Cognitive Enhancement: A Review of Technology

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Introduction

Cognitive enhancement aims at amplifying or extending the abilities of the mind through internal or external hardware or software. Up until recently only internal software in the form of trained efficient mental algorithms and the general enhancing effects of paper-based information management was available. As cognitive neuroscience has advanced the range of potential internal enhancement treatments have increased[3], as well as the availability and power of external hardware/software support.

A Taxonomy of Cognitive Enhancement

A basic taxonomy of proposed cognitive enhancements can be based on whether the enhancement amplifies an existing capacity or adds a new capacity, and then proceed to list the possible capacities and the different means to achieve enhancement.

Many medical interventions aim to prevent loss of capacity through illness or ageing. In some cases this blends into enhancement by increasing the resiliency of the capacity. Memory or attention less affected by stress, reaction speed unaffected by tiredness or working memory "graceful breakdown" rather than confusion when subjected to an excessive number of inputs could all be considered cognitive enhancements. Such resiliency could be achieved by strengthening the core capacity, reducing the interference from other capacities or outside factors or enabling "backup" capacity.

- **Resilient capacities**
- **Amplify capacities**
    - Memory/Learning
        - Working Memory
        - Semantic/Episodic Long Term Memory
        - Procedural Memory
        - Cortical Reorganization
        - Enhanced epistemology
    - Executive function

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[3] (Farah, Illes et al. 2004)

        - Attention
            - Awareness
            - Focus
            - Multitasking
            - Searching
        - Self-control
        - Metacognition
    - Intelligence
        - Problem solving
        - Planning
        - Overview
        - Creativity
        - Avoiding biases
    - Mental imagery
    - Perception
    - Motorics
    - Language ability
    - Low-level mental function
        - Mental energy
        - Mental speed
        - Timing
        - Awakeness
- **New capacities**
    - New senses
    - New reflexes
    - Human-Computer Communication

Enhancement Technologies

Cognitive enhancement technologies can also be divided into whether they are external/internal to the user and whether they are hardware/software.

While the technologies involved in enhancement might be sorted into fields such as pharmacology, genetics, neuroscience or psychology, this might be less useful than a general distinction between invasiveness and material requirements. The reason is that the current technological convergence is blurring the borders between the technologies and academic disciplines. The old disjunction between psychotherapeutic and pharmacological mental health treatments is being dissolved as it is becoming clear that both approaches complement each other. Advanced cognition enhancing drugs may be just as much nanodevices as pharmaceuticals, while advanced user interfaces may consist of software, hardware and cognitive methods of learning how to apply them.

Internal hardware

Internal hardware deals with biological modifications such as genetic modifications (through hybridization or screening), surgery, tissue engineering, pharmaceutical or nutritional interventions and neural implants. External stimulation such as TMS can also be viewed as hardware changes. This is the category that has drawn most ethical attention.

Internal software

Internal software seeks to enhance cognition by learning improved cognitive strategies or making use of the plasticity of the brain. This is a very broad field, and this review cannot deal with cognitive behavior therapy, study techniques, teaching and learning theories, but these represents a vast amount of experience with mental software.

Many forms of mental training have been developed for religious reasons, performed mostly because they were seen as inherently valuable rather any practical utility (although acquisition of ”wisdom” may be viewed as a practical goal). James H. Austin argues that the meditation practices of Zen Buddhism aims at changing the state or reprogramming the arousal, attention and motivation systems of the brain[4]. In the long run these changes (hopefully) unlearn unhealthy behaviors and produce a state of effective, direct perception and action. Since attention regulates how much the cortex can reorganize itself[5] and meditation training attempts to achieve extreme states of attention it is plausible that they could permanent effects.

Other forms of mental training and visualization are in widespread use in sports[6] and rehabilitation[7], with apparently good effects. A likely explanation for their efficacy is that they activate the neural networks involved in executing a skill at the same time the task is held in close attention, which in turn enhances plasticity and reorganization/learning.

Even general mental activity, “using the brain muscle” can improve performance[8] and long-term health[9], as well as relaxation techniques to regulate the activation of the brain[10]. It has been suggested that the Flynn-effect[11], a general increase in raw intelligence test scores by 3 IQ points per decade in most western countries, can be explained by increased cognitive demands of abstract and visual thinking (although factors such as increased nutrition and changes in schooling also likely play a part)[12]. It does not appear to be an increase in general intelligence, but rather a change in which specific forms of intelligence are developed.

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[4] (Austin 1998)
[5] (Stefan, Wycislo et al. 2004)
[6] (Feltz and Landers 1983)
[7] (Jackson, Doyon et al. 2004)
[8] (Nyberg, Sandblom et al. 2003)
[9] (Barnes, Tager et al. 2004)
[10] (Nava, Landau et al. 2004)
[11] (Flynn 1987)
[12] (Neisser 1997; Blair, Gamson et al. 2005)

Although deliberate reprogramming of the brain has profound effects it is very rare. The amount of work needed is so large that most people are content with easier learning. Much what we learn in school is mental software for managing different fields: mathematics, categories of concepts, language and problem solving in particular subjects. This kind of mental software reduces our mental load through clever encoding, organization or processing. Instead of memorizing multiplication tables we compress the pattern into simpler rules of multiplication, which in turn (among very ambitious students) can be organized into efficient mental calculation methods like the Trachtenberg system[13]. Such specific methods have a smaller range of applicability but can improve performance within this range significantly. They represent a form of crystalline intelligence different from the fluid intelligence of general abilities and problem solving[14]. Cognitive enhancement aims at the harder problem of improving fluid abilities, but the relative ease and utility of crystalline abilities have made them popular targets of internal and external software.

External hardware and software

External aids and tools have a tremendous potential. Improving human cognition through external object has a long history. We use our bodies and nearby objects as extensions of working memory. The typically human ability to create objects for new purposes allows us to create objects to store information and to communicate. The first such objects may have been the small clay tokens found across the Near East dating from 8000 BC up to the time of writing in 3000 BC[15]. Originally depicting objects they were likely used as counting aids and records of possession. Over time their shapes became increasingly abstracted, eventually leading to writing on clay tablets. Once writing appeared human cultural evolution accelerated since information was stored and spread more efficiently. Formalized methods of organizing the information could be developed, from accounting systems to indexed archives.

A recent key breakthrough is that information is no longer stored in a passive form but instead can be actively read, processed, transferred and changed by computers. This allows us to outsource more and more of our cognitive systems into our environment.

