response, considerably more resistant to our proposals.

As context for our expectations, consider the impact of one of the central ideas with which we were taking issue, the claim that "willpower" is a resource that is consumed when self-control is exerted. To give a sense of the reach of this idea, in the same month that our target article was accepted for publication Michael Lewis reported in *Vanity Fair* that no less a figure than President Barack Obama was aware of, endorsed, and based his decision-making process on the general idea that "the simple act of making decisions degrades one's ability to make further decisions," with Obama explaining: "I'm trying to pare down decisions. I don't want to make decisions about what I'm eating or wearing. Because I have too many other decisions to make" (Lewis 2012).

Add to this the fact that a book based on this idea became a *New York Times* bestseller (Baumeister & Tierney 2011), the fact that a central paper articulating the idea (Baumeister et al. 1998) has been cited more than 1,400 times, and, more broadly, the vast number of research programs using this idea as a foundation, and we can be forgiven for thinking that we would have kicked up something of a hornet's nest in suggesting that the willpower-as-resource model was wrong. So we anticipated no small amount of stings from the large number of scholars involved in this research enterprise. These were our expectations before receiving the commentaries.

R2. The big picture

R2.1. Non-barking dogs

Our expectations were not met. Take, for example, the reaction to our claim that the glucose version of the resource argument is false (Kurzban 2010a). **Inzlicht & Schmeichel**, scholars who have published widely in the willpower-as-resource literature, more or less casually bury the model with the remark in their commentary that the "mounting evidence points to the conclusion that blood glucose is not the proximate mechanism of depletion." (**Malecek & Poldrack** express a similar view.) Not a single voice has been raised to defend the glucose model, and, given the evidence that we advanced to support our view that this model is unlikely to be correct, we hope that researchers will take the fact that none of the impressive array of scholars submitting comments defended the view to be a good indication that perhaps the model is, in fact, indefensible. Even if the opportunity cost account of effort turns out not to be correct, we are pleased that the evidence from the commentaries – or the absence of evidence – will stand as an indication to audiences that it might be time to move to more profitable explanations of subjective effort.

While the silence on the glucose model is perhaps most obvious, we are similarly surprised by the remarkably light defense of the resource view more generally. As **Kool & Botvinick** put it, quite correctly in our perception: "Research on the dynamics of cognitive effort have been *dominated*, over recent decades, by accounts centering on the notion of a limited and depletable 'resource'" (italics ours). It would seem to be quite surprising, then, that in the context of our critique of the dominant view, arguably the strongest pertinent remarks come from **Carter & McCullough**, who imply that the strength of the key phenomenon that underlies the resource model – two-task "ego depletion" studies – might be considerably less than previously thought or perhaps even nonexistent. Despite the confidence voiced by **Inzlicht & Schmeichel** about the two-task findings, the strongest voices surrounding the model, then, are raised against it, rather than for it. (See also **Monterosso & Luo**, who are similarly skeptical of the resource account.)

Indeed, what defenses there are of the resource account are not nearly as adamant as we had expected. **Hagger** wonders if there is "still room for a 'resource' account," given the evidence that cuts against it, conceding that "[t]he ego-depletion literature is problematic." Further, he relies largely on the argument that the opportunity cost model we offer might be incomplete, thus "leaving room" for other ideas. As is evident from the other commentaries, many alternatives beyond our own might fill the space he has in mind.

Harvey, although crediting that our argument is "convincing," suggests that a model in which depletable resources are allocated along the lines we propose is no worse than the one we advance. In the absence of a candidate for such a depletable resource, we favor our proposal, and are encouraged by the fact that Harvey offers no reason in principle to favor the depletable resource view over ours; he suggests only that the criteria that we believe apply to such models are overly "stringent." We of course cede his larger points. That is, we don't deny either that neurons need energy to function or that deficits in neurotransmitters have genuine, important effects on performance. We feel comfortable granting these points while retaining our opportunity cost view.

Bonato, Zorzi, & Umiltà (**Bonato et al.**) defend the view that the idea of "strictly depletable" resources is "the most economic explanation" for a set of findings in which brain-lesion patients demonstrate performance deficits when multi-tasking. Related, but departing from this "strict" view, **Hofmann & Kotabe** seem to favor what could be called a "husbanding" view, writing that "certain executive functions cannot be exerted infinitely without a state reduction in executive capacity," so "people are motivated to monitor and conserve capacity." We resist the husbanding view for reasons discussed in the target article.

On a similar note, **Brzezicka, Kamiński, & Wróbel** (**Brzezicka et al.**) consider a version of a resource account, but their version departs from the traditional model in at least one important way, as they construe the resource as neurophysiologically local, rather than the sort of general resource originally proposed. Their view refers to the possibility that what is being depleted are neurotransmitters or neuromodulators. Related, **Holroyd** proposes that the anterior cingulate cortex (ACC) regulates impulsive behavior "via an energy factor that depletes with use." We believe that there are difficulties with these "local resource" views, and we address these ideas in more detail below.

