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RESEARCH ARTICLE

Facilitation of Cognition in Older Adults: Traditional and Non-Traditional Approaches to Inducing Change

Denise C. Park*[a,b], Evan T. Smith[a,b]

[a] Center for Vital Longevity, University of Texas at Dallas, Dallas, TX, USA.
[b] Department of Behavioral and Brain Sciences, University of Texas at Dallas, Richardson, TX, USA.

*denise@utdallas.edu

ABSTRACT

Plasticity is a concept of major importance in understanding the process of cognitive aging. Differences among individuals in neuroplasticity play an important role in accounting for different trajectories of cognitive change over time. In the present paper, we define neuroplasticity as the ability to change brain and behavior and discuss cognitive training and cognitive engagement as mechanisms of change in the context of The Scaffolding Theory of Aging and Cognition (STAC). We review evidence for structural and functional plasticity in older adults as a function of different intervention strategies. We suggest that plasticity, particularly as expressed in changes in functional activation or connectivity, can provide a mechanism to remediate the effects of cognitive decline. While evidence that cognition can be preserved or even improved in later life by leveraging residual plasticity is growing, the field has far from a complete understanding of the mechanisms of plasticity and the factors which facilitate its expression, especially in later life.

Keywords: cognitive training, aging, engagement, cognitive plasticity, neuroplasticity ‘

Introduction

Plasticity is a concept of major importance in understanding cognitive aging and is of particular significance in accounting for different trajectories of cognitive change over time. There are many competing definitions and perspectives on plasticity,[1,2] and we adopt one of the simpler ones in this manuscript. Specifically, we define plasticity as the capacity or potential for change in brain and behavior. For example, a person with advanced Alzheimer's Disease (AD) would be described as having very little neuroplasticity- because his or her ability to learn new behaviors would be severely limited compared to a healthy adult of similar age and education. The major approach taken to cognitive plasticity has typically been through the study of external interventions designed to produce positive changes in cognition, which are, of course, mediated by changes in brain structure and/or function.[2,3] Interventions associated with cognitive aging usually have the goal of strengthening existing neurological pathways or creating new ones that are more effective than those that exist,[4] typically in regions homologous to those already activated in the left hemisphere.[5-8] In the present paper, we review evidence demonstrating that such interventions can reliably produce changes in structure and function in later life. We discuss not only traditional cognitive interventions designed to build scaffolds and support cognition, but also social/cognitive engagement and enrichment interventions which do not explicitly target discreet cognitive functions, but which nonetheless may produce change to a degree similar to classical cognitive intervention paradigms. The present paper is focused on plasticity in older adults and the factors which induce adaptive structural and functional changes in cognition, as well as highlights the limits of our current understanding in order to facilitate further investigations.

Plasticity and the Scaffolding Theory of Aging and Cognition (STAC) Model

The Scaffolding Theory of Aging and Cognition (STAC) proposed initially by Park & Reuter-Lorenz, 2009,[9] and later modified by Reuter-Lorenz & Park (2014),[10] integrates behavioral findings of cognitive aging with contemporary neuroimaging data and explicitly addresses the role of plasticity in maintaining optimal cognitive function with age. The original model is shown in Figure 1 and represents the important brain and behavioral variables that determine cognitive function. In this model, age combined with structural and functional brain deterioration operate to determine level of cognitive function. However, the brain can also be modified by two intervening processes—compensatory scaffolding manifested through spontaneous right frontal recruitment, neurogenesis, and distributed processing, and scaffolding enhancement that is the result of a direct intervention that could include exercise, cognitive training, or forms of lifestyle engagement. Thus, scaffolds are supportive structures that result from either spontaneous activation of the right prefrontal and parietal cortices, and as well as through specific training designed to build new neural pathways or scaffolding. This scaffolding results in better cognition than what would otherwise occur based on the extant structure and function of a given brain. Compensatory scaffolding and cognitive interventions both rely on the plasticity of the aging brain and its capacity for change and reorganization. A highly plastic brain will operate to support the declining structures and functions associated with aging by working harder through recruiting additional prefrontal and parietal cortex that the aging brain relies upon to perform cognitive tasks.[5-8,11,12] This phenomenon of additional right PFC activation in older adults has been widely observed across dozens of studies and the STAC model suggests that it occurs when additional neural pathways are forged that may not as efficient as the primary pathways used by young, but nevertheless provide additional support for performing cognitive tasks.[9,10]