The classic vision of external cognitive enhancement is Vannevar Bush's 1945 vision of the Memex[16], explicitly described as an extension of the user's memory. The memex would store all communications of its user as microfilms that later could be retrieved and associated. It combined what we today call hypertext with search engine functions. That it was technically impossible at that time did not matter: the idea stimulated research that eventually led in the direction of the Internet and Web. Inspired by the memex Doug Engelbart started the Augmentation Research Center in the 60's, in turn innovating interaction methods such as the mouse, graphical user interfaces, text processing,

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[13] (Trachtenberg 2000)
[14] (Cattell 1987)
[15] (Schmandt-Besserat 1997)
[16] (Bush 1945)

hypertext, e-mail and teleconferencing over networks. ARC's historical importance for computer development can hardly be overstated, but it was mostly the particular applications and tools that were used, not the overall vision of cognitive enhancement.

In computer science the forms of cognition enhancement that have been discussed can be roughly classified into:

- Collective cortex – systems that help groups of humans (or humanity as a whole) to improve their shared cognition.
- Artificial Intelligence - software that acts as an independent being, either general or task-specific.
- Software agents – software that acts on behalf of a person.
- Intelligence augmentation
    - Software – software intended to act as tools or environments simplifying human cognitive processes. This encompasses a sizeable fraction of all computer software.
    - Mediation - embedding the human within an augmenting "shell" such as wearable computers or virtual reality.
    - Smart environments – adding augmentation capabilities to objects in the environment. An example is the ubiquitous computing vision, where objects are equipped with identities, ability to communicate and to support the user[17]. The vision, "calm technology", is to avoid visible and attention-demanding equipment.

It should be noted that much software that fits into these categories was not developed with an explicit cognition enhancement goal in mind.

In both the mediation and smart environment approach the user is surrounded by an "exoself"[18] consisting of their files, software, webpages, bookmarks, online identities and other personal information. In a smart environment the exoself manifests itself through nearby objects, moving with the person (e.g. files can be viewed on any nearby PDA and printed on the closest printer). The exoself may have active components acting on the person's behalf or augmenting abilities.

This classification suggests a scale of independence from the enhanced person. AI and agents act outside the direct control of the person, while software takes the role of specific cognitive processes that have to be deliberately initiated and exoselves amplify the mental actions of the person. This can be applied to other forms of enhancements: the more enhancements become autonomous, the less they can be said to be personal enhancements and the more they become external things.

One of the most philosophically aware variants of human-computer interfacing is the humanistic intelligence concept of Steve Mann[19]. Within this framework a worn

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[17] (Weiser 1991)
[18] The term is borrowed from Greg Egan, *Permutation City*, Eos 1995.
[19] (Mann 2001)

computer is considered a second brain and its sensory modalities additional senses that merge with the user's senses. Ideally the relationship should be a reciprocal integration: the computer should use the human's mind and body as peripherals just as the human uses the computer as a peripheral. The aim is synergy with the human, using the physical proximity and close link to achieve constancy (the system is always ready for use, just like our normal cognitive capacities), augmentation (enhancing the intellect or senses, without distracting from primary tasks) and encapsulating mediation that affords solitude (by acting as a filter of incoming information) and privacy (by filtering outgoing information). Mann has also coined the term existential technology for technology that promotes the user's self-determination, self-expression and self-actualization[20]. To achieve this the user needs to be able to control the technology (not necessarily consciously), ideally to the extent that it is experienced as an extension of the body of the user. At the same time it is observable, in the sense that its information and activities can be monitored, yet unmonopolizing of attention or perception.

Humanistic intelligence/existential technology represent a human-computer interaction perspective of cognition enhancement where information flow, affordances and functional integration are central. The computer and software are not independent of the user but may still be attentive of information in the environment the user is not aware of. The system may be proactive (such as in an application where it is continuously storing a buffer of visual data, saving the images leading up to a startle response[21]) but it is proactive in the same sense as non-conscious mental modules are proactive (e.g. the midbrain balance system). By being intimate, unrestrictive and controllable it promotes a sense of being an extension of the user rather than something independent.

The usability of extern hardware and software is limited by design, mobility, energy and size. As electronics shrinks ever more size has become increasingly irrelevant: today it is user finger size that determines how small cell phones can become, not the electronics. The shrinkage increases mobility together with the spread of wireless communication.

Providing electronics with energy is more problematic. Cables limit mobility and forces the device to be used in a particular (indoor) environment, in turn limiting potential uses. Advances in battery technology and power saving electronics has improved battery lifetimes significantly but explicit recharging requires that the user places the device in a recharger. In a smart environment nearly anything may contain electronics, making this inefficient. In the future it is likely that the energy for larger units may come from fuel cells and for personal systems the user's body or body movements[22]. The environment may power low energy devices through solar cells or induction from radio requests.

This leaves the design issue: how does the hardware and software interact with the users, and does it fit into their lives? Unlike the other issues design does not have any defined engineering answer. Given the diversity of human desires, cognition and lifestyles it is likely that few constructions would fit all.

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[20] (Mann 1997; Mann and Niedzviecki 2001)
[21] (Healey and Picard 1998)
[22] (Starner 1996)

Social Cognitive Enhancement

The traditional approach to cognition enhancement deals solely with individual cognitive abilities. But as remarked earlier, much of human cognition is distributed across many minds.

The WWW and e-mail are among the most powerful kinds of cognitive enhancement sofrware developed so far. Using such social software the collected intelligence of large groups can be concentrated and distributed[23].

This potential was understood by Vannevar Bush in his memex paper[24]. He suggested that documents should be associable through hypertext both within an individual user's files but also between users, enabling them to share an expanded memory. Connected systems allow many people to collaborate in the construction of shared knowledge and solutions: the more that connect, the more powerful the system becomes[25]. The information is not just stored in the documents themselves but in how they relate to each other. When such interconnected information resources exist automated systems such as search engines[26] can extract useful information from them. The information may have been created and linked for entirely other purposes than it is being used for. This newly extracted information increases the utility further, and contributes to the accumulation of ever more knowledge.

A group of people working together produces ideally a result proportional to the time used and the number of participants. Each individual produces their own result as well as extra results due to group synergies. The later factor can be assumed to grow with the size of the group since more members are available with their talents and knowledge to each member. But the drawback of large groups is that to collaborate the members need to coordinate with each other, something that takes up valuable work time. The larger the group the more time is "wasted" in meetings. A sufficiently large group would spend all its time on internal administration and none in productive work: a pure bureaucracy. The coordination problems can be reduced by selecting some members to specialize in communicating or through hierarchical forms of organization, but they will not disappear.