More commonly, commentators have defended alternative models that explain subjective effort not by exhaustion of depletable resources, but rather by reference to certain tasks being inherently difficult and/or certain cognitive processes carrying intrinsic costs. Many of these alternative models refer in general terms to resources, energy, or capacity that are demanded by some mental tasks and that people are motivated to conserve. For example, both **Gendolla & Richter** and **Wright & Pantaleo** assume that effort is something that is expended in proportion to task difficulty or task demands. **Hofmann & Kotabe** similarly talk about a capacity that is exerted in proportion to task demands, and **Huizenga, van der Molen, Bexkens, & van den Wildenberg** (**Huizenga et al.**) propose a model in which resources are allocated to tasks in proportion to task difficulty. **Hennecke & Freund** argue that "subjective effort is a function of the resources a person perceives to invest into the pursuit of the target goal in relation to the subjectively available goal-relevant resources." In all of these cases, people are averse to effort and avoid it if possible – they are motivated to use as little of their resources, energy, or capacity as possible.

Two other commentaries are more specific in locating the intrinsic costs of certain kinds of mental activity. **Navon** argues that cognitive operation of "decoupling" is inherently aversive; **Kool & Botvinick** argue that cognitive control carries intrinsic costs.

Below, we discuss some of the specific details of each of these commentaries, including clarifying our definition of effort and the fact that effort is both the output of some computations and an input to others. Relevant to all of these commentaries, however, is that we disagree with the notion that costs are *intrinsic* to certain kinds of mental activity or that difficulty is *inherent* to certain kinds of tasks. This kind of alternative model, in our view, does away with the notion of depletable resources, but fails to provide in its place any explanation for *why* certain kinds of mental activity are effortful. Our opportunity cost model is an attempt to provide such an explanation – that cognitive processes are costly or aversive to the extent that employing these processes carries substantial opportunity costs. Whether or not our model turns out to be the correct one, alternatives to the resource account must provide some explanation for why certain cognitive processes are costly, including the currency of the putative costs.

So, while there are traces of evidence of defenses of variants of the resource view, by and large these defenses are relatively mild and relatively rare. From this somewhat puzzling state of affairs – the contrast between our sense that many scholars in particular communities take the resource account more or less for granted, and the anemic defense of the account – we conclude that outside of the community of researchers currently working on this model, there is little appetite for a defense of it.

Related, but perhaps not as surprising, few commentators have taken serious issue with the assumptions that underlie our approach, especially the idea that this puzzle will be solved by invoking the language of *computation* and the evolutionary principle of *function*. While there are traces of resistance to these ideas in the comments, by and large the flavor of the remarks reflects an acceptance of our claim that these ideas will be useful in trying to understand and explain both the phenomenology and the behavioral data.

The context here is a disconnect between the literatures we are engaging, the "ego depletion" literature, on the one hand, and the vigilance literature, on the other (cf. **Malecek & Poldrack**). In the former, the language of cognition is nearly absent, with models built from metaphor – reservoirs, resources, and so on – whereas in the latter the building blocks of explanations are computational. By and large, members of the latter community we understood to welcome the idea that the language of computation ought to be brought to bear on the phenomena in the "ego depletion" literature. Recent thinking on decreases in performance on vigilance tasks over time is resonant with our approach, in particular in characterizing the vigilance decrement as a rational response to a task that demands sustained attention without rewarding attention (or punishing inattention) (Hancock 2013).

An exception is found in **Iran-Nejad & Zengaro**, who say that "the computation metaphor, if used for other than a mathematical tool of science, is an Achilles heel." We find their example of where a computational account fails – explaining variation on moral judgments in the famous Trolley Problem (Greene & Haidt 2002) – ironic. In our view, Mikhail's (2007) formidable account of this variation represents a signal example of how the application of computational language can illuminate and explain previously puzzling patterns of data.

Given the controversy that continues around evolutionary approaches to psychology (Pinker 2002), we were surprised and gratified to find so little resistance to that element of our approach. The only serious worry along this front comes from **Cohen & Saling**, but their objection is founded on an unfortunate misunderstanding. Our claim is not that "being a utility-maximiser is adaptively optimal," as they have rendered our view. Instead, our claim is that evolution selects for systems that guide adaptive behavior, and that the language of utility and maximization models are useful in the context of building computational models (cf. Cosmides & Tooby 1994). Outside of these brief worries, little mention is made of this key assumption, despite our expectations, themselves derived from the ambiance of debate that surrounds evolutionary approaches to psychology.

Similarly, there is very little objection to the general conclusions we reached from a summary of the neuroscience literature. As we have indicated above, no one rose to defend the idea that global levels of brain glucose serve as a resource that limits performance in mental tasks. No one questions that the current state of the neural evidence was broadly consistent with a cost-benefit type of account. As we discuss in section R6, several commentaries have made alternative proposals regarding the specific computational role that different neural systems might play in a cost-benefit framework, and a few have proposed hypotheses regarding other potential resources, but our basic framework has not been fundamentally questioned.

