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Why Aren't We Smarter Already: Evolutionary Trade-Offs and Cognitive Enhancements

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Abstract

Pharmacological enhancers of cognition promise a bright new future for humankind: more focus, more willpower, and better memory, with applications ranging from education to military combat. Underlying such promises is a linear, more-is-better vision of cognition that makes intuitive sense. This vision is at odds, however, with our understanding of cognition's evolutionary origins. The mind has evolved under various constraints and consequently represents a delicate balance among these constraints. Evidence of the trade-offs that have shaped cognition include (a) inverted U-shaped performance curves commonly found in response to pharmacological interventions and (b) unintended side effects of enhancement on other traits. Taking an evolutionary perspective, we frame the above two sets of findings in terms of within-task (exemplified by optimal-control problems) and between-task (associated with a gain/loss asymmetry) trade-offs, respectively. With this framework, psychological science can provide much-needed guidance to enhancement development, a field that still lacks a theoretical foundation.

Keywords

cognitive enhancements, trade-offs, constraints, evolution, side effects

Pharmacological enhancers of cognition appear to hold considerable promise for expanding human potential. There is already evidence that they improve various forms of cognition, including the amelioration of depression with fluoxetine, the focusing of attention with amphetamines, and the enhancement of alertness with modafinil. These effects hold the potential for the pharmacological improvement of school performance, the reduction of age-related cognitive decline, the improvement of human performance in combat, and even the enhancement of scientific productivity (e.g., Greely et al., 2008). In the mid-20th century, Paul Erdös, arguably the most prolific mathematician of all time, with close to 1,500 publications, kept himself fortified with daily doses of "ten to twenty milligrams of Benzedrine or Ritalin, strong espresso, and caffeine tablets" (Hoffman, 1998). In his day, Paul Erdös was likely to be an exception; today, the reliance on pharmaceutical enhancement has become commonplace, with reports showing usage of cognitive enhancers as high as 1 in 5 people (see Greely et al., 2008).

The development of cognitive enhancers is undeniably exciting. However, their luster rests on a potentially dangerous assumption—one that not only users of cognitive enhancers but also some of their scholarly advocates appear to make (e.g., Greely et al., 2008). The assumption is that cognitive traits conform to a linear model in which more means better: More memory is better; more focus is better; more self-control and willpower are better; and so on. Just as we cherish faster processing speed and larger memory in our digital electronics, we may assume that boosting a particular cognitive trait will bring better mental performance and affective well-being. A logical consequence of this assumption is Greely et al.'s claim that "the drugs . . . should be viewed in the same general category as education, good health habits, and information technology" (p. 702).

Comparing pharmaceuticals with education, good health habits, and information technology, however, leads to an important evolutionary question. Education, health habits, and information technology are subject to horizontal (i.e., cultural) transmission but not to evolutionary selection. The targets of cognitive enhancements—for example, attention and memory—*are* subject to selection. Therefore, the question is: Why have we not already evolved the abilities that cognitive enhancers offer? If better memory, for example, is unequivocally beneficial, why do seemingly trivial neuromolecular changes that would enhance memory, such as the overexpression of NMDA receptors in the hippocampus (Tang

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et al., 1999), not (to our knowledge) exist in natural populations? If it is so easy to evolve superior cognitive capacities, why aren't we smarter already?

The resolution of this evolutionary paradox is the focus of this article. We conclude not only that the categorical more-is-better assumption is false in relation to cognition (see Hertwig & Todd, 2003) but also that a linear model of cognition is false in two distinct ways, both of which we derive from the evolutionary reality that natural selection optimizes over trade-offs—that is, it produces the best outcome possible given the constraints of the ecological, cognitive, and physiological systems over which it operates. This does not mean that the human mind is optimally designed or that it cannot be improved. It means that cognitive traits have evolved under both ecological and physiological constraints. Without these constraints, selective forces associated with improved performance (and thus fitness) would drive the performance capacities of cognitive traits ever upward. As we will explain, all known evolutionary trajectories inevitably run up against constraints that prevent such runaway selection. The costs eventually outweigh the benefits. To enhance cognition in a truly beneficial way, we must understand the constraints that have kept us from being enhanced already.