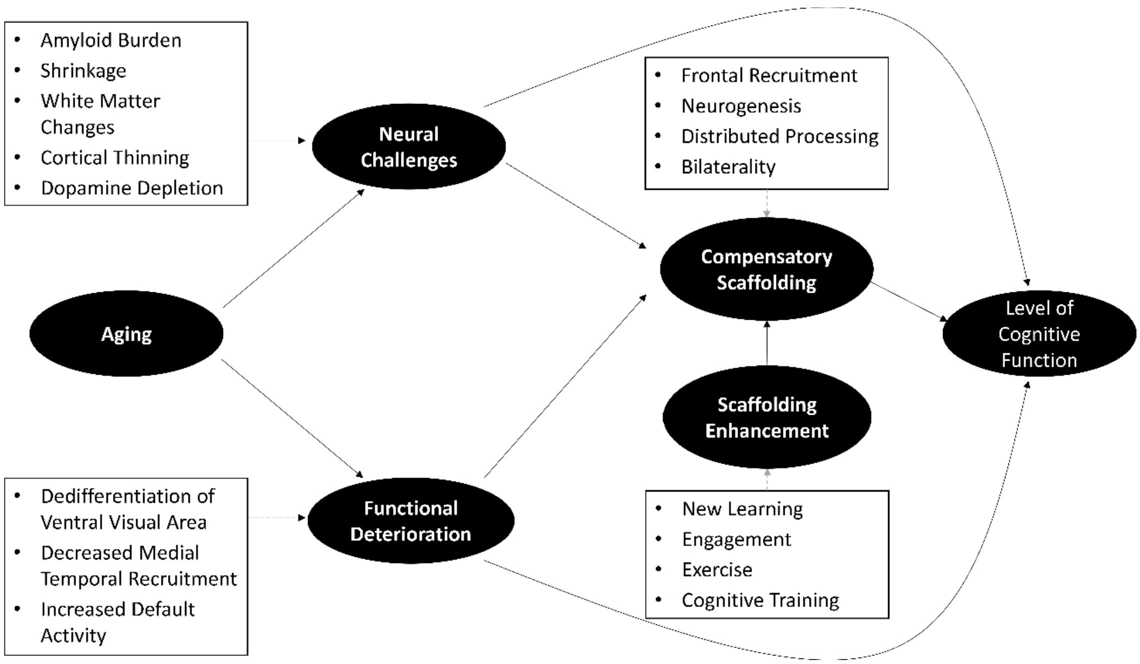

Fig. 1. This Scaffolding Theory of Aging and Cognition as depicted in Park and Reuter-Lorenz (2009) [9].

In a later paper[10], the STAC model was revised to a version labeled "STAC-r" (i.e. "STAC revised") and is depicted in Figure 2. The model was refined to include not only negative factors included in the original STAC model that deplete the brain and lead to brain shrinkage and inefficient brain activity, but also to include enrichment factors that lead to healthy brain structures and optimal function. These enrichment and depletion factors interactively affect brain structure and function. Moreover, STAC-r suggests that brain structure affects brain function and vice versa in a continuously iterative process. As in the original model, various forms of compensatory scaffolding can improve brain function. STAC-r encompasses the entire life-course and addresses both the absolute level of cognitive function that an individual attains, as well as the rate of change in cognition—both of which are determined by the interplay among the factors comprising the model.