For the sake of completeness, we add that our assumptions surrounding phenomenology, surely a subject on which there is no shortage of diverse and strong opinion, has met with curiously little objection (but see **Craig**). To be sure, some commentators raise the issue of the extent to which the processes we have in mind are conscious versus non-conscious (see next section), but by and large we find it remarkable that so little attention was paid to what might have been a very basic objection to the worldview (Cosmides & Tooby 2000) that enrobes our proposal.

R2.2. Terms and assumptions

As is frequently the case in scholarly debate, some of the disagreements derive from differences in the meanings attached to terms and non-shared assumptions. In this subsection we discuss several such cases, with an emphasis less on resolving the disputes – people are of course free to use terms to mean whatever they wish – and more on clarifying our own uses and commitments.

R2.2.1. Terms. First, *rational* and the related term *rationality* have consistently posed conceptual challenges. To clarify, we resist the notion that our proposal should be viewed as suggesting "a mechanism that rationally allocates processors" as **Harvey** renders it. An even grosser mischaracterization of our view is **Inzlicht & Schmeichel**'s assertion that our model "assumes that people calculate costs and benefits in an objective, dispassionate manner." We made no claim about what "people," broadly, do, let alone what passions influence their calculations; rather we made a proposal, narrowly, about the causal variables that underlie the phenomenology of effort and decisions in the context of a particular set of tasks. Our proposals are no more an endorsement of *homo economicus*, broadly, than are ideal observer models or optimal foraging models, as we indicated in the target article.

Relatedly, our claim is neither that "[people's] most basic motivation is to maximise utility," nor that "being a utility-maximiser is adaptively optimal" (**Cohen & Saling**). The use of the language of utility might have, reasonably, recruited readers' sense that our assumptions echoed those of economists, which is why we tried to be explicit about our assumptions in the target article. Our claim is that natural selection tends to fashion systems whose properties can be modeled as maximizing, as is frequently done in literatures ranging from visual perception (Simoncelli & Olhausen 2001) to foraging (Charnov 1976). This does not entail that maximizing utility is either the most basic motive, or that doing so is necessarily optimal.

In short, our claim was not one of rationality, which we would take to be a strong one, but rather a weaker claim that the explanation for the phenomena in which we are interested is to be located in the conceptual primitives of costs and benefits (more about which below). Mechanisms can operate in virtue of cost/benefit calculations while departing (systematically) from predictions derived from a normative model of rationality. Indeed, the only time the word "rational" appears in the target article is when we are describing our starting point for the enterprise, and in that passage we hastily assert that the cognitive mechanism in question might depart from rationality.

The terms *effort* and *motivation* are similarly potentially contentious. In our article, we tended to use the word "effort" in the context of our own model, as an aspect of phenomenology, as in the titular use of "subjective effort" – though, as **Huizenga et al.** point out, we ourselves were not entirely consistent. Still, we are uncertain what to make of it as a dependent measure, as in Figure 1 of **Gendolla & Richter**'s commentary. From their later remarks that "the energy conservation principle is that organisms do not invest more resources than *necessary* for an action," and that "motivational intensity theory posits that effort rises with subjective demand as long as success is possible and justified," we take Gendolla & Richter to be equating effort and energy, an equation we would strenuously resist, as should be clear from the target article.

In addition, while our model is explicitly concerned with explaining phenomenology and performance during mental tasks, we readily concede **Monterosso & Luo**'s point that the constructs of self-control and executive function are not synonymous. We conceptualize self-control as behavior consistent with valued long-term goals at the expense of less valued but more immediately attainable goals (i.e., temptations). Certainly, there are many instances in which deploying executive function in the service of a subjectively valued long-term goal (e.g., completing a manuscript) conflicts with using the same computational processes to attain a less valued but more immediate alternative (e.g., checking email). However, the exercise of executive function need not entail such a conflict. That is, executive functions are often used to manage lower-level computational processes in the absence of temptation. And, while executive function certainly facilitates self-control, so, too, do a variety of metacognitive strategies (e.g., commitment, selective attention, and psychological distancing).

Finally, we note that while different communities use the term "motivation" in multiple ways, we take our model to be a *motivational* model, with the opportunity cost calculation being a causal antecedent of the deployment of computational mechanisms; on our view, such causal pathways are the essence of "motivation."

R2.2.2. Assumptions. As indicated above, we are gratified that many of our assumptions have gone unchallenged. Of course, not all of them were. **Huizenga et al.** reject our assumption that an important opportunity cost calculation stems from "daydreaming," which they deny requires executive functions. We stand by our broader claim that many of the sorts of things that subjects might do when they release their attention from vigilance or self-control tasks do recruit executive functions, though of course we are open to evidence on this point. (For opposing views on this issue, see Smallwood & Schooler 2006, and, in response, McVay & Kane 2010.)