In what follows, we describe the two kinds of evolutionary trade-offs to which research on cognitive enhancement must pay heed. We then provide theoretical and empirical evidence for their existence. Finally, we outline specific implications for future research and suggest contexts in which enhancements may be most likely to succeed.

Evolutionary Cognitive Trade-Offs

The evolution of any living system is the result of trade-offs over multiple constraints. Consider the human female pelvis. Because its dimensions are small relative to a baby's head, obstetric complications during labor are common. Why hasn't evolution improved the survival chances of both mother and baby by selecting for a larger female pelvis? The widely accepted explanation is that the optimal pelvis for bipedal locomotion and the optimal pelvis for encephalization (the progressive increase in the baby's brain size) place competing demands on the human pelvis. Bipedal locomotion requires substantial skeletal changes, including alterations in the pelvic architecture (Wittman & Wall, 2007), and such changes must compete (in an evolutionary sense) with the obstetric demands of human babies' relatively large brains.

Cognition is the product of similar trade-offs over multiple constraints. Notably, these arise from two different sources: (a) the kinds of problems a flexible intelligence has evolved to solve and (b) constraints on the underlying biology. These two kinds of constraints generate within-domain and between-domain trade-offs, respectively. These trade-offs have typically been confounded in the literature on enhancement, but their distinctness is evident in the ubiquity of *inverted U-shaped performance functions* (henceforth ∩-shaped performance functions) and the *side effects* of enhancement (Cools & Robbins, 2004; Husain & Mehta, 2011), respectively. These two kinds of trade-offs explain why we are not smarter than we are.

Trade-offs within domains: ∩-Shaped performance functions

Performance functions that are ∩-shaped are often observed for optimal-control problems in which the goal is to maximize benefits subject to some cost function (i.e., specified constraints). Such problems often require deciding when to stop taking one action and switch to another. Specific examples include when to accept a particular job candidate or a mating partner rather than to continue looking for another, when to leave one resource patch to move to another, and when to stop collecting information and make a decision. Cognition must solve these kinds of attention-switching problems in countless domains that combine poorly defined completion criteria (i.e., in which it is unclear when to stop) with opportunity costs (Hills, Todd, & Goldstone, 2010). Furthermore, even in problems that provide well-defined completion criteria, there may be multiple possible trajectories to a solution, and finding a solution may involve abandoning an approach that is not working.

The cognitive problems of everyone, from nematodes to office workers, have been formulated as optimal-control problems (e.g., Pirolli, 2007). The ecological regularity of such problems has led to the proposal that regulating goal maintenance and abandonment (i.e., persistence in action) is one of the key capacities that led to the flexible intelligence associated with executive cognition (Hills et al., 2010). For support, this proposal points to the shared structure of control problems across domains and the shared neural correlates and cognitive function of the processes that solve these problems across species. As one example, domain-general cognitive-control processes related to working-memory span are governed by attentional control and updating (see Unsworth & Engle, 2007). These control processes, by their nature, influence how attention is distributed over potential goals in an environment.

Mathematically, optimizing the control of attention over opportunity costs can be reduced to a search problem (see Pirolli, 2007), in which cognition attempts to maximize its payoff by choosing how long, t^*, to perseverate on one action or goal state before switching to another. With the realistic assumption that any course of action is associated with reduced payoffs over time, $F(t^*)' < 0$, and that it costs some amount of time, T, to switch between actions, the optimal t^* solves the equation

$$F(t^*)' = \frac{\bar{F}(t^*)}{t^* + T},$$

where $\bar{F}(t^*)$ is the mean payoff associated with all other action payoff functions. In words, the giving-up (or abandonment) rate, $F(t^*)'$, associated with one action should be related to the opportunity costs associated with switching to other possible actions. For any problem that fits this basic framework, a ∩-shaped performance curve arises naturally over the values of t^* (see Fig. 1). Given that problems of optimizing over subgoals make up a significant portion of real and laboratory cognitive tasks (e.g., Tower of London, category fluency, and operation span), one should expect to find ∩-shaped dose–response curves among people who have taken pharmaceuticals designed to increase the duration of focused attention, t, with respect to a given task.

