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Minding the Aging Brain: Technology-Enabled Cognitive Training for Healthy Elders

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Abstract *Cognitive training* refers to theory-driven behavioral intervention, ideally supported by a strong conceptual framework and specified neurocognitive mechanisms. Within this field, neurotechnology promises many advantages, and a growing literature establishes technology-enabled cognitive training as a promising modality to promote positive cognition in consumer, research, clinical, and public health settings. Methodologic challenges remain, and specific cognitive training recommendations for healthy elders must be tentative in the context of an emerging evidence base.

Keywords Cognitive training · Cognitive enhancement · Cognitive enrichment · Cognitive aging · Enabling technology · Neurotechnology · Technology trials · Brain · Fitness · Positive cognition · Clinical trials · Healthy aging · Prevention · Cognitive reserve · Cognitive neuroscience · Control processes · Executive control · Memory training · Aging technology · Behavioral interventions · Aging

Introduction

Mentally engaging activities encompass a gamut of life experiences ranging from educational, occupational, and recreational endeavors to mnemonics, puzzles, games, and software-based neurotechnology. More broadly, various creative, spiritual, and mind–body practices can be adopted explicitly, if not exclusively, to support healthy brain function. However, because the cognitive demands and goals of these activities differ so vastly across settings and between individuals, it is difficult to summarize their purported benefits or begin to develop an evidence base spanning diverse intervention modalities. More generally, *cognitive enrichment* also may result from physical and social activities [1••], and *brain fitness* further incorporates emotional regulation, balanced nutrition, and other health-promoting lifestyle goals [2].

Emerging Role of Cognitive Training Neurotechnology

No consensus lexicon exists yet to describe the various means by which cognition can be modulated to achieve desired lifestyle or clinical aims. Terms adopted in this review to differentiate the approaches are presented in Table 1. Among intellectual activities intended to improve brain function, *cognitive stimulation* refers to nontargeted engagement that generally enhances mental functioning. *Cognitive training* refers to theory-driven intervention, ideally supported by a strong conceptual framework [3] and specified hypotheses regarding invoked neurocognitive mechanisms. *Cognitive rehabilitation* strategies address impairments resulting from neuropsychiatric disorders. Admittedly, there are commonalities among these approaches, but the distinctions are instructive and reflect a synthesis of published perspectives [1, 4, 5, 6•, 7]. *Positive cognition* is introduced as a descriptive concept that subsumes these approaches as well as enhancement [8] or cosmetic neurology [9], which may involve pharmaceutical or direct neuromodulation via magnetic, electrical, or optical energy. The essential feature of positive cognition is the intent to influence lifespan cognitive trajectories toward the optimal, or even to extend the range of possibilities

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Table 1 Proposed lexicon for positive cognition interventions

Cognitive intervention	Intended meaning	Illustrative quotations	Examples
Stimulation	Nontargeted engagement that generally enhances mental functioning	"[A]ctivities…designed to increase cognitive and social functioning in a non-specific manner" [5] "[B]road-spectrum effects…mediated through a number of mechanisms, such as attitudes, beliefs, and aspirations" [1••]	Book club Life review, scrapbooking Classes, workshops
Training	Grounded in conceptual framework, ideally with specified neurocognitive mechanisms and hypotheses	"…[T]heoretically driven 'guided practice' on tasks reflecting specific cognitive functions" [4] "…[T]heoretically motivated strategies and skills" [5] "Specific cognitive mechanisms are isolated and trained…" [6•]	Technology-enabled task training Mnemonic strategy training
Rehabilitation	Addresses impairments resulting from clinical neuropsychiatric disorders	"…[A]chieve or maintain an 'optimal level of physical, psychological and social functioning' in the context of specific impairments arising from illness or injury" [7] "[T]argeting individual areas of weakness…to improve or compensate for these difficulties" [4]	Poststroke speech and language therapy Computer-based cognitive and productivity training in schizophrenia
Enrichment	Positive cognition achieved through a range of health-promoting lifestyle behaviors	"…[A]ll behaviors that potentially enhance cognition" [1]	Brain fitness programs involving cognitive, physical, social, and nutritional modalities

whose bounds are constrained by biological limits. (See Hertzog et al. [1••] for the conceptual framework that models cognitive trajectories and neuroplasticity in the context of lifespan development, influenced in particular by the work of psychologist Paul Baltes.)