Cognitive enhancement can affect the productivity of a group in three ways. It can improve individual capacities, something which affects the result proportionally to the size of the group. It can improve the group synergies, making the result grow with the square[27] of the group size: the improvement is more noticeable for large groups. It can

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[23] (Surowiecki 2004)
[24] (Bush 1945)
[25] (Drexler 1991)
[26] (Kleinberg 1999)
[27] Assuming that the synergy is proportional to the number of other members for each member.

make coordination more efficient, in turn enabling larger groups or giving more productive time.

The Internet is an example of a massive social cognitive enhancement. If costs of communication can be reduced more people can contribute. If software reduces the coordination costs (through mailing lists, web forums, address books and search engines) very large and inhomogeneous groups can collaborate on shared projects. Such groups of shared interests such as amateur journalist "bloggers" and open source programmers have demonstrated that they can not only achieve large projects (such as online campaigns, the Wikipedia encyclopedia or the Linux operating system) but also efficient error correction[28].

Traditionally the scientific method has been based on error correction by repeated and independent experiments, reports of contradictions that are spread and that scientists are expected to criticize each other's publications. Even if individual scientists and experiments are fallible the total effect is a tendency to suppress erroneous results in the long run. This has occurred within a community dominated by strong values and supported despite a fairly high cost. The same method can now be applied in other areas, in informal groups and at a lower cost, for example in the development of open source software and online journalism.

An interesting variant of knowledge aggregation and signaling is information markets. Here participants trade in predictions of future events, and their prices will tend to reflect the best information available of whether they will occur[29]. Such markets also appear to be self-correcting and resilient[30].

Social software appears to benefit large and rich groups that can afford to use it in an early stage and can exploit their economies of scale. But small groups are also made more effective and often have proportionally lower costs and faster reactions. There is also the possibility of forming very large groups on an informal basis thanks to low thresholds of entrance, such as blog communities, something that can overshadow the earlier large groups' economies of scale. The result is that broad but not "high" (i.e. strictly organized) organizations are promoted.

In the long run it is possible that the shared social intelligence of humans will be complemented by artificial intelligence. While AI is often described as a replacement or substitute of human intelligence, it seems likely that the main application will be to amplify human intelligence. Today the results of AI - speech recognition, expert systems, pattern recognition, machine learning and agents – are at the core of much cognition enhancement software. Independent programs able to learn, reason flexibly and act would be a great complement to human problem solving and knowledge representation strategies. They would be embedded within the shared social cognitive enhancement

[28] (Raymond 2001; Giles 2005)
[29] (Hanson, Polk et al. 2003)
[30] (Hanson, Opre et al. 2006)

networks, attracted to them if nothing else by self-interest and the law of comparative advantage.

State of the Art of Cognitive Enhancement

Memory and Learning Enhancement

Genetic Memory Enhancement

Genetic memory enhancement has been demonstrated in rats and mice. In normal animals during maturation expression of the NR2B subunit of the NMDA receptor is gradually replaced with expression of the NR2A subunit, something that may be linked to less brain plasticity in adult animals. Tsien et al.[31] modified mice to overexpress the NR2B. The NR2B "Doogie" mice demonstrated improved memory performance, both in terms of acquisition and retention. This included unlearning of fear conditioning, which is believed to be due to learning a secondary memory[32]. The modification also made them more sensitive to certain forms of pain, showing a potentially non-trivial trade-off[33].

Increased amount of brain growth factors[34] and the signal transduction protein adenylyl cyclase[35] have also produced memory improvements. An interesting observation was that unlearning of a task in the first study and fear conditioning in the second took longer for the modified mice than unmodified mice, unlike the mice in the Tsien study. Different memory tasks were also differently affected: the second study enhanced recognition memory but not context or cue learning. Mice with a deleted cbl-b gene had normal learning but long-term retention enhancement, presumably indicating that the gene is a negative regulator of memory[36]. These enhancements may be due to improved neural plasticity in the learning task itself, or that the developing brain develops in a way that promotes subsequent learning or retention.

The cellular machinery of memory appears to be highly conserved in evolution, making the interventions likely to have close counterparts in humans[37]. Genetic studies have also found genes in humans whose variations account for up to 5% of memory performance[38]. These include the genes for the NMDA receptor and adenylyl cyclase that were mentioned above, as well as other parts of the synaptic signal cascade. These are clear targets for enhancement.

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[31] (Tang, Shimizu et al. 1999)
[32] (Falls, Miserendino et al. 1992)
[33] (Wei, Wang et al. 2001)
[34] (Routtenberg, Cantallops et al. 2000)
[35] (Wang, Ferguson et al. 2004)
[36] (Tan, Liu et al. 2006)
[37] (Edelhoff, Villacres et al. 1995; Bailey, Bartsch et al. 1996)
[38] (de Quervain and Papassotiropoulos 2006)

Given these early results it seems very likely that there exist many potential genetic interventions that directly or indirectly improve aspects of memory. If it turns out that the beneficial effects of the treatments are not due to changes in development presumably some of the effects can be achieved by supplying the brain with the substances produced by the memory genes without resorting to genetic modification. But the modification makes the individual independent of an external supply and guarantees that the substances end up in the right place.

Memory Enhancing Drugs

Memory enhancing drugs is a broad field that has developed since the 1970's, although it has been known for a long time that stimulants can improve learning performance[39]. Today we have several families of memory enhancing drugs affecting different aspects of the learning and encoding process. They range from stimulants[40], nutrients[41] and hormones[42] over cholinergic agonists[43] and the piracetam family[44] to ampakines[45] and consolidation enhancers[46]. It should be noticed that learning enhancement or modification might not just be useful for traditional memory but also for unlearning phobias and addictions[47], potentially allowing memory modification.

The earliest cognition enhancing drugs were mainly nonspecific stimulants and nutrients[48]. Glucose is the major energy source for the brain, which cannot store it and relies on a continuous supply to function. Increases in availability (either due to ingestion or short-term stress hormones) improve memory[49]. Stimulants enhance memory either by increasing the amount of neuron activity or by releasing neuromodulators, both factors that make the synaptic changes underlying learning more likely. The growing understanding of memory allowed the development of more specific drugs. Stimulating the cholinergic system, which appears to gate attention and memory encoding, was a second step. Current interest is focused on intervening into the process of permanent encoding in the synapses, which has been elucidated to a great extent and hence has become a promising target for drug development. The goal would be drugs that not just allow the brain to learn quickly but also facilitate selective retention of the information that has been learned. It is known that the above families of drugs can improve performance in particular memory tests. It is not yet known whether they also promote useful learning in real-life situations.