For illustration, consider amphetamines, Ritalin, and modafinil, all of which have been proposed as cognitive enhancers of attention. These drugs exhibit some positive effects on cognition, especially among individuals with lower baseline abilities. However, individuals of normal or above-average cognitive ability often show negligible improvements or even decrements in performance following drug treatment (for details, see de Jongh, Bolt, Schermer, & Olivier, 2008). For instance, Randall, Shneerson, and File (2005) found that modafinil improved performance only among individuals with lower IQ, not among those with higher IQ. Farah, Haimm, Sankoorikal, and Chatterjee (2009) found a similar nonlinear relationship of dose to response for amphetamines in a remote-associates task, with low-performing individuals showing enhanced performance but high-performing individuals showing reduced performance. Such ∩-shaped dose–response curves are quite common (see Cools & Robbins, 2004). Inconsistent with the notion that more is inescapably better, these results suggest that optimal control of attention represents a delicate balance between too much and too little focus.

Trade-offs between domains: Cognitive side effects

Even when behavior does not suffer within-task trade-offs, enhancement gains may not be a free lunch. The reason is interdependencies across domains. Recall our example of the female pelvis. Expanding the birth canal would reduce the likelihood of

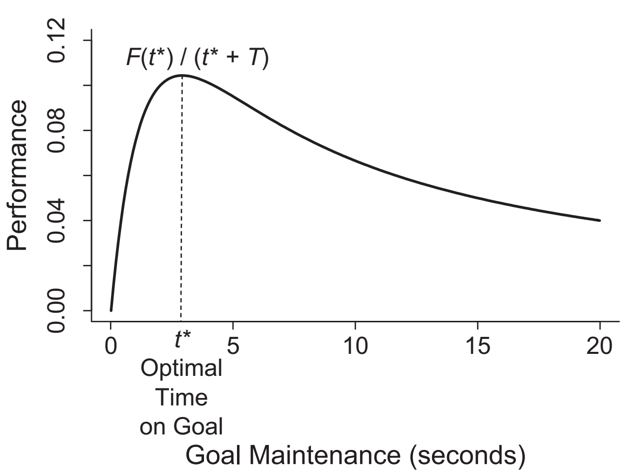

Fig. 1. Optimal allocation of attention to a goal state. Performance scores associated with resource intake per unit time are optimal when the local goal, attending to a specific target or action, is maintained for an intermediate value of time, t^*, before switching to a new action with a similar cumulative payoff function. For visualization purposes, we let $T = 5$ seconds and $F(t) = 1 - e^{-0.6t}$.

obstetric complications at the expense of efficient bipedal locomotion. Such interdependencies apply across cognitive domains as well as between cognition and other more general domains, such as mental and physical health. One common example is the rise in anxiety and loss of fine motor control often found following high doses of caffeine (Smith, 2002).

The Ashkenazi Jew population provides a less well-known but more dramatic example of between-domains trade-offs (see Cochran, Hardy, & Harpending, 2006). Among the Ashkenazi Jews, the average IQ is approximately 0.7 to 1 standard deviation above that of the general European population. Recent evidence indicates that this rise in IQ was the consequence of evolutionary selection for greater intelligence among European Jews over approximately the last 2,000 years. However, this greater capacity for learning appears to have come with a specific side effect: a rise in the prevalence of sphingolipid diseases, such as Tay-Sachs, Niemann Pick, Gaucher, and mucolipidosis. Central to our point, these diseases are correlated with the same neural causes that rendered possible increased IQ, such as increased dendrite development.