Here, we focus on software-based cognitive training in adults older than 65 years without neurocognitive disorders, for several reasons. An extensive literature already exists on strategy-based mnemonic and reasoning training that does not rely on technology, and has been reviewed elsewhere [6•]. A growing literature instructs on related lifestyle and behavioral interventions—notably, aerobic physical activity and social engagement—intended to promote brain fitness [1••]. However, the unique role of technology deserves attention.

Within the area of cognitive training, technology promises advantages in reliability, scalability, and cost. Technology can be implemented for the purposes of intervention or assessment. With evolving device and software capabilities, such technologies can be embedded within home and community environments and amass ongoing everyday performance data through unobtrusive health monitoring [10]. The advantages of technologies have been especially evident in task training, requiring extensive practice and real-time adaptation to user performance. However, an important emerging trend is evident in technology-enabled strategy training and personalized "coaching."

In the following sections, the public health and strategic rationale for cognitive training is reviewed briefly before the limited published clinical trial evidence for cognitive technology trials in healthy elders is considered. Critical, unresolved methodologic issues for the field and consideration of how cognitive training might be incorporated into broader therapeutic contexts are addressed.

Framework and Rationale for Cognitive Intervention

A replicated finding in longitudinal observational studies of aging associates cognitively stimulating behaviors throughout the lifespan with a reduced risk or delayed onset of developing Alzheimer's disease [11–14]. *Cognitive reserve* refers to the concept that factors including cognitive stimulation or technology-enabled cognitive training can mediate against the clinical expression of accumulating brain pathologies [15•]. Thus, enhancing cognitive reserve serves as a suitable target for interventions involving healthy elders.

Putative Benefits

There is confusion about the putative benefits of training and difficulty navigating claims made by commercial vendors of consumer neurotechnology [2]. As summarized in Table 2, it is instructive to consider a range of intended benefits of cognitive training, bearing in mind that the published studies to date address only some of the following possible outcomes: 1) task-specific improvement, 2) transfer to nontrained task improvement, 3) self-reported gain in positive cognition, 4) performance gains in everyday functions, and 5) prevention or delayed onset of neurocognitive disorders.

Crucial issues remain to be resolved, including optimizing training intensity and achieving maintenance of benefit. Nevertheless, even immediate or time-limited cognitive enrichment can support functional independence and productivity. Definitive evidence for slowing the aging process may be considered a decrease in the rate of cognitive decline among mentally engaged individuals [16], whereas others propose that ongoing enrichment, with continuous or intermittent boosts in an individual's cognitive performance, would be tantamount to a modification of normative cognitive decline [17].

Recent Findings in Technology-Enabled Cognitive Training

To date, there are two randomized controlled trials involving software-based cognitive training that enrolled a substantial number of healthy elders.

Advanced Cognitive Training for Independent and Vital Elderly (ACTIVE), sponsored by the National Institutes of Health, enrolled 2,832 independently living, diverse adults over age 65 from six sites beginning in 1998. Baseline [18], 2-year [19], 5-year [20••], and ancillary results have been reported, whereas ongoing follow-up will allow consideration of long-term training effects. This randomized single-blind study compared three cognitive training interventions—memory, reasoning, and speed of processing—and a no-contact control with respect to cognitive and everyday functional outcomes. Each training arm consisted of 10 60- to 75-minute small-group sessions over 6 weeks. The speed-of-processing training made use of the computerized Useful Field of View (UFOV) program, described later. "Booster" training was administered to a random subsample over four 75-minute sessions at approximately 1 year and 3 years from enrollment to determine whether such reinforcement would support long-term maintenance of training benefits.