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[39] (Lashley 1917)
[40] (Soetens, Dhooge et al. 1993; Lee and Ma 1995; Soetens, Casaer et al. 1995)
[41] (Foster, Lidder et al. 1998; Korol and Gold 1998; Winder and Borrill 1998; Meikle, Riby et al. 2005)
[42] (Gulpinar and Yegen 2004)
[43] (Iversen 1998; Power, Vazdarjanova et al. 2003; Freo, Ricciardi et al. 2005)
[44] (Mondadori 1996)
[45] (Ingvar, AmbrosIngerson et al. 1997; Lynch 1998)
[46] (Lynch 2002)
[47] (Pitman, Sanders et al. 2002; Ressler, Rothbaum et al. 2004; Hofmann, Meuret et al. 2006)
[48] During antiquity honey water, hydromel, was used for doping purposes.
[49] (Wenk 1989; Foster, Lidder et al. 1998)

Even common herbs and spices such as sage can improve memory and mood through chemical effects[50]. An important aspect of these results is that sage is a common, traditional and unregulated spice. While less powerful than dedicated cholinesterase inhibitors it demonstrates that attempts to control access to cognition enhancing substances will be problematic. Even chewing chewing gum has been shown to affect memory, possibly through increased arousal or blood sugar[51].

A notable form of chemical enhancement is pre- and perinatal enhancement. By giving choline supplementation to pregnant rats the performance of their pups was enhanced, apparently by changes in neural development[52]. Given the ready availability of choline such prenatal enhancement may already (inadvertently) take place. Deliberate changes of maternal diet may hence be seen as part of the cognitive enhancement spectrum.

Enriched rearing environments have been found to increase dendritic arborisation and produce synaptic changes, neurogenesis and improved cognition[53]. There is evidence that Alzheimer's patients who discontinue the use of cholinestrase inhibitors have slower cognitive decline than patients who got placebo[54]. Based on this a study was done to compare the effects of chronic exposure to cholinergic cognition enhancers to the effect of an enriched rearing environment in rats[55]. It was found that the drugs and the rearing environment did improve spatial learning and resistance to memory disruption, even after the drugs had been discontinued. Neural changes during memory consolidation were also similar. This suggests that the drugs produced a more robust and plastic neural structure able to learn more efficiently. The combination of drugs and enriched environment did not significantly improve the rats' abilities.

Memory Training

The classic form of cognitive enhancement software is learned strategies to memorize information. Such methods have been used since antiquity[56]. In the roman rhetoric manual Ad Herennium (attributed to Cicero) a method is described to memorize lectures and other sequences that came to be called “memory palaces”, the “method of loci” or just “Ars Memoriam”. The user imagines a building, either a real and well-known building or an entirely imaginary location. In his imagination he then moves from place to place, placing different objects that evoke associations to the subject at the locations. During retrieval the user retraces the route and retrieves the information by the sequence of associations of objects. This system uses the built in navigation and association affordances of the brain to support memory. Later memory systems makes use of other

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[50] (Kennedy, Pace et al. 2006)
[51] (Wilkinson, Scholey et al. 2002)
[52] (Meck, Smith et al. 1988; Mellott, Williams et al. 2004)
[53] (Walsh, Budtz-Olsen et al. 1969; Greenoug.Wt and Volkmar 1973; Diamond, Johnson et al. 1975; Nilsson, Perfilieva et al. 1999)
[54] (Farlow, Anand et al. 2000)
[55] (Murphy, Foley et al. 2006)
[56] (Yates 1966)

aspects of memory to improve retention, such as rhyming, improved memory of dramatic, colorful or emotional scenes, replacing hard to recall concepts such as numbers with letters that can be shaped into concrete, easily associable words. While the early memory arts were used in rhetoric and as replacement for books, modern memory popular arts appears to be more aimed at every day needs such as remembering codes, shopping lists, names and study techniques[57].

In a study of exceptional memorizers (participants in the World Memory Championships) compared to normal subjects it was found that there were no systematic differences in brain anatomy[58]. However, the activity during encoding was different, likely mirroring a deliberate encoding strategy. Especially areas of the brain involved in spatial representation and navigation were found to be consistently activated in the memorizers, regardless of the subjects were learning numbers, faces or snowflakes. When asked about their memory strategies nearly all memorizers also reported using the method of loci.

It is instructive to compare to the study of London taxi drivers that demonstrated that the more experienced drivers had greater hippocampal volume than less experienced drivers and non-drivers[59]. They hold a very broad spatial representation that is used in skilled planning and action rather than a constrained memorization strategy.

In general it appears possible to attain very high memory performance on specific types of material using memory techniques. They work best on otherwise meaningless or unrelated information such as sequences of numbers, but do not appear to help skilled everyday activities[60]. In "skilled memory theory" it is proposed that people could develop domain-specific encoding skills to expand their effective working memory by relying on storage in long term working memory[61]. This explains the superior memory of experts for material within their field, such as chess masters of chess positions (but only 'meaningful' chess positions)[62] and how previous knowledge of a topic improves reading comprehension[63]. The relationship between domain-specific encoding, the use of known constraints, effective representations and the availability of more potential memory-supporting associations remains an active area of study in expert memory performance.

External Systems

External memory exists in a wide variety of forms, from reminder notes to libraries.

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[57] (Lorrayne 1996; Minninger 1997)
[58] (Maguire, Valentine et al. 2003)
[59] (Maguire, Gadian et al. 2000)
[60] (Ericsson 2003)
[61] (Ericsson and Kintsch 1995; Ericsson, Patel et al. 2000)
[62] (Chase and Simon 1973; Gobet and Simon 1996)
[63] (Kintsch 1998)

Remembrance agents[64] act as a vastly extended associative memory. The agents have access to a database of previous information such as a user's files, email correspondence etc. and suggests relevant documents based on the current context.

A well-designed environment can enhance proactive memory[65]. Such systems can both provide new capabilities and amplify existing cognition.

Given the availability of external memory support hardware, from writing to wearable computers, it appears likely that the crucial form of memory demand will be the ability to link together data into usable concepts and associations rather than storage and retrieval. Storage and retrieval functions can be offloaded to a great extent from the brain, while the knowledge, strategies and associations linking the data to skilled cognition so far cannot generally be offloaded.

Working Memory

Working memory can be modulated by a variety of drugs. Drugs that stimulate the dopamine system have demonstrated effect as well as cholinergic drugs (possibly by improved encoding)[66]. Modafinil has been shown to enhance working memory in healthy test subjects, especially at harder task difficulties and for lower performing subjects[67] (similar greater improvements for low performers were seen among the dopaminergic drugs). On a larger battery of tasks it was found to enhance digit span, visual pattern recognition memory, spatial planning and reaction time/latency on different working memory tasks[68]. An explanation may be that modafinil enhances adaptive response inhibition and performance accuracy, making the subjects evaluate a problem before responding to it. The working memory effects are hence just part of a larger enhancement of executive function.