Luria's (1968) famous examination of a man named Shereshevskii, whose memory appeared to have "no distinct limits" (p. 11) provides still another illustration. Luria concluded that a seemingly unlimited memory was likely too much of a good thing. For example, "S" complained that his memory for faces was poor: "People's faces are constantly changing; it's the different shades of expression that confuse me and make it so hard to remember faces" (p. 64). "Unlike others, who tend to single out certain features by which to remember faces," Luria remarked, "S. saw faces as changing patterns . . . , much the same kind of impression a person would get, if he were sitting by a window watching the ebb and flow of the sea's waves" (p. 64). One interpretation of S's poor memory for faces is that key cognitive processes such as abstraction, generalization, and trend detection are hampered by a memory that cannot separate the important from the inconsequential.

The benefits of limited memory have also been proposed to explain the curious constraints on working-memory span to a limited number of information chunks (for several related examples, see Hertwig & Todd, 2003). Similar trade-offs have been observed between the rate of initial learning and long-term retention, leading to the counterintuitive proposal of *desirable difficulties* (Bjork, 2011). These complications represent conditions that—though they present difficulties for early learning—boost long-term retention and transfer. Cognitive enhancers, in contrast, promise that learning and retention can become easier at the same time.

Perhaps the clearest natural evidence for between-domain trade-offs in performance across tasks comes from savants, whose spectacular skills in one domain are associated with poor performance in other domains. Those associations are not coincidental. Savant-like skills can be induced in healthy participants by *turning off particular functional areas of the brain*—for example, via repetitive transcranial magnetic stimulation (Snyder, 2009).

The occurrence of cognitive side effects also depends on individual differences. As an example, working memory is correlated with performance on many cognitive tasks, such as the Scholastic Aptitude Test. However, individuals with high working-memory capacity often fail to hear their own name in a cocktail-party task and recall fewer items from a list after experiencing a context change (see Unsworth & Engle, 2007). These results demonstrate that the effects of enhancements should be viewed as we view adaptations: Enhancement is only meaningful with respect to specific individuals in specific environments. Although the empirical possibility of a domain-general, cognitively enhanced "supermind" remains, evolutionary theory would suggest it is extremely unlikely.

Cognitive Enhancement: What Follows From the Evolutionary View?

Previous debates on pharmacological enhancement of cognition have been concerned primarily with issues such as the drugs' potential physiological side effects, addictive potential, and ethical implications (e.g., Greely et al., 2008). Our aim here is to bring some theoretical predictability to the arguments by attempting to provide an answer to the evolutionary question: Why aren't we smarter already? The answer can provide much-needed direction in determining where cognitive enhancers may be truly beneficial and where their success is likely to be compromised by trade-offs. We believe that the following points are crucial to an evidence-based approach to cognitive enhancement.

First, the commonality of ∩-shaped performance functions (Fig. 1) suggests that investigations of cognitive enhancers need to describe the performance functions associated with the tasks for which they are intended to produce optimal behavior; these task-specific performance functions then need to be combined with dose–response curves. Second, such investigations should report performance expectations relative to individual differences in baseline performance in the task, as well as more general measures of intelligence. Between-subjects designs that overlook such differences are almost guaranteed to over- or underestimate actual effects and invite improper generalizations of their usefulness to people of different abilities. Third, the possibility of performance trade-offs between domains suggests that researchers need to cast a wide net for potential side effects until principled methods for predicting prospective side effects are developed.

Identifying cognitive side effects is crucial because optimization over multiple constraints implies a *gain/loss asymmetry*. Figure 2 illustrates this asymmetry. Assuming that the values of a cognitive trait (and related performance scores) follow decelerating functions (i.e., gains in functionality have diminishing returns), then beyond the point of the optimal trade-off, t^*, between two traits A and B, shifting the values of trait A upward (through cognitive enhancers) yields a gain ($\Delta T1$) on performance scores correlated with trait A but simultaneously a loss ($\Delta T2$) in performance of larger magnitude on trait B. Such an asymmetry is an evolutionary necessity for any trait that has reached an evolutionarily stable state. That is, the asymmetry of gains and losses stabilizes selective forces around an optimal trade-off (for examples related to mental disorders, see Keller & Miller, 2006).

