Sensory and cognitive plasticity: implications for academic interventions

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Research in neuroscience has great potential for transforming education. However, the brain systems that support academic and cognitive skills are poorly understood in comparison to the systems that support sensory processing. Decades of basic research have examined the role that brain plasticity plays in the genesis and treatment of developmental visual disorders, which may help to inform how cognitive training approaches can be tailored for students who experience environmental disadvantage. In this review, we draw parallels between visual and cognitive intervention approaches, and suggest research avenues that could inform educational practice in the future.

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Introduction

Fluid cognitive skills, such as reasoning, working memory, and processing speed, are highly correlated with performance in school [1,2]. Many attempts have been made to improve cognitive skills in children with varying degrees of success [3,4], and with only limited evidence of transfer to academic performance [5,6]. Failures in cognitive training studies are so common that some have argued that cognitive skills are fixed [7]. However, the concept of fixed cognition is difficult to reconcile with the overwhelming evidence that brain systems are highly plastic [8]. More likely, we simply have not yet discovered the optimal way to promote cognitive plasticity.

The basic science of cognitive plasticity is in its infancy, as is the translational science of developing cognitive interventions. In contrast, the visual system offers a well-studied paradigm of neuroplasticity, both in terms of basic mechanisms, and in terms of real-world applications. In this review, we discuss important findings from visual neuroscience and their relationship to the development of treatments for individuals with visual deficits. Then, we draw analogies to the neuroscience of cognitive plasticity, and to efforts to improve fluid cognitive skills and academic achievement in children from disadvantaged backgrounds. Finally, we discuss future directions for research on visual and cognitive plasticity, and how these fields can be mutually informative.

Visual neuroscience and clinical treatment: a test-case for neuroscience-informed intervention

It is well known that the visual system requires experience for the development of normal visual function [9]. If the brain is deprived of the normal patterns of visual experience during development, enduring deficits can result. In the extreme, some visual functions are subject to "critical periods" – fixed and finite durations of heightened brain plasticity, often occurring early in life. Studies in animals suggest that the mediation and eventual closure of critical periods in visual cortex rely on a diverse set of mechanisms including: myelination [10], the maturation of inhibitory neurons [11], and the formation of perineuronal nets that stabilize cellular structures [12,13]. Many such studies use monocular deprivation paradigms, in which one eye is physically occluded or otherwise weakened with respect to the other. Because primary visual cortex is organized in ocular dominance columns, these studies allow for the close examination of how deprivation affects cortex devoted to input from each eye.

In humans, a relatively prevalent example of deprivation during a critical period is amblyopia, a condition that can occur in young children if one eye has a much larger refractive error than the other (is more out of focus) or is misaligned with the other ("lazy eye"). Amblyopia is estimated to affect approximately 3% of the population [14], and encompasses a constellation of visual deficits that range from poor visual acuity (or clarity) in the weaker eye, to lack of stereovision, to higher-level issues related to visual processing. The similarities between amblyopic visual experience and animal models of monocular deprivation suggest that their effects on the visual system may be mediated by similar neural mechanisms [15]. Related to this idea, recent interest in how therapies for amblyopia may exploit different aspects of neural plasticity has led to rapid advances in our understanding of the time course and potential outcomes of both conventional and new amblyopia treatment types.

The treatment of amblyopia almost always begins with correcting the weaker eye, either with optics or surgery. That is, *the first step is to remove the original cause*. In some cases, this may be sufficient to restore normal vision within a few months [16]. If visual deficits persist even after the ocular cause is removed, this confirms the presence of a neural deficit. For centuries, the mainstay of amblyopia therapies has been patching: the stronger eye is covered with a patch, and the child must perform daily tasks using the weaker eye on its own. It is thought that patching exploits plasticity in the early visual pathways to strengthen the processing of signals coming from the weaker eye. However, children's responsiveness to this treatment is highly age-dependent: *earlier intervention is more effective*. Cross-sectional studies report that children under the age of seven respond best to patching, confirming standard clinical practice [16,17]. Older children can respond to treatment, but the efficacy is substantially worse and thus the condition is less likely to fully resolve.

At the same time, animal work has also established that different visual functions have different critical periods, suggesting a developmental progression of plasticity within the visual system [18,19]. In recent years, there has been growing interest in new therapies that improve amblyopic visual function beyond the conventional critical period, highlighting the idea that *different treatments can be tailored for different ages*. Two recent studies show that visual function can continue to improve if targeted "dichoptic" treatment is adopted after any improvements gained with patching have plateaued [20,21]. The dichoptic method involves encouraging the two eyes to work together, rather than forcing the use of one eye on its own. Other "perceptual learning" therapies involve intensive training of the weaker eye on specific visual tasks [22].

The precise mechanism of improvements in juvenile and adult amblyopia with these new therapies remains controversial [23], particularly because a variety of different approaches have produced similar results [24]. However, it is appealing to propose that the improvements with non-patching treatments reflect the hierarchical nature of visual plasticity. While patching may be effective at times when early visual pathways are most malleable, the maturation of higher-level modulatory circuits may be necessary to induce different types of plasticity later in life [25,26]. There is much left to learn, but it is clear that the plasticity of the visual system changes drastically from infancy to adulthood, and that understanding these changes has tangible consequences for the timing, type, and efficacy of interventions.

Improving cognitive skills: lessons from visual neuroscience

The treatment of amblyopia serves as an example of a productive bidirectional relationship between neuroplasticity research and intervention development that can be considered analogous to the development of interventions to improve fluid cognitive skills. We will limit the scope of discussion to the skills typically assessed by fluid intelligence tests: fluid reasoning, working memory, and processing speed [27]. We will focus on the case of children whose cognitive skills are impacted by environmental disadvantage, such as low socioeconomic status [28,29], as these children represent a large proportion of students who struggle in school.