Procedural Memory

An area that has been studied relatively little is enhancing procedural memory. Since procedural memory includes skill learning, enhancements here could have profound effects compared to the more easily augmented semantic and episodic memory systems.

Blocking receptors in the basal ganglia on cognitively impaired aged rats through injections of a cholinergic antagonist did improve procedural memory, but this effect might be more due to an excess of acetylcholine in the old rat than evidence for a

[64] (Rhodes and Starner 1996)
[65] (Sellen, Louie et al. 1996)
[66] (Barch 2004).
[67] (Muller, Steffenhagen et al. 2004)
[68] (Turner, Robbins et al. 2003)

cognition enhancement method[69]. Direct electrical stimulation of the basal ganglia improved procedural learning rate in monkeys[70].

Procedural enhancement" is the effect that motor skills often improves after training during overnight sleep, a likely result of memory consolidation in the basal ganglia and other systems involved in procedural memory[71]. This is especially pronounced for harder tasks[72] and consciously learned tasks[73]. Given that patients taking schizophrenia medications did have impaired enhancement[74], it appears likely that there might be pharmacological interventions that amplify this process, possibly by improving sleep conditions or extending the phases of sleep during which enhancement occurs.

Cortical Reorganization

The cortex can be reorganized through training to meet new needs. Loss of one sense can create compensatory expansion of other senses: there is evidence that blind have enhanced auditory spatial sense, echo cues and self-location[75], spatial attention[76] and tactile resolution[77]. Even myopic people appear more sensitive than normal people to echo cues[78]. A likely explanation for this is cortical plasticity, where less used cortical areas acquire new functionality. It has been demonstrated that in congenitally blind the occipital areas used as visual cortex in seeing are used in tactile recognition such as reading Braille[79]. Conversely, well used areas expand. Increased tactile stimulation causes the representations of the stimulated skin areas to expand[80], and musical training induces plastic changes in the brain[81]. This is of great interest to rehabilitation, but could also be useful for cognitive enhancement.

Noradrenergic agonists such as amphetamine have been shown to promote faster recovery of function after a lesion when combined with training [82]. A likely explanation is that the higher excitability increases cortical plasticity, in turn leading to synaptic sprouting and remodeling[83]. An alternative to pharmacologic increase of neuromodulation is to electrically stimulate the neuromodulatory centers that normally control plasticity through attention or reward; in monkey experiments this produced faster cortical reorganization[84].

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[69] (Lazaris, Cassel et al. 2003)
[70] (Williams and Eskandar 2006)
[71] (Walker, Brakefield et al. 2002)
[72] (Kuriyama, Stickgold et al. 2004)
[73] (Robertson, Pascual-Leone et al. 2004)
[74] (Manoach, Cain et al. 2004)
[75] (Lessard, Pare et al. 1998; Despres, Boudard et al. 2005; Dufour, Despres et al. 2005)
[76] (Collignon, Renier et al. 2006)
[77] (Sathian 2000; Van Boven, Hamilton et al. 2000)
[78] (Despres, Candas et al. 2005)
[79] (Cohen, Celnik et al. 1997; Buchel, Price et al. 1998; Sadato, Pascual-Leone et al. 1998)
[80] (Jenkins, Merzenich et al. 1990)
[81] (Johansson 2006)
[82] (Gladstone and Black 2000)
[83] (Stroemer, Kent et al. 1998)
[84] (Kilgard and Merzenich 1998; Bao, Chan et al. 2001)

Transcranial magnetic stimulation can increase or decrease the excitability of the cortex, in turn changing its level of plasticity[85]. TMS of the motor cortex that increased its excitability enhanced learning of a procedural learning task[86]. TMS in suitable areas has also been found beneficial in a motor task[87], motor learning[88], visuo-motor coordination tasks[89], working memory[90], finger sequence tapping[91], classification[92] and even declarative memory consolidation during sleep[93].

TMS appears to be a very versatile cognition enhancement tool. It is noninvasive and able to improve performance on a variety of cognitive tasks. A drawback might be the short duration of the exciting effect (minutes to an hour after stimulation). However, some results suggest that pharmacological manipulations of the dopamine system might allow consolidation or longer effects of the TMS intervention[94]. There is also a great deal of interindividual variety in responses that might require careful testing of suitable stimulation intensities, frequencies and locations.

Executive function

Drugs improving executive function – working memory, attention control, etc – have been harder to achieve than long-term memory drugs but some progress have occurred here too[95]. Given that these functions are closely linked to what is commonly seen as intelligence, they may be the first step towards true intelligence enhancing drugs.

A common task demanding much executive function is teamwork, especially under stress. Distributing cognitive demands across a team diminishes them on individual members and allows specialization but the price is the need to develop a shared understanding of the situation, something that often introduces communications demands that outweigh the benefits of dividing the task.

One solution to this is to insert software agents into the team, allowing them to act as intermediaries and collaborators in decision making. The R-CAST model of agents, based on Klein's Recognition-Primed Decision framework[96], have been demonstrate to improve team performance in a simulated real-time stressful military decision task[97]. The

85 (Hummel and Cohen 2005)
86 (Pascual-Leone, Tarazona et al. 1999)
87 (Butefisch, Khurana et al. 2004)
88 (Nitsche, Schauenburg et al. 2003)
89 (Antal, Nitsche et al. 2004; Antal, Nitsche et al. 2004)
90 (Fregni, Boggio et al. 2005)
91 (Kobayashi, Hutchinson et al. 2004)
92 (Kincses, Antal et al. 2004)
93 (Marshall, Molle et al. 2004)
94 (Nitsche, Lampe et al. 2006).
95 (Elliott, Sahakian et al. 1997; Kimberg, DEsposito et al. 1997; Mehta, Owen et al. 2000; Turner, Robbins et al. 2003)
96 (Klein 1998)
97 (Fan, Sun et al. 2005)

agents learn what actions have worked under similar circumstances and how to detect deviations from expectations (a sign that a new approach is needed, from experience or a human). Agents can also be used to share information between them, showing their human user information they believe is relevant for the user's particular task[98]

Good human-computer interfaces may support better concentration by reducing working memory load, exploiting the broad attention abilities of the visual system and increasing automaticity[99].