Psychological science has much to offer to the development and understanding of cognitive enhancements. First, it can demonstrate in what tasks and for whom behavior diverges from "optimal" performance and thus point to environments and populations in which enhancements may be likely to be most effective. Second, it can identify interdependencies

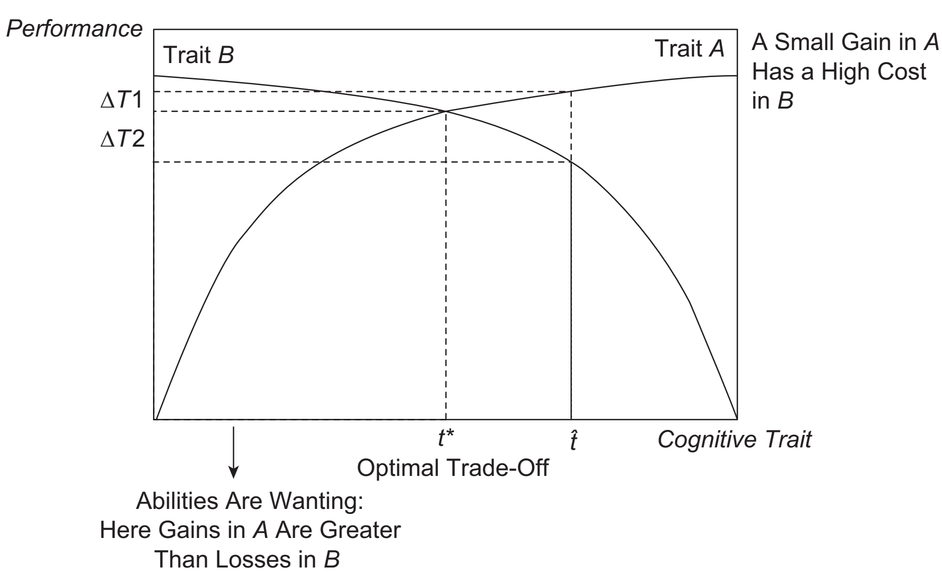

Fig. 2. A gain/loss asymmetry. Performance scores associated with traits *A* and *B* follow decelerating functions (i.e., gains in functionality have diminishing returns); t^* represents the point of the optimal trade-off between both traits. Shifting the values of trait *A* upward (through cognitive enhancers) yields a performance gain ($\Delta T1$) associated with trait *A* that is smaller in magnitude than the corresponding performance loss associated with trait *B* ($\Delta T2$).

between cognitive traits (see Miyake et al., 2000) and thus indicate where cognitive side effects should or should not be expected. Therefore, in our view, psychological science faces an important opportunity to provide critical direction to enhancement research, a field that is only beginning to understand its subject matter.

Recommended Reading

Cools, R., & Robbins, T.W. (2004). (See References). A comprehensive review of the paradoxical effects of cognitive enhancements—that is, the simultaneous occurrence of increased cognitive performance and cognitive side effects.

de Jongh, R., Bolt, I., Schermer, M., Olivier, B. (2008). (See References). A comprehensive review of enhancements targeting memory, attention, and affect.

Grant, A.M., & Schwartz, B. (2011). Too much of a good thing: The challenge and opportunity of the inverted U. *Perspectives on Psychological Science, 6*, 61–76. A thought-provoking review of nonmonotonic inverted-U-shaped effects across various domains of human activity including choice and virtues.

Hills, T.T., Todd, P.M., & Goldstone, R.L. (2010). (See References). Discusses the generality of trade-offs over tasks with multiple competing subgoals and offers an evolutionary perspective on the consequences for cognition.

Husain, M., & Mehta, M.A. (2011). (See References). A clearly written, user-friendly, and accessible review on cognitive enhancements, reviewing some of the effects—positive and negative—that cognitive enhancements have on healthy people and patients.

