One size does not fit all: Cognitive enhancement as a multidimensional construct

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Abstract

Cognitive abilities are the key to success in almost all areas of life. Faster information processing and more efficient recall, greater (working) memory capacity and stronger inhibition of irrelevant stimuli, higher mental flexibility, and efficient associative memory, are some of the more specific cognitive processes underlying not just academic and professional success, but also success in everyday activities. Dynamic everyday life with an increasing flow of information places stronger and greater demands on our limited cognitive capacities. Recently, a larger number of strategies and interventions have been proposed, which are aimed at augmentation of brain functions and enhancement of processing capacities. Cognitive enhancement is relevant for a wide range of "users" - from children with ADHD or those raised in poverty, professionals with cognitively demanding workload, older adults with normative cognitive aging, to people with traumatic brain injuries or neurodegenerative diseases. Not surprisingly, the brain-training industry is one of the fastest growing market branches. Nevertheless, the (in)effectiveness of interventions has been the subject of long-standing controversy and argumentation among researchers. A synthesis of research from different scientific fields suggests that the answer to the effectiveness question requires a departure from the monolithic understanding of cognitive enhancement as a one-dimensional construct. If we accept its multidimensionality, we can discuss the effectiveness of interventions depending on their biochemical, physical, or behavioral nature, the targeted cognitive domain or process, the characteristics and individual variables of the participants, the duration of the intervention, and even the wider social acceptance of the idea of possible enhancement.

Keywords: *cognitive enhancement; cognitive training; individual differences; motivation*

The popularity of interventions aimed at cognitive enhancement and maintenance of cognitive abilities is widely evident in both scientific research and professional practice. An abundance of theoretical and empirical studies aimed at validation and evaluation of numerous interventions has been published in the past decades. This is well illustrated by a literature search using the keyword "cognitive training" or "cognitive intervention" in the PsychINFO database, which yields 518 peer-reviewed empirical articles, published between 2000 and 2010, and 2979 articles published in the following ten years. The reasons behind this surge are threefold: 1) evidence of cognitive and neural plasticity which is not limited to infancy and early childhood, but extends throughout the lifespan, 2) technology burst, which facilitates precision in capturing behavioral and neural changes induced by cognitive training, as well as the development of new and effective forms of training, such as computerized cognitive training (CCT) and video games, 3) the so-called greying of the population with the ever-growing share of older adults believed to show a decline in various cognitive functions. These arguments are corroborated by the observation that between ages 60-70 the decline is more evident in cognitive rather than physical abilities (Salthouse, 2009).

Large demand for cognitive interventions has opened various avenues of pursuing maintenance or enhancement of cognitive abilities. Proposed interventions vary deeply from one another in terms of implementation and the mere nature of intervention. They can be broadly categorized by their strategic approach into biochemical, physical and behavioral interventions. Although not exclusively, psychologists mostly deal with behavioral strategies which are based on new learning and cognitive engagement. Since various proponents advocate and present evidence in favor of their approach, it may seem that one can benefit from whichever procedure.

When discussing factors related to post-intervention gains in various aspects of cognition, studies point to different factors underlying these benefits. These factors are the focus of this paper. First, we will present the key findings which have led to the inauguration of the idea of cognitive intervention, i.e., evidence of interindividual variability in cognitive aging, and how different environments are manifested in this variability. Next, we turn to the brain industry and cognitive training as the most prominent of behavioral interventions. In the final chapter, we will discuss some predictors of training efficacy, which indirectly signal the route towards the personalization of cognitive interventions.

Cognitive development and interindividual differences in plasticity

Probably the best-known finding in the field of cognitive development is the dichotomy of fluid and crystallized abilities (e.g., Cattell, 1963). Fluid abilities are innate abilities of processing and assimilating information and solving problems. The culmination of the development of fluid abilities, such as attention, working memory (WM), executive functions (EF), speed of information processing, takes place throughout the third decade of life, followed by their decline at an average rate of -2% SD per year (Salthouse, 2012). Crystallized knowledge and abilities, such as vocabulary and general knowledge, are more resistant to change, even to brain injuries (Brown, 2016). Therefore, they are often used to assess cognitive functioning before the injury itself. Crystallized abilities are maintained well into older adulthood. Since the initial findings, the fluid-crystallized dichotomy has somewhat softened. The new perspective is based on the evidence of: 1) crystallized abilities, which are not only maintained, but accumulated knowledge and experience, can even promote their increase well into the sixth and seventh decade (0.3-2% SD; Salthouse, 2012), 2) intensive exercise, which can enhance fluid abilities (e.g., Jaeggi et al., 2008) and slow down their decline (e.g., Willis & Nesselroade, 1990; Anguera et al., 2013).