This relates as well to **Charney**'s doubts about our assumption that tasks cannot be inherently boring (or exciting, etc.). We would defend our assumption. We don't take boringness as something that inheres; rather, we take boringness to be a relationship between a nervous system and a task. We would make the same argument with respect to task "difficulty" (**Bonato et al.**), how "demanding" a task is (**Gendolla & Richter),** and "monotony" (**Prudkov**). Consider the computations involved with recovering a three-dimensional image from retinal data; computationally, this is a terribly difficult challenge (Marr 1982). Yet, it is in no interesting sense "difficult" for people (with normal vision) to see. What is difficult (boring, monotonous) depends on the arrangement of the nervous system. That is, some tasks are difficult *for our nervous system*, and some are easy. We therefore resist the notion that difficulty – or boredom, and so on – inheres to tasks. In short, we take boringness as a relationship between a subject's mind and a task, and as such, a relationship to be explained, rather than an inherent property of a task that plays an explanatory role.

We take a similar position on the notion that executing tasks that require cognitive control carry "intrinsic" costs (**Kool & Botvinick**). That is, we resist the notion that costs are the sort of thing that can be "intrinsic." We are of course sympathetic to the notion that cost computations accompany the sorts of tasks Kool & Botvinick have used, but we prefer to think of these cost representations as computational *outputs* to be explained, as opposed to "intrinsic" properties of the tasks or computational processes.

We reiterate that the sensation of effort, according to our view, depends on the systems recruited by the task in question. So, contrary to **Charney**'s view, even if the identical alternative tasks are available to two subjects, they will experience different sensations of effort if the two tasks recruit different computational mechanisms. It is the alternative uses to which recruited computational mechanisms, together, can be put that, according to our proposal, produce the experienced sensation of effort.

R3. Critiques of the opportunity cost model

A number of commentators have granted many or most of our assumptions but have taken issue with various elements of the substance of the proposal. In this section we address some of these challenges, with an emphasis on computational inputs/outputs, potential alternative conceptualizations, and our interpretation of some of the results to which commentators have drawn our attention.

R3.1. Inputs and outputs

According to our proposal (see, e.g., Fig. 1 in the target article), sensations of subjective effort should be understood to be the *output* of mechanisms computing opportunity costs, as well as *inputs* to decision processes designed to guide adaptive behavior with respect to the decision regarding whether to continue to pursue the present task. This dual role corresponds to our conception of phenomenology in other domains. For example, fear is both the *output* of a set of mechanisms monitoring risks in the environment (e.g., predators, violence, dangerous heights) and an *input* to mechanisms designed to motivate adaptive avoidance. Similarly, hunger is both an *output* of a set of mechanisms monitoring energetic requirements and an *input* into decision mechanisms that motivate food search and consumption behaviors.

We noted this dual nature of subjective effort in multiple instances. Despite our attempts to be explicit about our commitments, as when we suggested that "sensations are the outputs of mechanisms designed to produce inputs to decision-making systems" (sect. 2.3.2, para. 1), some commentaries reflect a certain amount of confusion on this point. For example, **Hennecke & Freund** suggest an alternative model whereby "[r]ather than being an *output* of computations that compare costs and benefits of the target and competing goals, effort enters these computations as an *input*." **Hofmann & Kotabe** similarly misconstrue our model of subjective effort as reflecting *only* the output of opportunity cost–monitoring mechanisms, suggesting that we take into consideration the idea that "subjective task effort may also enter as a cost *input* into the cost-benefit analysis that underlies the utility calculation of each activity involved." We, of course, agree.

Related to the point above, we did not intend to give the impression that opportunity cost computations would be the only input to decision-making systems. **Molden** helpfully points out numerous plausible inputs, including voluntarily chosen (vs. coerced) task engagement and beliefs about the source of experienced effort. Similarly, **Harrison & McKay** point out that religious priming could potentially change the experience of effort. We agree that beliefs (as Molden puts it, "top-down orientations") about the world should affect both experienced subjective effort and motivation to persist. Beliefs – and even metabeliefs (cf. **Hofmann & Kotabe**) – could do this in multiple ways, including altering the perceived probability of success, altering the perceived utility of task completion, and altering the perceived utilities of alternative activities. The number of inputs is likely substantial – and certainly would include computations surrounding reputational effects of the sort that Harrison & McKay allude to – and, given our ability to arbitrarily coin reward (see **Ainslie**), potentially a great deal more.

R3.2. Necessity and sufficiency

A number of commentaries have endorsed elements of our approach while taking issue with the details of our proposal. For instance, **Kool & Botvinick** broadly endorse our approach, in particular the "motivational turn" in the allocation of mental processes and our emphasis on a "value-based perspective." Along these same lines, several commentaries emphasize the fields of behavioral economics and neuroeconomics, in particular as sources of methods for testing our model. **Westbrook & Braver** note that the model might be "untestable without objective cost measures." We agree, and think this points to a substantive advantage of cost-benefit models over resource-based models, which seem difficult to falsify (Navon 1984). Indeed, we are currently using methods drawn from behavioral and experimental economics to test various aspects of the model.