Self-control

Attempts to improve self-control and self-regulation has mainly been psychological so far, since the concept deals more with the everyday life and cognitions of a person than any isolatable brain system. However, at least some aspects of self-control rely on the ability to inhibit responses, an ability that appears to be strongly linked to frontal lobe function. Hence treatments that improve the functions of the frontal lobes or their ability to inhibit undesirable behaviors or thoughts may improve self-control.

A second avenue of research is the "ego depletion" theory. According to this theory exerting self-control consumes a limited resource, reducing the amount available for subsequent self-control efforts. Various experiments have documented that previous self-control exertion (including coping with stress, suppressing aversive thoughts and resisting temptation) increases the likelihood that subsequent self-control attempts will fail, despite not affecting performance of behaviors that do not require self-control[100]. The effect might also extend to other forms of volition[101]. While this resource has mainly been seen as a metaphor, recent studies suggest that at least part of it may be energy in the form of blood glucose, and that consuming glucose drinks after depleting tasks improves self-control during a subsequent task[102]. If these results hold it appears likely that pharmacological or physiological interventions (to improve glucose regulation) may be used to improve self-control abilities.

Intelligence

If the multiple intelligence model of intelligence holds, it consists of a number of more or less independent modules (presumably evolutionary adaptations or developed during early training). Hence enhancement of one such module would not improve performance on the other modules, but improving the function of more specialized modules might be easier than improving the function of a general form of intelligence.

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[98] (Fan, Sun et al. 2005)
[99] (Schneiderman and Bederson 2005)
[100] (Muraven and Baumeister 2000)
[101] (Baumeister, Bratslavsky et al. 1998)
[102] (Gailliot, Baumeister et al. 2006)

Studies of the genetics of intelligence suggests that there is a large number of genetic variations affecting individual intelligence, but each only contributes a very small (<1%) factor[103]. This implies that genetic enhancement of intelligence either through selection or direct insertion of a beneficial allele is unlikely to be efficient.

Creativity

Although creativity is not particularly well understood it appears possible to stimulate it.

One approach is to reduce inhibitions that normally keep fantasies and ideas down. Certain cases of brain damage suggest that reduced inhibitions can release creative abilities. Right frontal lobe lesions have caused compulsive bouts of creative expression[104] and enthusiasm for fine eating[105], and frontotemporal dementia have sometimes caused development of exceptional and unexpected artistic skills[106]. It is not implausible that reversible changes of this type could be achieved through drugs or TMS.

Snyder et al. demonstrated how TMS inhibiting anterior brain areas could change the drawing style of normal subjects into a more concrete style and improve spell-checking abilities, presumably by reducing top-down semantic control[107].

A study using alcohol demonstrated that a mild dose of alcohol could improve the results of a creative process[108]. The test subjects were asked to invent a new test of “nature vs. nurture”, with their proposals being judged by an independent panel for innovativeness. The improvement only occurred when the subjects got the alcohol during the “incubation phase” of the creative process, the period when they were not actively working on the problem but presumably their unconscious might have been active. Giving alcohol in a picture drawing task during the later verification phase did not promote creativity[109].

Creative thinking does not just include divergent and disinhibited thinking, but also requires convergent thinking to focus on the realization of the insight[110]. Excessive divergence or lack of inhibition may be similar to the situation in ADHD. Adult ADHD individuals show a profile of divergent thinking and do badly on convergent thinking and inhibition tasks[111]. Hence medications affecting ADHD might promote convergent thinking. Methylphenidate, the most common treatment and a dopamine reuptake inhibitor, did not appear to impair flexible thinking in ADHD individuals[112]. Giving L-dopa, a dopamine precursor, to healthy volunteers did not affect direct semantic priming

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[103] (Craig and Plomin 2006)
[104] (Giles and McHugh 2004)
[105] (Regard and Landis 1997)
[106] (Miller, Ponton et al. 1996; Miller, Boone et al. 2000; Gordon 2005)
[107] (Snyder, Mulcahy et al. 2003; Snyder, T. et al. 2004)
[108] (Norlander and Gustafson 1996)
[109] (Norlander and Gustafson 1997)
[110] (Cropley 2006)
[111] (White and Shah 2006)
[112] (Solanto and Wender 1989; Douglas, Barr et al. 1995)

(faster recognition of words directly semantically related to a previous word, such as 'black-white') but did inhibit indirect priming (faster recognition of more semantically distant words, such as 'summer-snow')[113]. This was interpreted by the authors of the study as dopamine inhibiting the spread of activation within the semantic network, i.e. a focusing on the task.

Creative thinking also occurs in a social sphere. The "Genex" framework of Ben Schneiderman describes an ideal integrated set of software tools for a four part model of creativity[114]. The tool set would enable users to:

- Collect information within an existing domain of knowledge
- Create innovation using various tools that allow users to manipulate objects within the domain.
- Allow consulting with peers, mentors and experts in the field
- Disseminate the results widely.

The Genex framework is an ideal, but software tools for all elements of the process do exist today and can be made more integrated.

Perception

It is possible to improve resolution, contrast and clarity of vision by correcting for defects in the eye using adaptive optics[115]. Using wavefront sensing it may be possible to construct "ideal" corrections that may reach to the limit of photoreceptor spacings (20/8 to 20/10)[116], although such corrections might need to be different at different pupil sizes/light levels and might entail making trade-offs between different types of optimality[117]. However, prototypes of implantable adaptive lenses have been demonstrated[118].

Senses can substitute for each other. In visual-tactile substitution an array of vibrators on the back of a person are attached to a camera, producing a tactile "image" of what is seen[119]. Healthy test subjects who were receiving information from a remote controlled vehicle in a maze did not just succeed in following the "visual" cues but also reported a subjective experience of being in the maze[120].

External tools can extend our sensory range, both through amplification/dampening (e.g. sound volume) or by transducing new modalities into our present modalities (e.g. IR night vision goggles or sonification in metal detectors). While it is debatable whether they should be included under the heading cognitive enhancement since they are easily

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[113] (Kischka, Kammer et al. 1996)
[114] (Shneiderman 1998)
[115] (Liang, Williams et al. 1997; Miller 2000)
[116] (Applegate 2000)
[117] (MacRae 2000)
[118] (Vdovin, Loktev et al. 2003)
[119] (Bach-y-Rita, Collins et al. 1969)
[120] (Segond and Weiss 2005)

detachable and usually experienced as external to the self, some forms of mediated vision using wearable computers appear to come close to a perceptual cognitive enhancement. These systems perform perceptual operations such as image warping, filtering out information, adding information, seeing fast motions as well as recording composite imagery[121]. Here the perceptual process is equipped with a preprocessing step, possibly under control of other parts of cognition[122]. The limits appear to be mostly set by video quality, detection of movement (especially important for integrating informations in 3D environments) and control ability, since nearly any kind of perceptual software can be run.