The diverging age trajectories of the two types of abilities, sustained by the marked intraindividual changes in cognitive outcomes over time, have led to the compensation hypothesis, which suggests that individuals might compensate the decline in fluid abilities by gains in the crystallized ones (Tucker-Drob et al., 2022). This heterogeneity of abilities in aging is indirectly corroborated by implicit theories of aging; when asked to estimate the usual course of cognitive abilities in aging, lay people agree in the belief that abilities generally weaken, but they still predict better cognitive future for their parents rather than their parents' peers (Vernon, 1996; Haimovitz et al., 2011). Long tradition of cognitive aging research has led to the identification of three classes of factors related to cognitive decline: non-modifiable (e.g., genotype), modifiable (e.g., lifestyle, physical activity), and potentially controllable factors (e.g., health conditions such as substance abuse, obesity, hypertension). Interactively or independent from one another, these factors can modify our cognitive trajectories.

Early introduction of modifiable protective factors, such as educational stimulation, physical activity, or rich social network, into one's lifestyle seems to support latent level changes. Mimicking the latent learning paradigm (Tolman, 1948) or the effects of enriched environment (Rosenzweig & Barnes, 2003), the advantage of mental and physical activities, i.e., healthy lifestyle, can be evidenced much later - when one is faced with age-related weakening or loss of abilities, and even more so when affronted with neurodegenerative diseases or some pathological events and processes (e.g., lesions, damage). The term *cognitive reserve* has been proposed to describe the fascinating phenomenon in which education, stimulating activities and work enable the aging brain to better cope with its losses, particularly with dementia and pathological characteristics of various types of dementia (Stern et al., 1994). In older age, cognitive reserve can contribute to the involvement in lifestyle activities and thus further perpetuate itself (Martinčević & Vranić, 2021). Studies in clinical cognitive neuroscience have taken the reserve terminology one step further; while *brain reserve* constitutes a passive capacity, dependent upon the brain structures, cognitive reserve represents a behaviorally expressed way of coping with brain pathology (Stern, 2002).

The model of reserve is substantiated by the findings of wide-spread age-related decreases in various neural parameters which are paired with the increased frontal engagement. Increased prefrontal engagement is related to a better behavioral performance in older adults (e.g., Gutchess et al., 2005; de Lange et al., 2016). More specifically, neuroimaging studies on aging show age-related volume shrinkage in specific brain regions (e.g., cerebral ganglion and cerebellum), decreases in cortical thickness and white-matter integrity, lowered dopaminergic and posterior brain activity (e.g., hippocampi and occipital areas), yet increased functionality of prefrontal cortex (Cabeza et al., 2004; Reuter-Lorenz et al., 2000). Although with much heterogeneity, destructive neurofibrillary plaques and volume reduction in some brain structures can be found even in highly functioning elderly people (Park & Reuter-Lorenz, 2009). In sum, neuroimaging studies reveal selective changes in the aging brain that can reflect neural decline, as well as compensatory neural recruitment.

To account for this phenomenon of slowed-down decline in the abilities, i.e., a decrease in specific neural parameters, and a compensatory increase in prefrontal activity, the so-called *scaffolding theory* of aging and cognition has been proposed (STAC; Park & Reuter-Lorenz, 2009). Scaffolding postulates a normative life-long circumvention of neural decline via advancement of alternative neural routes to achieve cognitive goals. STAC postulates that functional age-related changes are a part of a life-long compensatory cognitive scaffolding, which represents an attempt to alleviate cognitive decline associated with aging. For example, well-functioning older adults with the greatest hippocampal reduction show greatest activation in the right PFC (Persson et al., 2006).

Aging can be related to a number of neural changes while the behavior stays intact. This has led to the suggestion of functional reorganization which occurs in the aging brain, i.e., older adults functionally adapt to the neural changes and consolidate their brain interconnectivity with regard to these changes. Available evidence suggests that the ability to use functional reorganization is strengthened by cognitive engagement (Zhang et al., 2015; Deng et al., 2019). In sum, STAC considers an aging mind to be a result of neural challenges and functional deterioration, upon which compensatory scaffolding (e.g., frontal recruitment, neurogenesis, distributed processing) and scaffolding enhancement can be exhibited. The interaction of these factors is a key determinant of one's level of cognitive functioning.