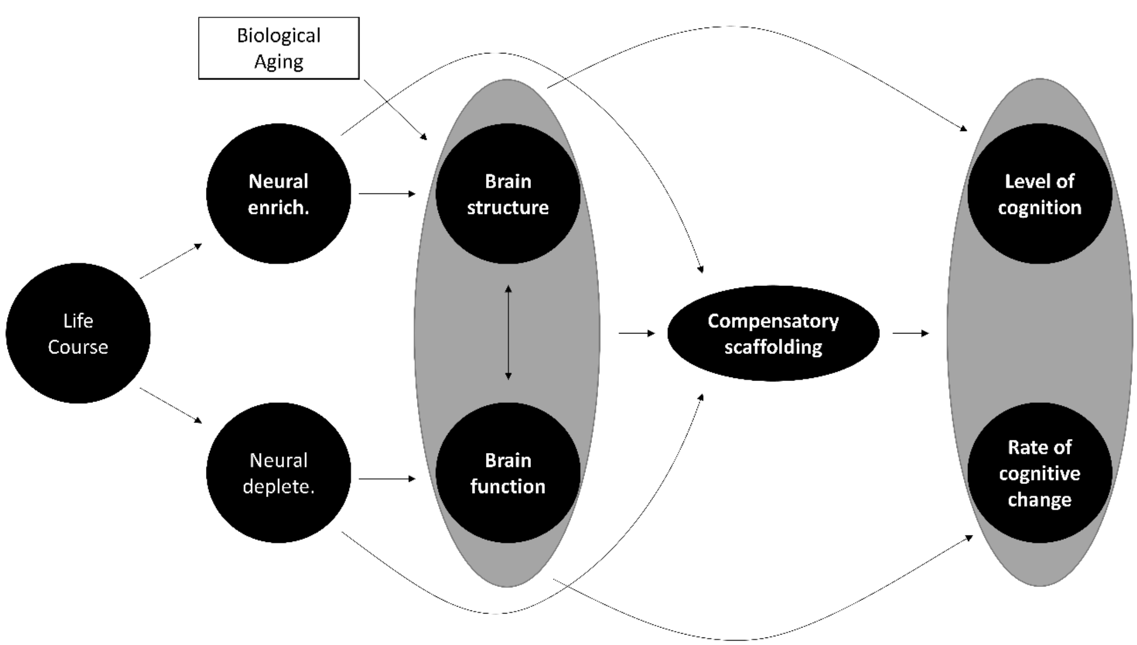

Fig. 2. The revised model, now as "STAC-r" in Reuter-Lorenz and Park (2014) [10].

Zajac-Lamparska (2020)[13] has suggested that the STAC model remains largely untested, particularly with respect to interventions. She indicates that it is important to link magnitude of compensatory scaffolding to intensity of interventions and to use appropriate control groups where the study design is clearly embedded within a theoretical framework. We heartily endorse this perspective and recognize that more effort should be focused on whether cognitive training induces scaffolding. There is relatively clear evidence that the additional activation in right PFC generated in older adults is indeed compensatory. For example, Chen et al. (2021)[14] reported that subjects who maintained cognition over six to eight years longitudinally were more likely to show right frontal recruitment than those who declined over the same period – a finding which confirms earlier studies regarding compensatory right-lateralized activation in older adults.[5-8,12] Importantly, aggregate evidence from numerous cognitive training studies demonstrates that this pattern of compensatory activation can be induced with some reliability (see Duda & Sweet., 2020[15] for a meta-analytic review).

Targeted Cognitive Interventions.

In addition to spontaneous recruitment of frontal and parietal regions, the STAC model also suggests that interventions can be designed to create new paths, or scaffolding, with training explicitly designed to repair, or support, cognition.