Still, despite agreement about the value of a motivational approach, broadly, several commentaries suggest that our proposal surrounding opportunity costs is unlikely to be able to account for all cases of subjective effort (**Ainslie**; **Gendolla & Richter**; **Hennecke & Freund**; **Kool & Botvinick**; **Molden**). We welcome these comments, and we agree that we failed to draw an important distinction in our discussion of opportunity cost. First, because executive systems can be put to use for activities (e.g., planning) more or less independent of opportunities afforded by the environment, there might be opportunity costs that inhere whenever these systems are put to use. Second, potential opportunities in the environment – using a cell phone, for example – represent a second, distinguishable opportunity cost. We are committed to the view that the first sort of opportunity costs explains why tasks that recruit executive systems are perceived as effortful even in environments in which there are no tempting alternative activities. (See **Harrison & McKay** for a dissenting view.)

Ainslie similarly endorses the "motivational turn" (as does **Molden)** in explaining subjective effort, but argues that opportunity costs are unnecessary to explain subjective effort, preferring instead the notion of "endogenous reward." We are broadly sympathetic to this notion, and suspect that our perspectives might be compatible. For instance, Ainslie suggests that there exists a "baseline level of reward that does not depend on external contingencies," and that when idle (e.g., daydreaming), individuals appear to generate their own rewards, potentially even arbitrarily. This echoes examples we used in the target article of mind wandering and daydreaming as potentially valuable alternatives precluded by use of executive function–related processes.

Navon also raises the question of how people can "rank on-line, albeit implicitly, the costs/benefits of all alternatives (or even the most salient ones) sufficiently for estimating opportunity costs." Navon also raises the important point that some sources of distraction (e.g., a flying bird stuck in an office) make it hard to maintain executive function–related processes but represent very low or even zero opportunity cost.

We think this is a critical question, which we did not address for reasons of space, though we do not think the problem is insurmountable. Under conditions of uncertainty and incomplete information, people must perforce estimate the expected value of alternatives – such estimates need not be perfectly accurate to be useful guides to behavior. In the case of the trapped bird, our guess is that the formal properties of the stimulus, by and large, are the sorts of things these systems were designed to attend to. Historically, nearby animals or objects – especially fast-moving ones – were sources of threat or opportunity, and it seems reasonable to design the mind to value attending to them, even if not every instance results in an incurred cost or benefit.

R3.3. *Devil in the details (of costs/benefits)*

Other commentaries, while also broadly in agreement with the cost-benefit approach, take issue with specific details of the nature of costs/benefits in task persistence and task switching. **Nicolle & Riggs** suggest that the anticipated regret of switching might bias people toward staying on task. We find this plausible, and, as we have indicated above, concede that opportunity costs are only one input into the decision-making systems that govern task switching.

Inzlicht & Schmeichel similarly agree with the starting point of costs/benefits – "[s]ome version of this view seems likely to be correct" – but argue that our model failed to capture the dynamics of costs/benefits over time. We respectfully disagree. In the target article we argued that people acquire information about the value of a task as they perform it, accounting, we think, for phenomenological and performance dynamics. On this note, we take seriously the point that feedback is important to task persistence, as is information about beliefs about whether task success is possible in the first place. **Gendolla & Richter** cogently make this second point, noting that we failed to distinguish *task choice* from *task execution*, which, they argue, led us to neglect *task demand*. We broadly agree that efficacy is an important consideration and might be another input into decision-making systems. The way we think about this issue is that representations of one's ability to achieve success on a task enter into the expected benefit computation of continued deployment of computational resources on the task in question. As indicated above, we take "task demand" to be a relationship between the person doing the task and the details of the task, as opposed to a property of the task in itself.

Relatedly, **Bruyneel & Dewitte**, while sympathizing with our broad approach, note that cost/benefit computations might themselves depend on executive function–related processes. This carries the entailment that the quality of cost/benefit calculations depends in part on how much executive function–related processes are devoted to some task other than cost/benefit calculating. We certainly allow that this is a possibility, though our views veer more toward **Ainslie**'s and **Kool & Botvinick**'s. That is, we think it plausible that executive processes might not be required for the sorts of opportunity cost computations we have in mind, though we take Bruyneel & Dewitte's point about the empirics. Still, in terms of the particular empirical pattern they point to – the two-task paradigm – as **Carter & McCullough** indicate, these results might not be as robust as previously believed (Hagger et al. 2010a), inclining us toward caution about what to infer from this line of work. The suggestion Bruyneel & Dewitte offer regarding the interpretation of these results is intriguing, however; and we look forward to additional work disentangling alternative explanations.

R4. Individual and group differences

Several commentaries raise the issue of individual or group differences, either in the sustained performance of mental tasks over time or in the concomitant phenomenology associated with performing these tasks. For example, **Hagger** points to evidence in his meta-analysis (see Hagger et al. 2010a) that individual difference variables moderate the effect sizes observed in "ego depletion" experiments, suggesting we elaborate how individual difference variables could "bias individuals' tendency to interpret the opportunity costs of their responses relative to the next most desirable action." We agree that any complete account of subjective effort should explain both changes within individuals over time as well as between-individual differences in these trajectories. Indeed, exploring the extent to which our model can explain individual and group differences constitutes an important direction for future research. Our hope is that our necessarily brief remarks on this topic highlight useful first steps toward that end. Extending the logic of our model, individuals might vary (a) in their valuation (i.e., implicit estimation of the expected value) of the target task, (b) in their valuation of the next-best alternative task to which the same cognitive processes may be deployed, and (c) in how they appraise or interpret feelings of subjective effort.