Brain-training industry

Scaffolding enhancement can be achieved via different strategies and actions: new learning, cognitive engagement, exercise and cognitive training. All these activities have a common denominator – active and consistent investment in one's own cognitive processes. Brain-training industry (smartphone applications, computerized cognitive training, even action video-game) rests upon this notion. Although evidence of the efficacy of smartphone apps and casual games is ambiguous and remains in question, an abundance of smartphone applications (apps) offer brain training to their users (e.g., Martinčević & Vranić, 2020). An online survey conducted in 2015 has shown that nearly 56% of smartphone users have used some brain training app (Torous et al., 2016). Interestingly, in the subsample of participants over age 60, brain training apps were more downloaded by male participants. Majority of them report that brain training has helped them with different aspects of cognition; 66.9% have experienced aid with thinking processes, 69.3% with attention, 53.3% with mood, 65% with memory. Still, 14.9% of app users have reported that they felt there may be dangers with app use. Two complementary points need to be considered here: 1) the majority of sample was young (only 10% of participants were between ages 46-60, and only 2% of participants were older than 60); 2) smartphone ownership at the time of the study was reaching saturation with younger participants. As smartphone owners age, the positive relation of age and brain training apps will increase. This relation will be complemented by the next wave of growth in brain training apps market which will undoubtedly target older population.

A sophisticated step further from the smartphone brain-training apps are cognitive computerized trainings (CCT). CCT provide users with well-known and often validated tasks taping specific processes. These tasks are then implemented within a personalized training protocol, and with the intent to maintain and/or enhance targeted cognitive ability (e.g., attention, working memory, fluid reasoning) (e.g., von Bastian & Oberauer, 2014; Strobach & Huestegge, 2017; Martinčević & Vranić, 2019). CCT is a multimillion dollar industry featuring popular training platforms, such as Lumosity (Lumos Labs, 2007), Peak (Brainbow Limited, 2014), Elevate (Elevate Inc, 2014), and CogniFit Brain Fitness (Cognifit, 1999). A recent online study, with the age-stratified sample of 18-65-year-olds, has investigated attitudes and beliefs toward CCT (Goghari et al., 2020). The data analysis has shown that CCT was used by half of the sample. Among the users, 72% of participants have self-reported psychological or neurological conditions, and were therefore more likely to use the CCT than participants who did not report these difficulties. Furthermore, 45% of CCT users have spent anywhere from one month to more than a year using these apps, and 65% have engaged with brain apps two or more times per week.

The cognitive assessment and training market are projected to grow from USD 3.2 billion in 2020 to USD 11.4 billion by 2025, at a compound annual growth rate (CAGR) of 29.3% during this period. For comparison purposes, CAGR for a well-known firm like Microsoft and AstraZeneca is 13% and 10.21%, respectively (*Cognitive assessment and training market size, share and global market forecast to 2025*, 2020). Increased endorsement of gamification in cognitive assessment, as well as e-learning practices associated with recommendations for social distancing during the COVID-19 pandemic, are expected to push the endorsement of the cognitive assessment and training market even further.

Predictors of training efficacy

Research on cognitive interventions, as well as its market share is expanding rapidly. This expansion is accompanied by the continuous development of experimental designs, i.e., training designs, which are determined by progress in various fields. The main principles of learning, such as distributed learning, adequate difficulty and its adaptivity, or feedback, have always been the guiding principles of training, but nowadays changes are reflected in how technology enables these principles to be incorporated into interventions. Technology has enabled the development of extremely immersive training (e.g., VR) and the use of more complex measurements. Training algorithms have been improved, and gamification is a key element of more and more training software. In addition to technology, the development is aided by the emerging consensus around the method itself (control group, selection of tasks necessary for generalization of the conclusion) (Green et al., 2019).

Despite this burst in knowledge and technology, the results regarding the efficacy of interventions are still ambiguous. What is it that determines training success, what predicts one's achievement in the program? If we were to reach even far back into classical works in the field, the answer on predictors of training efficacy would include cognitive and non-cognitive factors alike. Galton has considered the importance of intelligence and diligence for one's achievement, and zeal and hard work would be in the core of Darwin's thoughts on the problem (Duckworth et al., 2019). Today's studies on predictors of cognitive training efficacy can often be summed up under the umbrella term of the so-called *baseline dependency*. In the following paragraphs, we will consider some cognitive factors believed to have the baseline dependency with regard to the training outcomes (e.g., cognitive ability, sleep). We will then review the findings on non-cognitive predictors, such as lifestyle, personality, motivation and belief about intelligence, as either fixed or incremental ability.

Cognitive factors. A key cognitive factor associated with cognitive training gains is the baseline cognitive performance. A recent systematic literature synthesis and meta-analysis confirms the baseline dependency of the training efficacy upon the pre-training level of cognitive abilities (e.g., Traut et al., 2021; Vranić et al., 2021). Participants with initially lower abilities gain more from cognitive training than those who were more proficient before the training. This is particularly so in the case of executive function cognitive training (Lövdén et al., 2012; Karbach & Unger, 2014), video games training (Whitlock et al., 2012) and brain stimulation (Habich et al., 2017). Dependency of training gains on the pre-training ability level brings to mind the importance of the adaptivity of the training. Training difficulty must be set according to the baseline performance and should be adjusted to the level of acquired skills during the course of the training. It is interesting to note that certain medications seem to interact with the baseline cognitive ability resulting in differential training outcomes. For example, some substances, such as amphetamine, modafinil, and methylphenidate work mainly in individuals with low baseline performance (Illieva et al., 2013; Finke et al., 2010) and can sometimes even lead to impairments in individuals with higher baseline performance. These findings call for caution and indicate the necessity of an anamnestic checkup at the pretest of any intervention.

