

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).