As an example, the N-Back task is frequently used in cognitive training (CT) studies.[16,17] Subjects see a stream of digits or numbers and then are presented with a probe that indicates that they should recall the digit that was "N back", that is two or three digits back. The task difficulty is varied by the number back that is required. There is no question that with training subjects become more efficient and increase their N-back capabilities, this improvement occurring due to more efficient disposal of irrelevant information, expansion of the focus of attention, an enhanced ability to suppress irrelevant information, or a combination of all these factors.[18-20] The specific improvement can be observed through neuroimaging of different control processes. For example, numerous neuroimaging studies have demonstrated a reduction in task-related activation of the frontal-parietal control network after a regimen of n-back training, with this reduced activation correlated with increased performance on the task and interpreted as neural efficiency.[21-23] There are innumerable such neuropsychological tasks which can be practiced for thousands of trials to improve a specific brain circuit. Many video games serve a similar function by inducing thousands of responses over prolonged periods of time that share many of the attributes of cognitive training.

Increasingly, neuroscientists are focused on strengthening coordinated brain networks that perform specific operations, such as the control network or default network, with the aim of producing cognitive improvement beyond the trained task by strengthening a network useful to a wide range of activities.[24,25] Further, there is evidence that new scaffolding may be more efficiently developed under conditions of multitasking.[16,26] It seems likely that it is not multitasking per se that creates network changes, but rather task difficulty and intensity – the much greater demands that occur on the cognitive system with multitasking results in more finely honed networks that develop more rapidly than when less demanding single task paradigms are used.

Numerous cognitive training interventions have demonstrated the capacity to engender gray and white matter plasticity in the aging population (see Kristensen et al., 2018[27], and Nguyen, Murphy, and Andrews, 2019[28] for meta-analytic reviews). Interestingly, gray matter increases that result from cognitive intervention are frequently right-lateralized and in frontal and parietal regions known to support executive function.[29-32] This pattern of structural change bears a clear resemblance to the common pattern of right-lateralized compensatory activation seen in older adults and described earlier.[5-8] It seems plausible that the observed right-lateralized structural changes are serving as a substrate to allow for compensatory recruitment of right fronto-parietal regions in older adults. If this is the case, we would expect degree of gray and white matter change to mediate the effects of cognitive training on right-lateralized recruitment, though to our knowledge this assertion is yet to be directly tested.

While evidence of training-evoked functional plasticity in the form of additional regions of brain matter or altered patterns of task-positive recruitment have been known about for some time, more recent advances in the mapping of functional connectivity have allowed for new insights into how functional plasticity can be expressed. Early work in this field by Chan and colleagues (2014)[33] demonstrated that functional networks tend to become less distinct or less segregated with age. Importantly that same study found that, after controlling for age, network segregation was inversely related to memory ability, such that individuals with less segregated functional networks demonstrated poorer episodic memory. These results identified longitudinal change in functional connectivity – specifically network segregation – as a plausible contributor to cognitive decline. Later work by a Chen et al. (2021)[14] would go on to demonstrate that this pattern of decreasing segregation is reversible with the application of cognitive training. Specifically, Chen et al. found that older adults who successfully learned a combined recognition memory and response inhibition task over the course of a CT intervention demonstrated both increased segregation between functional networks and increased within-network clustering, and that the change in these metrics was related to the degree of improvement on the task. Interestingly, the effects of cognitive training on functional network organization appear to qualitatively differ at different points in life: a study by Iordan et al (2021)[34] identified an increase in task-positive network modularity in younger, but not older, adults as a result of training on a working memory task. Conversely, Iordan et al., also identified evidence of training-related efficiency of some functional networks in older, but not younger, adults, resultant from the same training paradigm. These results suggest that, while adaptive functional plasticity can be evoked across the range of the adult lifespan, the mechanism of this plasticity may differ between early and late adulthood.