Why might individuals derive different benefits from performing identical mental activities? As **Westbrook & Braver** point out, it is an empirical fact that people vary in their willingness to perform tasks that generate feelings of mental effort (see also Cacioppo & Petty 1982). Likewise, for sensation-seeking individuals, mental tasks might be perceived as higher in value to the extent they are novel or unpredictable and lower in value to the extent they are repetitive and monotonous. More conscientious individuals might assign higher value to task performance to the extent that their standards for performance are higher throughout the task. Likewise, more compliant or agreeable individuals may assign greater benefits than others might to fulfilling an experimenter's expectations.

Estimates of opportunity costs might also differ between individuals. For instance, some of us might be more inclined to daydream (e.g., to remember past events, to prospect into the future), an activity that conflicts with task-oriented processing. Opportunity cost estimates might also differ as a function of how vividly individuals tend to generate counterfactuals, whether consciously (Frederick et al. 2009) or, as we have argued, implicitly. Moreover, opportunity costs or sensitivity thereto might vary across individuals because of differences in cognitive processing capacity. As **Westbrook & Braver** point out, in a willingness-to-pay paradigm older adults must be paid more to engage with challenging mental tasks than younger adults. Likewise, limitations in cognitive processing capacity might explain the evidence summarized by **Bonato et al.** In their experiments, brain-damaged patients showed increasingly compromised performance in one task, detecting visual stimuli in the periphery, as the demands of a second task performed simultaneously increased. Healthy controls did not show this decrement. Brain-damaged patients likely have more limited cognitive processing capacity, and as more of this limited (but, in our view, not depletable) capacity is allocated to the second task, performance on the first task starts to fail.

Finally, individuals might differ in how they interpret the sensation of subjective effort. For instance, people who believe that mental resources are depletable might construe such qualia as evidence they are "running out of willpower." Such an attribution might incline these individuals to give themselves a break, allocating computational processes away from the target task to some easier alternative (see Clarkson et al. 2010; 2011; Job et al. 2010). In contrast, individuals might learn to interpret feelings of subjective effort as indicating their willpower is being challenged, an inference which, when experimentally induced, improves performance (Magen & Gross 2007). Similarly, individuals might infer from the experience of subjective effort that they are engaged in something worthwhile (i.e., that reward is imminent), perhaps from the repeated association of subjective effort with eventual reward (Eisenberger 1992). Or, individuals well-practiced in mindfulness meditation might be more aware of feelings of subjective effort yet be less inclined to react to them (see Holzel et al. [2011] for a review).

R5. Why do people persist?

We discern two concerns regarding our model's predictions of task persistence. First, why don't people persist indefinitely on mental tasks whose value exceeds that of all other possible uses of the same computational resources? Second, why do people persist at all on tasks that provide no immediate reward when immediately pleasurable alternatives (i.e., temptations) are available? We believe that our proposal addresses both of these concerns: Persistence depends on favorable cost/benefit calculations of the task relative to alternative uses of the same computational processes.

Considering the first question, **Hagger** worries that "in the absence of 'next-best' tasks, task persistence will be indefinite, which seems unfeasible" (see Hagger's Abstract). Likewise, **Hoffman & Kotabe** suggest that in our model, "because effort is treated as the result of a relative utility comparison of opportunity costs, people should go on almost infinitely (experiencing virtually no effort) pursuing a cognitively demanding option A when the value of this option is very high and no alternative option B comes close in utility."

Our position is that, indeed, some individuals *do* sometimes persist on mental tasks for hours and hours, stopping perhaps only to attend to basic physiological needs such as sleep or food, when these activities yield consistently greater utility than next-best alternatives. As an extreme case, so-called idiots savants (to use Michael Howe's term) are known to devote hours and hours to a single task, reaching exceptional levels of performance despite subnormal general intelligence (Howe & Smith 1988). Furthermore, our specific claim is that a monopoly on computational processes can be sustained over time without feelings of subjective effort when the perceived benefits are also maintained over time. The possibility of sustained, "effortless" mental activity over time is consistent with the substantial literature on *flow*, the subjective state of being completely involved in a challenging, intrinsically rewarding activity "to the point of forgetting time, fatigue, and everything else but the activity itself" (Csikszentmihalyi et al. 2005, p. 600).

It is also true, however, that flow is rare. We see two reasons for its rarity. First, over time, there is almost always *some* alternative activity that becomes more valuable than the task at which we have been laboring. Moreover, for most of us, most of the time, there are diminishing marginal returns for mental tasks. Speaking for ourselves, we have rarely sat down to write a paper and found that our good ideas kept flowing at full force hour after hour after hour. As the rate at which our good ideas come diminishes (and may even become negative insofar as we end up mangling previously well-argued passages), the relative value of alternative activities increases. Instead of making (slower and slower) progress on our paper, we could, for instance, answer email, talk to colleagues, make plans for dinner, and so on. Our view is that the estimation that we could better use our limited cognitive processing capacity for better ends leads to feelings of fatigue and restlessness, prompting us to direct our attention to a rival task of greater expected utility.