Lifestyle. Lifestyle, such as sleep, nutrition, socioeconomic factors and their resulting health status, also seems to be baseline dependent in terms of training efficacy. Sleep appears to enhance memory performance in participants with a higher baseline memory ability (Wilhelm et al., 2012), working memory (Fenn et al., 2012) or intelligence (Fenn at al., 2015). Genzel et al. (2012) found that cognitive performance benefits from nap in men, while this is evident in women only in the luteal phase of their menstrual cycle (high progesterone, low estrogen). As for nutrition, nutrition rich in omega-3 fatty acids and curcumin appear to elevate levels of brain-derived neurotrophic factor (BDNF), while saturated fats seem to do the opposite. BDNF is a neurotrophic which regulates neurogenesis (Numakava et al., 2017) and stimulates plasticity in adult brain (Miranda et al., 2019) by modulating the energy metabolism of nerve cells. Furthermore, the overall health status affects the level of cognitive benefit derived from medications and cognitive enhancers, mnemonics and sleep (Dresler et al., 2019; Genzel et al., 2015). Lastly, socioeconomic factors might play a role in the outcomes of cognitive interventions since studies strongly suggest that they moderate age-related differences in brain organization and functionality across the lifespan (Chan et al., 2018).

Personality. Studies on personality and their impact on training success are not numerous, and they yield unambiguous results. Double and Birney (2016) have investigated non-cognitive factors in registered users of a commercial brain-training platform with regard to their training success and adherence to the program over an 18-month period. Conscientiousness seems to have guided adherence during shorter training period and, more often, with a younger sample. It appears that individuals who are more open and exhibit higher need for cognition desire novel and challenging activities and are more likely to discontinue the training. A systematic review of 10 studies which have investigated the role of personality in training outcomes have suggested that: 1) Openness to experience and need for cognition are positively related to improvement (e.g., Bekavac & Vranić, 2015); and 2) conscientiousness and agreeableness have a positive moderating effect on the response to intervention, i.e., conscientious and agreeable participants improve significantly more than those scoring low on these traits (Marr et al., 2020).

Beliefs about intelligence. Growth mindset - the belief that intelligence is a malleable quality that can increase through efforts – seems to be related to training outcomes, but mostly regarding the adherence and/or discontinuation of the training. Regardless of their age, participants with fixed beliefs regarding intelligence are more likely to withdraw from participation and to perceive the tasks as too demanding (e.g., Double & Birney, 2016; Grant & Dweck, 2003). Regardless of use history, participants believe that attention and memory are most amenable to positive change through CCT use, followed by reasoning, multi-tasking, intelligence, and social cognition. Recent studies suggest that training-related gains are unlikely due solely to a placebo effect (Liu et al., 2021; Tsai et al., 2018), and expectations may increase motivation and attention during training, which in turn, improves posttest results (Parong et al., 2022).

Motivation. Jaeggi et al. (2014) suggests that intrinsic motivation, pre-training ability and need for cognition determine whether a person will choose to participate and remain engaged in a cognitive training. The most commonly reported reasons to engage in and continue to use CCT are curiosity, cognition enhancement, cognitive decline prevention and maintenance of cognitive abilities, restoration of perceived cognitive losses and, finally, the pleasure of playing (Goghari et al., 2020). Overall, highest training gains are found in participants who are given no incentive or a very small incentive for their participation (e.g., $20 in Jaeggi et al., 2010), with lower transfer gains found with higher incentive, which operationalizes extrinsic motivation (e.g., $150 in Anguera et al., 2012, Exp. 2; Studer-Luethi et al., 2010). Substantiating these findings, three other research groups, which have motivated their participants with larger incentives ($130 - $800) have also found no training transfer (Chooi & Thompson, 2012; Redick et al., 2013; Thompson et al., 2013). Effect sizes of gains in training studies with low incentive is found twice the size of the gains in the studies with high incentive. In so far, studies seem to unequivocally agree on the importance of intrinsic motivation to participate in interventions.

Conclusion

Future studies should address the extent and type of generalization induced by training paradigms while considering the many possible patterns of improvements from training. Patterns of benefits vary across training types as well as individuals, and understanding individual differences in training benefits will help advance the field. Overall, general population perceives interventions aimed at cognitive maintenance and enhancement as relatively useful. This underlines the critical importance of clear and precise communication of the scientific status of the effectiveness of CCT, as a large portion of population uses brain-training apps and CCT and wants to participate in organized training sessions.

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