Wearable computers might also be able to enhance emotional intelligence, the ability to perceive emotions in others and respond appropriately. A prototype system exists, consisting of a camera recording the facial expressions of a discussion partner, face and emotion processing software that estimates the most likely emotional state, and a display that displays a cartoon of it together with suggestions for a proper response[123]. The accuracy compares favourably to humans.

The system is intended to help teach children with Asperger syndrome to socialize, and is hence at most a form of palliative treatment of the underlying condition. But the functionality could presumably be adapted to normal ("neurotypical") people, augmenting their emotional perception. It is not inconceivable that a wearable system could monitor an audience and give a speaker hints on their state; while normally not necessary in a small group it might help in large audiences where the speaker cannot keep track of all parts of the group. Boredom detection connected to feedback might train people into becoming more engaging discussion partners, and a visceral signal might simulate humor by detecting jokes and triggering a laugh response[124]. Turning the camera in the opposite direction may allow the system to detect misbehavior and adjust it, as well as allowing more responsive interfaces.

Motorics

Motor performance depends on the function of the primary motor cortex, the anterior motor planning areas and a number of subcortical and spinal structures. Motor planning, skilled execution of movements, hand-eye coordination and dealing with complex environments clearly require significant cognitive processes, albeit often on a less conscious level than the more traditional forms of cognition.
Several of the interventions discussed in the procedural learning and cortical reorganization sections appear useful for improving motorics. L-dopa has been found to improve the learning rate of a motor memory in healthy young volunteers and returning

[121] (Mann 1994)
[122] (Healey and Picard 1998)
[123] (El Kaliouby and Robinson 2005)
[124] A fictional example of this can be found in Wil McCarthy, *Bloom*, Del Rey 1998.

elder adult performance to levels comparable to those seen in younger subjects[125], likely by stimulating cortical reorganization.

One finding from the TMS studies was that increasing the excitability of the motor cortex on the opposite side impaired performance on tasks requiring a particular area of motor cortex. There is apparently a competition or inhibition effect occurring. Stimulation and anesthesia of limbs have been found to influence excitability, and inducing transient anesthesia in one hand can improve both motor and tactile tasks in the other hand[126]. For specific tasks selectively reducing body input and motor output might hence be useful.

Mental training can significantly improve both performance[127] and long-term health[128]. This includes adjustments of arousal[129], showing the link between emotional modification and cognitive enhancement. Mental training has been used among athletes for a long time[130] and for rehabilitation[131], and may act through re-training parts of the brain used in executing the skill as well as autonomic changes[132]. Such techniques of training-based performance enhancement are widespread and enjoy a broad acceptance in society, but at their core they correspond to deliberate modification of the neural networks of the brain.

Language ability

Few studies have been done on pharmacological improvements of language learning. Amphetamine improved learning of an artificial language[133], but the language had more in common with a memory task than a real language.

Low-level mental function

Mental energy

Great achievers are in general not just equipped with great cognitive abilities but also an abundance of mental energy[134]. Aspects of this energy are the ability to focus on a problem for a long time, a strong motivation to succeed, the ability to stay awake and work hard. It might also be a temperament[135], potentially linked to hypomanic or manic states. While mental energy borders on mood enhancement rather than cognition

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[125] (Floel, Breitenstein et al. 2005)
[126] (Werhahn, Mortensen et al. 2002; Werhahn, Mortensen et al. 2002; Bjorkman, Rosen et al. 2004; Bjorkman, Rosen et al. 2004)
[127] (Nyberg, Sandblom et al. 2003).
[128] (Barnes, Tager et al. 2004)
[129] (Nava, Landau et al. 2004)
[130] (Feltz and Landers 1983)
[131] (Jackson, Doyon et al. 2004).
[132] (Decety 1996; Oishi and Maeshima 2004)
[133] (Breitenstein, Wailke et al. 2004)
[134] (Lykken 2005)
[135] (Jamison 2004)

enhancement, it is clear that interventions improving it will have enabling effects on other cognitive capacities. Stimulants may be able to produce more mental energy.

Awakeness

Sleep and awareness are important for cognition. Sleep appears to play an important role in memory consolidation and homeostasis[136]. Lack of sleep impairs most cognitive abilities, increases risk of error and decrements mood (performance decrements of 30-40% can occur during the first night of sleep deprivation, and 50-70% the following[137]). But time spent sleeping is also unavailable to conscious cognition and action. In many situations the trade-off between sleep and consciousness may be changed by task demands, something that is complicated by the deep regulatory systems controlling sleep, awareness and diurnal rhythms. Napping has beneficial effects but also cause performance impairing sleep inertia for a period afterwards.

Diurnal rhythms are controlled by the superchiasmatic nucleus in the hypothalamus, located on top of the optic nerve and receiving light information from it. This information entrains its natural rhythm to fit the day in the environment. Ever since the widespread introduction of artificial light this signal has become a less and less reliable Zeitgeber, something which may contribute to current sleep disorders. Spending an evening in front of a television or computer screen in a well-lit room might delay the internal clock, promoting going to bed later, which in turn reduces the amount of sleep before the set time for awakening. Shift-work and jet-lag are well documented to decrease mental performance. This internal clock can be regulated through the hormone melatonin, allowing reset after transatlantic trips or changes in day patterns[138].

Traditional stimulants have a large number of well documented risks and side effects, making their use complicated. Caffeine takes a special place, being a cognitive enhancer, stimulant, widely available, socially acceptable and relatively safe. One problem with caffeine is that doses large enough to improve vigilance also tends to promote nervousness, irritability, diuresis and tremor. Like most stimulants it promotes quick, automatic and well-learned reactions rather than careful thought.

However, new sleep- and awakeness-controlling medications such as modafinil appear to promote heightened function with small risks of direct side effects and dependency[139]. The effects of modafinil and amphetamine on sleep-deprived aviators were found to be similar, but with modafinil showing fewer side effects[140]. Naps are more effective in maintaining performance than modafinil and amphetamine during long (48h) sleep deprivation than short (24h), and naps followed by a modafinil dose may be more efficient than either individually[141]. The drug also improved attention and working

[136] (Siegel 2005; Stickgold 2005)
[137] (Angus and Heslegrave 1985)
[138] (Cardinali, Brusco et al. 2002)
[139] (Teitelman 2001; Buguet, Moroz et al. 2003; Myrick, Malcolm et al. 2004)
[140] (Caldwell, Caldwell et al. 2000)
[141] (Batejat and Lagarde 1999)

memory in sleep-deprived physicians[142]. Modafinil also allows sleep when appropriate and has frontally acting cognition enhancing effects (see above).