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Declaration of Conflicting Interests

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References

Bjork, R.A. (2011). On the symbiosis of forgetting, remembering, and learning. In A.S. Benjamin (Ed.), *Successful remembering and successful forgetting: A Festschrift in honor of Robert A. Bjork* (pp. 1–22). London, England: Psychology Press.

Cochran, G., Hardy, J., & Harpending, H. (2006). Natural history of Ashkenazi intelligence. *Journal of Biosocial Science, 38*, 659–693.

Cools, R., & Robbins, T.W. (2004). Chemistry of the adaptive mind. *Philosophical Transactions of the Royal Society London A, 362*, 2871–2888.

de Jongh, R., Bolt, I., Schermer, M., & Olivier, B. (2008). Botox for the brain: Enhancement of cognition, mood and pro-social behavior and blunting of unwanted memories. *Neuroscience and Biobehavioral and Reviews, 32*, 760–776.

Farah, M.J., Haimm, C., Sankoorikal, G., & Chatterjee, A. (2009). When we enhance cognition with Adderall, do we sacrifice creativity? A preliminary study. *Psychopharmacology, 202*, 541–547.

Greely, H., Sahakian, B., Harris, J., Kessler, R.C., Gazzaniga, M., Campbell, P., & Farah, M.J. (2008). Towards responsible use of cognitive-enhancing drugs by the healthy. *Nature, 456*, 702–705.

Hertwig, R., & Todd, P.M. (2003). More is not always better: The benefits of cognitive limits. In D. Hardman & L. Macchi (Eds.), *Thinking: Psychological perspectives on reasoning, judgment and decision making* (pp. 213–231). Chichester, UK: John Wiley & Sons.

Hills, T.T., Todd, P.M., & Goldstone, R.L. (2010). The central executive as a search process: Priming exploration and exploitation across domains. *Journal of Experimental Psychology: General, 139*, 590–609.

Hoffman, P. (1998). *The man who loved only numbers: The story of Paul Erdös and the search for mathematical truth*. New York, NY: Hyperion.

Husain, M., & Mehta, M.A. (2011). Cognitive enhancement by drugs in health and disease. *Trends in Cognitive Sciences, 15*, 28–36.

Keller, M.C., & Miller, G. (2006). Resolving the paradox of common, harmful, heritable mental disorders: Which evolutionary genetic models work best? *Behavioral and Brain Sciences, 29*, 385–452.

Luria, A.R. (1968). *The mind of a mnemonist: A little book about a vast memory*. New York, NY: Basic Books

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., & Wager, T.D. (2000). The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks: A latent variable analysis. *Cognitive Psychology, 41*, 49–100.

Pirolli, P. (2007). *Information foraging theory: Adaptive interaction with information*. New York, NY: Oxford University Press.

Randall, D.C., Shneerson, J.M., & File, S.E. (2005). Cognitive effects of modafinil in student volunteers may depend on IQ. *Pharmacology Biochemistry and Behavior, 82*, 133–139.

Smith, A. (2002). Effects of caffeine on human behavior. *Food and Chemical Toxicology, 40*, 1243–1255.

Snyder, A. (2009). Explaining and inducing savant skills: Privileged access to lower level, less-processed information. *Philosophical Transactions of the Royal Society B, 364*, 1399–1405.

Tang, Y.P., Shimizu, E., Dube, G.R., Rampon, C., Kerchner, G.A., Zhuo, M., . . . Tsien, J.Z. (1999). Genetic enhancement of learning and memory in mice. *Nature, 401*, 63–69.

Unsworth, N., & Engle, R.W. (2007). The nature of individual differences in working memory capacity: Active maintenance in primary memory and controlled search from secondary memory. *Psychological Review, 114*, 104–132.

Wittman, A.B., & Wall, L.L. (2007). The evolutionary origins of obstructed labor: Bipedalism, encephalization, and the human obstetric dilemma. *Obstetrical & Gynecological Survey, 62*, 739–748.