Turning to the second question, why people persist at all, **Hillman & Bilkey** wonder how our model might explain the incontrovertible fact that animals (e.g., scientists) persist through subjectively effortful tasks over extended time periods (e.g., "months of executive function–demanding writing, research, and teaching"; Hillman & Bilkey) when alternatives (whose varieties are all too familiar to the present readership) present significant benefits. In a similar spirit, **Inzlicht & Schmeichel** suggest that our model does not adequately 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." As **Zayas, Günayadin, & Pandey** (**Zayas et al.**) point out, the benefits of common effortful mental tasks (e.g., working on math homework) are often abstract and delayed in time, whereas temptations (e.g., texting) are associated with immediate, salient rewards.

We thank **Hillman & Bilkey** for, in essence, answering the same question they pose. They reason that when individuals persist on a task whose benefits are removed in time, "the discounting of the primary goal that normally occurs under conditions of temporal distance, uncertainty, or exertion, could be attenuated during the cost/benefit evaluation. Alternatively, the degree of discounting of competing tasks could be increased." We could not agree more. Persisting at a task that provides delayed rather than immediate benefits is facilitated by mentally representing the task as valuable, either because it is part of a valued pattern of behavior or because its execution is instrumental to some superordinate goal (Rachlin 2000). Likewise, resisting a temptation is facilitated by diminishing its subjective value, for example, by using attentional or reappraisal strategies (Magen & Gross 2010; Mischel et al. 1989).

R6. Neuroscience of resources and motivation

In the target article, we reviewed the relevant neurophysiological evidence and concluded that the current state of the evidence is consistent with a cost-benefit account of subjective effort, but not a resource account. In particular, the evidence is inconsistent with the idea that the depletion of global levels of brain glucose leads to reductions in performance of mental tasks and the feeling of subjective effort (Kurzban 2010a), and no evidence has yet been mustered for any other proposed resource. In contrast, many of the elements necessary for a cost-benefit account have been established, including neural representations of costs and benefits, neural systems involved in executive function whose engagement entails substantial opportunity costs, and potential mechanisms through which the former can influence the engagement of the latter.

Although several commentaries have addressed the neuroscience section of the target article, very few have challenged these general conclusions. Rather, the commentaries focus on two areas: (1) alternative proposals for a physical resource whose depletion leads to the sensation of subjective effort, and (2) alternative proposals regarding the specific computational role that particular neural systems play in a cost-benefit account.

R6.1. Alternative proposals for a physical resource

Three commentaries offer alternative proposals regarding a physical resource whose management constrains subjective effort and performance. In the target article, we allowed that there might be other candidate resources beyond glucose, though we knew of no explicit proposals. **Brzezicka et al.** provide one, arguing that the pool of readily releasable neurotransmitters might be a local resource that gets depleted with continued activity in the same circuit. In the target article we listed several questions that any resource proposal would need to answer, and Brzezicka et al.'s "local resource depletion hypothesis" does not yet seem to address the one that is perhaps most central: Why do some forms of mental activity but not others feel effortful? For example, why does the fairly continuous operation of the visual system during waking hours not run afoul of this constraint? Why is doing math problems effortful, but not watching a sunset? Maintaining a pool of available neurotransmitters would seem to be a constraint that affects all neural circuits, not just the ones whose activity is associated with the phenomenology of subjective effort. Absent a satisfying answer to such questions, we remain very skeptical of local resource explanations.

Holroyd provides a more general defense of the resource position, arguing that resource and computational accounts are not mutually exclusive. We do not disagree, though we see little reason to explore hybrid accounts if computational accounts prove sufficient (Navon 1984). Holroyd also states that: "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." Again, we do not dispute that the brain is a biophysical system that obeys thermodynamic laws, nor do we dispute that the design of the brain is at some level constrained by energetic concerns (Lennie 2003; Montague 2006b). Where we disagree is with the notion that these principles are important to (or possibly even relevant to) explaining the phenomenology of subjective effort and task performance changes. The brain consumes a large amount of energy at "rest" and the amount of energy consumed does not increase dramatically for different kinds of mental tasks. The largest local changes in energy consumption that we know of are in the visual cortex when one opens one's eyes, yet that activity is not generally perceived as effortful. Thermodynamic principles certainly provide a general constraint on brain design, but we see no evidence that energetic differences are the primary factor driving transitions between different patterns of neural activity.

As we understand their proposal, **Tops, Boksem, & Koole** (**Tops et al.**) argue that the energetic resource being conserved is not in the brain at all, but rather in peripheral systems. They argue that novel and unpredictable environments disrupt predictive homeostatic regulation and thereby engender physiological costs that need to be monitored, and that the accompanying mental state of "reactive control" feels effortful. This proposal accords with the evidence that to the extent that subjectively effortful mental tasks do in fact consume additional glucose, then the relevant increases are in the periphery rather than the brain. (See Gibson 2007, for a discussion of this claim.) However, there are several aspects of this proposal that are not entirely clear to us. Is "reactive control" effortful even when the physiological costs being monitored do not increase? Or can the subjective effort of monitoring and the amount of peripheral energy consumption be dissociated? If the latter, then the proposal seems to depart in important ways from a "depletion" framework. We also question whether the sensation of subjective effort only occurs in novel or unpredictable environments, which seems to be an important prediction of this hypothesis. We look forward to increasingly specific proposals regarding the possibility of a role for a physical resource so that such proposals can be empirically distinguished from the sorts of computational accounts that we favor.