Eighty-nine percent of subjects randomly assigned to cognitive training completed at least 8 of 10 sessions; 67% of enrolled subjects were retained for 5-year follow-up assessment. As hypothesized, each cognitive training approach yielded sustained, statistically significant improvements in the specific cognitive areas targeted. Small effect sizes were observed for memory (0.23) and reasoning (0.26), whereas a medium-to-large effect size was observed for speed-of-processing training (0.76). No improvements were observed beyond the specific cognitive domains of the intervention, either immediately post training or after 2 or 5 years. Broadly speaking, there was little evidence to support the study's primary hypotheses that the training would generalize to improve outcomes related to everyday function and independence. This likely is the result, in part, of the modest functional declines over the study period experienced by a carefully screened sample that was younger (mean age, 73.6 years), better educated, more likely to be married, and higher performing on physical and cognitive measures compared with the general population older than 65 years. Nevertheless, at 5 years, compared with those who had no training, the reasoning-trained group reported less difficulty with instrumental activities of daily living (IADLs), as assessed by a survey addressing meal preparation, housework, finances, health maintenance, telephone use, and shopping.

The speed-of-processing training relied on UFOV, a software program that provides assessment and training of visual attention. Briefly, the training focuses on improving the speed of visual search and the ability to attend to stimuli quickly, especially when presented for increasingly brief durations, at two screen locations simultaneously, or with visual distractors. A series of investigations demonstrated that reduced UFOV is a predictor of poor driving performance [21] and crash risk [22], and that the UFOV can be improved with training, leading to improved driving-related outcomes [23] and faster performance of timed IADLs [24]. Analyses of the speed-of-processing training arm in ACTIVE confirmed that individuals with reduced UFOV are at risk for imminent driving cessation [25] and that the intervention delayed the onset of driving

Table 2 Selected areas of putative benefit from cognitive training in healthy elders

Cognitive	Activities of daily living	Clinical–behavioral
Specific improvement on trained task	Driving	Psychological state (mood, stress, pain, sleep)
Improvement on nontrained task (transfer)	Financial decision making	Locomotion (gait, motor control)
Self-reported cognitive improvement	Medication management	Neurocognitive disorders (risk reduction, delayed onset)

cessation [26]. Additional studies demonstrated sustained improvement in cognitive self-efficacy [27], health-related quality of life [28], depressive symptoms [29], and health care expenditures [30]. ACTIVE frequently is cited as the first large-scale cognitive training trial that set the stage for ongoing and future investigations in the field. Although less emphasized, perhaps the most robust evidence provided by the study is for the superiority of neurotechnologic over traditional approaches to cognitive training.

Improvement in Memory With Plasticity-Based Adaptive Cognitive Training (IMPACT) evaluated the effects of a "brain plasticity–based" experimental treatment (ET) consisting of computerized auditory processing exercises self-administered at home [31••]. Five 1-hour sessions per week were to be completed for 8 weeks. The hypothesized mechanism motivating the training strategy addressed brain systems with temporal response patterns degraded by aging [32]. Proof of concept was demonstrated in an earlier-phase study [33]. In IMPACT, ET was compared with an active control intervention involving educational multimedia and content quizzes covering history, art, and literature. Among 487 randomly assigned subjects, the noncompletion rate was 10.5%; program usage, in terms of the number of hours spent in training, was not reported. Significant effects favored the ET group on the primary outcome measures of auditory memory and attention, with a small effect size of 0.23. Because the training did not specifically target these standardized measures, the authors concluded that the generalized performance improvement provided evidence that "robust gains occurred across systems serving auditory-based cognition." Further, there was a significant benefit in the ET group on the self-reported cognitive questionnaire.

Several limitations of IMPACT should be noted. The sample (95% Caucasian, average of 16 years' education, IQ of 114) was not broadly representative. Details on program usability and acceptability are not available. No follow-up data were presented to support the persistence of training benefits. The relatively low incidence of adverse events was similar in the ET and active control arms, except that reports of frustration were more common in the ET group. Nevertheless, IMPACT should be recognized for its first-in-kind research findings, demonstrating generalized improvement on untrained memory and attentional tasks in a large, well-characterized sample.