Perhaps the most direct evidence of the continued capacity of structural plasticity in later life comes from exercise and physical skill interventions. In an early study examining this continued plastic capacity, Boyke et al., 2008[35] (expanding on work from Draganski et al., 2004[36]) demonstrated that older adults who engaged in juggling training demonstrated transient increases to the volume of V5, the hippocampus, and the nucleus accumbens. Numerous other studies have demonstrated the capacity for various physical training interventions to produce plastic structural change in an older adult population. For example, Muiños & Ballesteros (2021)[37] found after a systematic review of dance interventions in older adults that, of 13 identified interventions which examined structural and/or functional outcomes, 10 studies demonstrated evidence of structural and or functional plasticity. Of those studies identified by Muiños & Ballesteros which demonstrated a structural impact of dance training, increased volume of the hippocampus or related structure (i.e. parahippocampal gyrus, fornix) was a commonly observed outcome. A systematic review of aerobic exercise interventions in older adults by Intzandt et al., (2021)[38] identified a similarly high proportion of studies which demonstrably improved gray matter volumes, with volumetric increases most commonly observed in frontal and parietal sub regions, as well as the hippocampus. These studies tell a common story: that volumetric change can be reliably induced in older adults via physical skill training, particularly in the hippocampus as well as in gray/white matter regions supportive of the trained task.

Engagement In Stimulating Environments as a Mechanism of Cognitive Change

Another approach to cognitive stimulation is exposing individuals to new learning and experiences in a natural environment[1]. The goal of such intervention is to provide a cognitively rich, sustained experience that will result in enhanced cognition through broad stimulation of many different systems. For example, two studies by Stine-Morrow et al. (2008, 2014)[39,40] found that older adult who underwent a social engagement intervention demonstrated gains in measures of fluid intelligence compared to control groups. The Synapse study by Park et al., (2014)[41] expanded on this previous work by comparing a similar social engagement condition to three different naturalistic skill training groups. Subjects in the Synapse study were given a baseline cognitive battery and then randomly assigned to learn quilting, digital photography, or both over a period of three months for 15 hours per week. The classes were demanding and at the end of three months cognition was again tested. Results showed that there was a significant improvement in memory and speed of processing, presumably due to the stimulation that was provided at multiple levels—cognitive through new learning; social via interacting with other participants; and perceptual motor due to task requirements. The improvements were relative to two matched control groups who participated in a social engagement condition that met the same number of hours as the learning-based condition but did not require new learning. These subjects engaged in story-telling, cooking and games that relied more on chance than strategies. Importantly, a subset of the subjects was imaged pre- and post-intervention.[42] The results of this investigation demonstrated increased task-positive activation of a robust bilateral network in high-demand subjects, which included the medial frontal, lateral temporal, and parietal regions - again recapitulating the pattern of compensatory right-frontal activation commonly seen in older adults.[5-8,10,12] Further, these results specifically demonstrate that the conjunction of skill learning and an engaging environment are efficacious in producing cognitive and structural plasticity in older adults.

The Synapse study[41,42] is not the only study which has utilized a naturalistic engagement intervention to challenge cognition – other studies utilizing naturalistic skill training interventions such as juggling or dance have been demonstrably efficacious in producing adaptive cognitive, structural, and functional plasticity.[35-37] However, due to the nature of these interventions, we cannot determine if the efficacy of such engaging physical training interventions are due to cognitive engagement, enhanced physical fitness, or perhaps more likely a combination of the two. A more direct example of the effect of naturalistic, cognitively engaging interventions on structural plasticity is the classic study by Woollett & Maguire (2011)[43] which demonstrated, though not in an older adult sample, that the process of studying for certification as a taxi driver within the city of London selectively improved hippocampal volume in those that successfully completed the certification exam, and that the degree of hippocampal volume increased was reflected in improved memory abilities of the participants.