R6.2. Alternative mappings of a computational account of neural systems

In the target article, we argued that several elements necessary for a neural implementation of our opportunity cost model, or cost-benefit computational accounts generally, had already been established. This includes neural representations of costs and benefits of the type required, neural systems involved in executive functions whose engagement entails opportunity costs, and potential mechanisms by which the former can influence the deployment of the latter. This last piece was by necessity speculative given the limited number of studies on subjective effort to date in the neuroscience literature. Several commentaries have added alternative proposals regarding neural systems that influence task engagement based on costs and benefits. We are excited by this wealth of hypotheses, seeing it as a sign of the promise of cost-benefit computational accounts generally, and look forward to the future studies necessary to distinguish among them.

In the target article, one of the linking mechanisms we proposed involved the anterior cingulate cortex. This region, because it both contains neural representations of costs and benefits and is engaged during executive tasks, is well placed to influence task engagement based on opportunity costs. We pointed to several studies that had reported anterior cingulate activity that was lower after performance of a mentally demanding task. We proposed that the higher activity during early task engagement might represent an opportunity cost signal, which subsequently led to task disengagement and declines in performance (Boksem et al. 2006; Inzlicht & Gutsell 2007; Lorist et al. 2005). Both **Holroyd** and **Hillman & Bilkey** argue for an alternative interpretation of this pattern, which essentially inverts the valence of the anterior cingulate signal. In their view, higher anterior cingulate activity early leads to continued persistence on the task, and activity declines later when people have disengaged from the task. These commentators argue that high levels of anterior cingulate activity signal that the benefits of the current behavior outweigh the costs, and this activity motivates or energizes continued persistence on the current task. We think a simple comparison between early and late performance does not discriminate yet between these alternatives. What is needed is either a trial-by-trial comparison, where our proposal predicts that high anterior cingulate activity on one trial will predict decreased performance on the subsequent trial, or an analysis of individual differences, where our proposal predicts that individuals with the highest anterior cingulate activity will show the largest decrements in performance. Holroyd and Hillman & Bilkey would predict the opposite in these two cases. Alternatively, human studies that examine the effect of anterior cingulate disruption on subjective effort and performance could distinguish the two accounts. We think it is a positive aspect of our theory – and of the cost-benefit framework more generally – that it generates further empirical predictions that remain to be tested.

Both **Craig** and **Tops et al.** point to the insula as an alternative region that might encode the costs of mental activity and act to promote disengagement from the current task when these costs are high. As these commentators nicely summarize, the insula receives information about bodily states and has long been implicated in emotion and subjective feeling. As Craig notes, the insula is also linked to the anterior cingulate, and the two regions are often coactive – including in response to feedback (Bartra et al. 2013). We think it is quite plausible, then, that both regions could play a role in promoting changes in task engagement based on costs and benefits.

The second linking mechanism we proposed in the target article was through dopaminergic projections from the brainstem to the lateral prefrontal cortex. **Malecek & Poldrack** propose another brainstem neuromodulatory system, the noradrenergic system, as a candidate for this role. This is another plausible hypothesis, which comports with early evidence that subjective effort is associated with increases in pupil diameter (Kahneman & Beatty 1966), which are now presumed to be mediated by noradrenergic signals (Nassar et al. 2012). We look forward to continued research that distinguishes the precise computational roles played by different neuromodulatory systems.

R7. Conclusion

In summary, while there are many points of contention and substantial empirical and conceptual issues to be resolved in the years ahead, we wish to return to where we began – the substantial and, to our thinking, surprising overlap in views surrounding how to go about understanding and explaining the subjective sense of effort that arises during certain kinds of mental tasks. In the recent history of this literature the prevailing view has been, at least within certain communities, that subjective effort and task performance reductions could be explained, at least in large part, with reference to diminishing resources. Although there are traces of continued embracing of such a view, our overall impression of the commentaries is that the bulk of scholars are open to, if not enthusiastic about, the computational approach that we favor.

To be sure, there remains disagreement about the details, but we feel that there is, with some important exceptions, relatively widespread agreement with (or conspicuous lack of criticism of) several propositions that we advanced in order to try to explain subjective effort:

1. A resource account is unlikely to be correct (in particular, the glucose version of a resource account).
2. Computation and function are necessary components of the explanation of subjective effort.
3. A cost-benefit approach is a promising general framework to understand the computations that underlie subjective effort.
4. Subjective effort should be understood as a *motivational* phenomenon.

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.

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[The letters "a" and "r" before author's initials stand for target article and response references, respectively]

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