Proof-of-Concept Cognitive Training Studies

Several smaller randomized controlled trials and other studies of software-based cognitive interventions are reported in the literature. By and large, these cannot translate easily to an evidence base for clinical and public health recommendations. Rather, these studies are best considered in terms of the neurocognitive mechanisms hypothesized to be useful for training healthy elders, as well as their ability to elucidate brain–behavioral relationships relevant to the field.

Early studies of off-the-shelf video game use in older adults reported short-term improvements in game performance and in reaction times [34–36]. Although the experience of engaging in such recreational technology may appear to be a form of nontargeted cognitive stimulation, video game use often may become habitual, a type of learning that may be associated with beneficial outcomes. Indeed, skill acquisition on the complex video game Space Fortress was associated with MRI volume of the striatum [37], a brain region implicated in habit formation [38]. Recently, "updating" training of executive functions demonstrated transfer to nontrained working memory tasks, and the effect was mediated by the activation in the striatum [39].

The neurocognitive training mechanism explored in a recent trial involved highly specific attentional training focused on suppression of distractions from sensory modalities other than the one demanded by a primary task involving identification and manipulation of letters, numbers, and words [40]. Repetitive, adaptive practice was designed to improve ability to focus on visual tasks and to ignore irrelevant but very salient auditory stimuli and, conversely, to focus on auditory stimuli in the face of visual distractors. The proposition is that highly targeted cognitive skills (namely resistance to cross-modal distraction) can have broad effects if the skill is applicable to a range of cognitive and everyday demands. The training was associated with increased posttraining resting blood flow in frontal regions [41]. To the extent that interventions target generalized improvement in processing efficiency, they have assimilated lessons from behavioral neuroscience and have focused on cognitive mechanisms that critically involve the prefrontal cortex (PFC) [1] and neural systems that demonstrate plasticity across the lifespan.

Training Cognitive Control Processes

Coordination of multiple tasks or task components ("multitasking") is a common and challenging demand of many everyday situations. The cognitive control processes required are deemed to be particularly dependent on the PFC and decline with normative aging. Flexible strategy training paradigms, particularly variable-priority [42] and emphasis-change [43] training, have been used to improve dual-task performance, accelerate acquisition of dual-task performance, increase levels of retention, and transfer to novel cognitively demanding situations [42, 44].

To illustrate the basic approach, one may consider driving an example of a complex task highly relevant to functional independence and public safety and health outcomes. All complex and demanding tasks can be subdivided into many subcomponents. For example, drivers must control the steering wheel, monitor and interpret instruments and gauges, monitor the out-of-the-window field of view to adjust their direction and speed, follow the rules of the road, and orient themselves geographically. All task segments must be attended to concurrently, under demanding time and space constraints. Because the tasks as a whole are too difficult for beginners to cope with, conventional training protocols decompose the tasks to segments and train subjects on parts before practicing the complete tasks (part-task training). By contrast, emphasis-change or variable-priority training maintains the complex task intact, as a whole, but at different practice sessions changes the emphasis on components and segments through instructions and augmented performance indicators. Introduction of systematic variability or multiple performance alternatives early in training leads subjects to an expanded exploration of the response strategy space and to the development of better strategies for coping with changing task demands.

Recently, a complex strategy-based, off-the-shelf video game that requires voluntary shifts in priority and attention was used as a vehicle for demonstrating transfer to executive control and memory processes [45•]. Forty video game novices (mean age, 69.6 years) were assigned to 15 90-minute training sessions on the Rise of Nations game or a no-contact control condition. Training was associated with improvements in executive control functions, such as those involved in task switching and working memory. Note that the benefit was significant for higher-level control processes but not for basic performance metrics (such as reaction time or accuracy) or for tasks unrelated to executive control. The findings suggest specificity of transfer based on the hypothesized mechanism of training. Study limitations include the absence of an active video game control condition or experimental procedures to systematically encourage and measure the successful adoption of the variable-priority training strategy.