Another domain through which the efficacy of leveraging cognitively engaging tasks to promote plasticity in the older brain is being explored is that of video-game training (VGT) interventions. VGT studies by-and-large utilize similar methodologies to the cognitive training studies with the exception that the commercial video games are utilized as the cognitive task of interest. As videogames are both cognitively demanding and engaging by design, their use as cognitive training interventions is intended to leverage the effects of engagement to produce positive neurocognitive impact while retaining the strict experimental control that direct CT interventions allow for. Though results of individual VGT studies vary, the preponderance of evidence suggests that VGT interventions may be effective in ameliorating some age-related cognitive decline and even produce gains in a wide variety of cognitive abilities, in older adult populations.[44-46] Further, at least two studies have demonstrated that video-game based interventions are capable of evoking structural plasticity in older adults: Kühn et al., (2013)[47] demonstrated that two months of regular video-game play elicited increases in gray matter volume in both the hippocampus and dorso-lateral prefrontal cortex, and that the degree of volumetric increase in these areas was positively related to participants' self-report of how engaged they were in the game training paradigm throughout the course of the study. West et al., (2020)[48] later replicated these results, finding that older adults who engaged in regular video game play for 6 months demonstrated selective gains to hippocampal, cerebellar, and dorso-lateral prefrontal volume compared to a control group. A notable feature of video games is that they provide pleasing sounds, points and other embellishments designed to entertain, reward and maintain the game behavior, a feature that might be useful to build into cognitive interventions. In aggregate, these results suggest that video-game training effectively exploit plasticity and produce cognitive and structural plasticity in older adults. However, it should be noted that VGT interventions have more in common with traditional cognitive training interventions than the more naturalistic engagement interventions utilized by Stine-Morrow et al.,[39.40] and Park et al., (2014).[41] Video games are theoretically more engaging than other lab-based cognitive interventions, yes, but VGT studies still by-and-large are conducted in laboratory environments under strictly controlled conditions and, importantly, without any meaningful social interaction involved. In this way, they lack the environmental richness that the Stine-Morrow et al. and Park eta al. investigations were able to capture.

Naturalistic designs such as the Synapse Study provide a good window into how everyday life events that are stimulating could result in brain changes to support cognition. Studies like these have much to recommend them in terms of understanding how lifestyle could be a powerful instrument that exploits brain plasticity and maintains brain health while engaging in pleasurable and interesting activities. At the same time, enrichment interventions are necessarily less controlled and subject to more unexpected and sometimes unknown influences than strictly controlled training interventions. It can be difficult, therefor, to isolate exactly what aspects of behavior caused brain changes observed from such studies. Further, facilitating cognitive engagement may not be consistently engaging process in all participants – naturalistic skill training outside of laboratory environments allows for a more enriched intervention experience, and also maximizes the chance that a given participant will find some aspect of said intervention to be engaging. Naturalistic engagement studies often activate a high degree of intrinsic motivation [49, 50], which traditional experimental paradigms (i.e. those with random assignment to conditions determined by the experimenter) will necessarily fail to induce in some participants. Nevertheless, in contrast, narrow, training-based manipulations are typically focused on a brain region or network where change can be more readily observed and understood. Both types of paradigms have the potential to yield important information to help in our understanding of neuroplasticity and how to activate it.

Conclusion

It is important to recognize in the context of a discussion of plasticity that it appears that with age, the brain has increasingly less plasticity and there are poorly understood limits to how much the brain is able to change as a result of training or experience.[26,34] It is likely that the mechanisms of neuroplasticity – at least on a functional level – decreased with age and there is also increasing neuropathology with age which may interfere with an intervention.[34] Furthermore, it is almost certain that there are other major individual differences in plasticity, originating from factors such as cultural background, genetic influences, learning strategies, etc. It would be very useful to develop instruments that provides an estimate of how much change is possible for a given individual and how readily change can be induced through experiences and training. There may be cases where, "you can't teach an old dog new tricks" and it would be useful to know where an investment of both training resources and participant effort would yield positive results.

In addition, relatively little is known about how environments can be engineered to take advantage of inherent neuroplasticity and whether such efforts can maintain youthful brains well into late adulthood with possible delays in the onset of Alzheimer's Disease. The study of neuroplasticity implies a positivity about human potential and optimism about the human condition that is worthy of much further study. There are undoubtedly some surprises awaiting investigators who meet the daunting experimental challenges posed by the questions that surround neuroplasticity and it is time to address thus important topic as a new frontier where we have much to learn and to gain.

Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

Denise C. Park and Evan T. Smith planned, drafted, and revised this manuscript in close consultation with one another.

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