New capacities

New senses

The spectral range of the human eye can be extended slightly into the ultraviolet by removing the UV-blocking lens. The result is that patients lacking lens (aphakia) or having an UV-transparent lens can perceive near UV (down to 314 nm) as “whiteish blue”[143].

People expressing more than three photopigments appear to have a slightly richer visual experience in terms of number of color bands they experience in a spectrum[144]. Depending on which extra opsin gene they have they experience two versions of the same fundamental color[145].

An interesting demonstration of a simple new sense is magnetic sensitivity. By inserting a small permanent magnet into a fingertip, Steve Haworth became able to sense magnetic fields due to their effect on the magnet[146]. The result was an extended perception of magnetic fields in the environment. Static fields were experienced as pressures while oscillating fields such as from electric motors were more noticeable vibrating sensations. Although intended more as a conceptual tool than an useful enhancement it demonstrates an entirely new sense.

Human-Computer Communication

The most dramatic potential internal hardware enhancements are brain-computer interfaces. At present development is rapid both on the hardware side, where multielectrode recordings from more than 300 electrodes permanently implanted in the brain are currently state-of-the art, and on the software side, where computers learn to interpret the signals and commands[147]. Early experiments on humans have shown that it is possible for profoundly paralyzed patients to control a computer cursor using just a single electrode[148] and experiments by Patil et al. have demonstrated that the kind of recordings used in monkeys would most likely function in humans too[149]. Cochelar implants are already widely used, and there is ongoing research in artificial retinas[150] and

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[142] (Gill, Haerich et al. 2006)
[143] (Stark and Tan 1982; Griswold and Stark 1992)
[144] (Jameson, Highnote et al. 2001)
[145] (Holba and Lukács)
[146] (Laratt 2004)
[147] (Carmena, Lebedev et al. 2003; Nicolelis, Dimitrov et al. 2003; Shenoy, Meeker et al. 2003)
[148] (Kennedy and Bakay 1998)
[149] (Patil, Carmena et al. 2004)
[150] (Alteheld, Roessler et al. 2004)

functional electric stimulation for paralysis treatment[151]. While such implants are not currently intended for enhancement purposes (and unlikely to be very desirable for the near future), the digital part of the implant could just as well be connected to any software, enabling various forms of enhancement. Experiments in localized chemical release from implanted chips also suggest the possibility to use neural growth factors to promote patterned local growth and interfacing[152].

These implants are mainly intended to ameliorate functional problems and will hardly be attractive for healthy people in the foreseeable future. But the digital parts of the implant can in principle be connected to nearly any kind of software and through it, hardware. This would enable enhancing uses such as access to software help, Internet and virtual reality applications. A demonstration of how a healthy volunteer could control a robotic arm using tactile feedback, both in direct adjacency and remotely, as well as a wheelchair and perform simple neural communication with another implant[153].

Discussion of Present Enhancement Capabilities

At present most biomedical enhancement techniques represent modest improvements of performance, as a rule of thumb about 10-20% improvement on a particular task. More dramatic results can be achieved using training and human-machine collaboration, techniques that are less ethically controversial at present. Mental software can achieve 1000% or more improvement of specific tasks (e.g. digit span[154]).

The biomedical enhancements discussed all manage to improve performance by some measure, and in all cases improve it beyond the average of tested organism. None of the pharmacological or genetic enhancements reach the limits of the normal performance range of the tested species. It is harder to say whether they improve performance to be "better than well" since the normal health range is contested.

The different enhancement technologies have many synergies. While pharmacological cognitive enhancements do not produce dramatic improvements in cognitive performance they are often general, acting on all different tasks making use of e.g. working memory or long term memory. External tools and cognitive techniques such as memorization are usually task-specific, producing huge improvements on narrow skills. Hence the combination can be expected to do better than the individual technologies, especially in everyday or workspace settings where a wide variety of tasks have to be done.

Some methods may be substitutes for each other, such as long-term memory enhancer treatment and enriched rearing. Here the enhancer would support individuals lacking enriched background, but may not have much effect on people with such a background.

[151] (von Wild, Rabischong et al. 2002)
[152] (Peterman, Noolandi et al. 2004)
[153] (Warwick, Gasson et al. 2003)
[154] (Ericsson, Chase et al. 1980)

Different methods also have different effects. Enhancements may help poorly performing individuals more than better performing (as in the working memory drugs), or vice versa as in the case of mnemonic skill.

Interindividual differences likely play a large role in the efficacy of different enhancements. For example, individual variations in neuromodulation likely underlie different responses to stimulants and memory enhancing drugs, and individual differences in excitability and geometry make TMS treatments different. This suggests that if enhancements become widely used they have to be individually tuned for maximum efficacy, a process that might be expensive even if the enhancement itself isn't.

Appendix: Measuring Enhancement

Measuring and comparing the results of applying different enhancement techniques can be hard even when an enhancement is just an improvement of a certain capacity. In most studies performed so far enhancement is measured by improved task performance in tasks that are believed indicative of the enhanced capacity. But the same enhancement may produce divergent results on different tasks, and comparing task score improvements between different tasks is in general impossible. New capacities or radical changes in how they function (e.g. the addition of a remembrance agent to memory) do not even have any established test tasks.

Ecological studies of cognitive enhancement are lacking. Such studies would examine whether different enhancement contributed positively to everyday life, professional performance or life satisfaction. Given the complexity, potential confounding factors and open-ended nature of the objective it is not surprising that few such studies have been done.

A theoretical framework for task metrics, the "Turing Ratio", suited to cognitive enhancement (although mainly proposed as a measure of progress on AI) was suggested by Masum, Chistensen and Oppacher[155]. The ratio is calculated by comparing the performance of different agents on a task using pair wise competition (or aggregate scores), producing a logarithmic scale of win expectancy or ability with median human level defined as zero. The tasks can be open-ended and ecological, and there is a natural way of comparing enhancement effects. While largely theoretical this approach may be used to judge the actual success of different enhancement approaches.

From a philosophical standpoint it may be enough with a simpler scale. Enhancement "strengths" can be ordered roughly as:

- Better (the person performs better at a task than he did before)

[155] (Masum, Chistensen et al. 2003)

- Better than normal (the person performs above the average of human performers thanks to the enhancement)
- Better than well (the person performs better than the standard that is set to denote wellness/health/sufficient performance)
- Better than normal range human species (the person performs above what any human could perform without enhancement)

Finally, it should be noted that some enhancements may have qualitative effects rather than quantitative, such as enabling new modes of perception, thinking or acting.

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