Emphasis-change training on the Space Fortress video game led to improved task mastery and transfer to improved flight performance among air force recruits [44]. The approach currently is being studied in older adults. Because such variable-priority training strategies specifically aim to enhance cognitive control processes that decline with aging and are mediated by the PFC, a region in the neural system associated with cognitive reserve, it is tempting to speculate that they can confer long-term protection against the emergence of cognitive impairment and decline by increasing neural efficiency or compensation. Unfortunately, no supportive data are available yet, because adequately powered studies of the magnitude required to test this hypothesis have not been attempted.

Methodologic Issues and Future Directions

Several expert reviews identified key methodologic issues to be considered in the ongoing effort to establish an evidence base for cognitive training in healthy older adults [1••, 3, 6•, 46]. The overarching theme is the necessity of grounding interventions in strong conceptual frameworks, but future work will need to establish the comparative effectiveness of different theoretic approaches. From a practical point of view, much work needs to be done to consider the minimum and optimal duration and frequency of training to achieve specified outcomes. It is possible that some failures to observe profound, generalized, and enduring training benefits may be attributed to the restricted range of training protocols implemented to date. An important, largely unknown factor is whether benefits achieved through targeted intervention are maintained following cessation of cognitive training, and to what extent periodic “boosters” or less-intensive ad-lib use can promote sustained benefit. ACTIVE did report a significant booster effect from reasoning and speed-of-processing training, but additional study is necessary to inform future studies and clinical practice.

More fundamentally, positive cognition inherently reflects plasticity within individuals. However, most training studies and clinical trials generally report changes in outcome at the level of the group mean, obscuring the relative contributions of nonresponders and subjects with robust intraindividual changes. There might be unknown or unmeasured predictors of training response, which may not be evenly distributed across experimental conditions despite randomization. Measurement [47] and analytic strategies [48] that reliably detect intraindividual changes within groups might improve statistical power, identify individualized predictors of training response, and form a foundation for personalized therapeutic recommendations. Along these lines, the importance of mediating factors such as personality and motivation merits careful consideration.

Finally, the cognitive training literature is not very informative with regard to the usability and acceptability of technology or the relevance of technologic attitudes in determining training success or adherence. The subjective experience of technology use likely will be a major factor in translating cognitive training to clinical and lifestyle environments. Future studies should collect and report such data, especially in samples of diverse ages and educational, socioeconomic, and technologic backgrounds.

Broader Contexts

There is an active and growing commercial market for brain fitness technologies. UFOV was acquired in 2008 by a leading producer of commercial brain-training software and is incorporated in the design of a visual training product. To further investigate the functional impact of this training modality, the insurance company Allstate partnered with the technology developer to distribute the program to thousands of older drivers in Pennsylvania with the expectation that there would be a reduction in crashes and claims.

Ultimately, cognitive training will need to be studied in the context of multimodal brain fitness interventions, in which benefits may supplement or magnify enrichment from physical, social, or nutritional endeavors. Integrative cognitive–conceptual models have been proposed to consider how divergent approaches to positive cognition can be considered simultaneously [49]. Evaluation of such programs would profit greatly from embedding research procedures in community environments, adopting measurement strategies that allow modeling of intraindividual cognitive changes, and considering alternatives to the randomized controlled trial [50].

Further, if technology-enabled cognitive training is to be integrated within health care delivery systems, regulatory bodies and third-party payors will require evidence of safety and efficacy, as in other clinical therapeutic areas. Hybrid trials with pharmacologic or direct neuromodulation treatment arms also should evaluate the role of cognitive training as an adjunctive therapy.

Conclusions

Technology-enabled cognitive training is a promising intervention modality to promote positive cognition in consumer, research, clinical, and public health settings. Results from several ongoing trials are expected to add to the growing evidence base. Methodologic challenges remain, and specific recommendations must be tentative. However, for healthy elders with informed expectations and realistic goals, technology-enabled cognitive training is a preventive lifestyle behavior that may be combined with physical, social, and nutritional activity within a multimodal brain fitness program.

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- •• Of major importance

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