1. The first step is to remove the original cause. In the case of amblyopia, the cause is relatively easy to both diagnose and treat. On some level, the same can be said of environmental disadvantage, even if the broader picture is more complicated: the cause is the lack of economic resources and the treatment is supplementing these resources. In adults, increased income, in the form of unconditional cash transfers [30] or increased wealth from a successful harvest [31], is associated with improved cognition. One possible mechanism for these effects is that the stress associated with poverty detracts from cognitive function. Indeed, just prompting individuals in poverty to think about their finances reduces cognitive performance [31]. Less is known about the impact of income on children. One study found that an increase in income amongst families in poverty is associated with emotional and behavioral benefits for children [32]. However, because it is often not practical to supplement family income directly, a more tractable goal may be to support parental socioeconomic mobility [33,34]. Alternatively, it may be effective to build caregiver capacities for buffering the stresses associated with economic disadvantage [35]: parenting interventions with this goal have had some of the most impressive and long-lasting effects on child cognitive skills [36,37]. Curricula that empower teachers to alleviate stress in the classroom may be similarly effective [38].

As with treating amblyopia, sometimes removing the original cause, in this case environmental disadvantage, may be sufficient to treat, or even prevent, cognitive disparities, depending on the age at which this type of intervention occurs. But in cognitive interventions, removing the cause is not always an option. Schools often cannot modify home environments and therefore must take alternate approaches to boosting cognition.

2. Earlier intervention is more effective. Patching treatment for amblyopia is more effective in younger children, perhaps because the early maturation of visual circuits leads to a critical period for ocular dominance that starts at a young age and closes around age seven. What do we know about the timing of the neural mechanisms that underlie critical, or more generally, "sensitive" periods for cognitive systems? Sensitive periods of cognitive development have been relatively well-studied in the case of language acquisition, with evidence supporting multiple periods of plasticity that include early and restricted, as well as later and more flexible, intervals [39]. It is still unknown whether there are analogous critical or sensitive periods for fluid cognitive skills and their neural substrates, such as association cortex.

Structural and functional properties of association cortex in

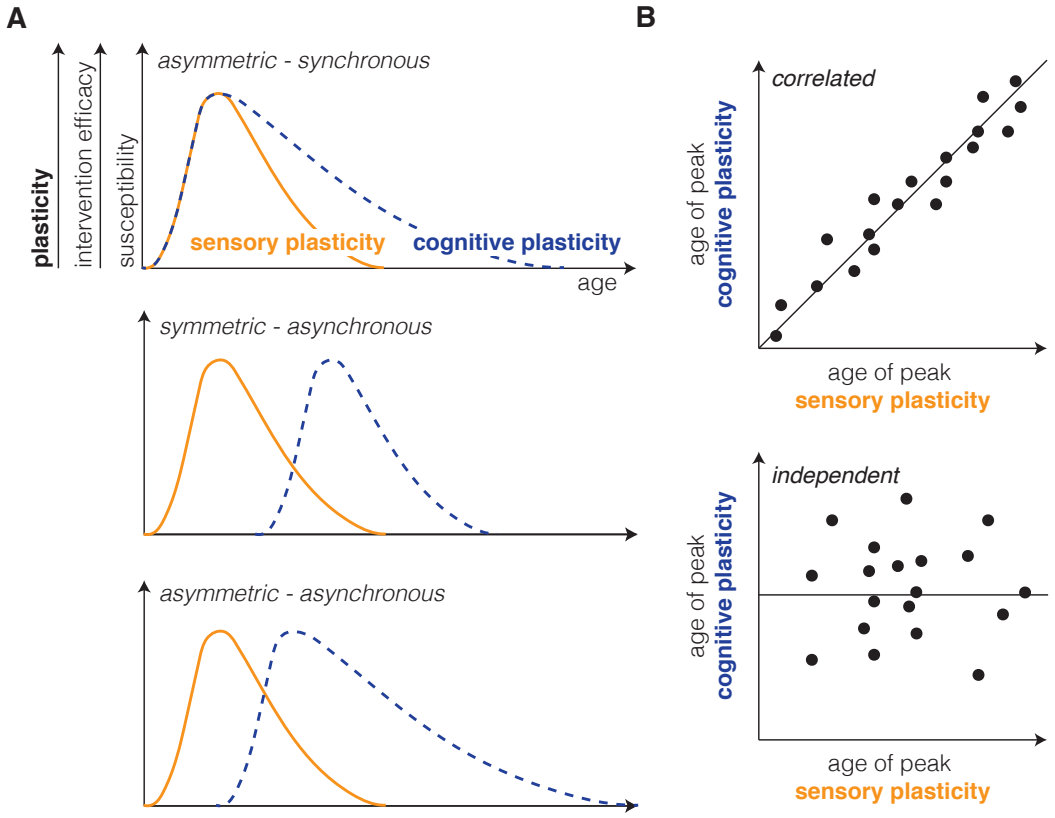

Fig. 1. Theoretical relationships between sensory and cognitive plasticity. **A.** Greater plasticity is associated with both greater intervention efficacy and greater susceptibility to deprivation and disadvantage. However, note here that efficacy reflects a response to an intervention applied at a fixed interval in time, not to the time at which the root cause is removed. The onset of peak plasticity may be synchronous or asynchronous across systems, and the systems might share the same duration of heightened plasticity (symmetric) or cognitive plasticity may last longer (asymmetric). **B.** Across individuals, the age of peak sensory plasticity may or may not predict the age of peak cognitive plasticity, i.e., they may be correlated or independent. Although not shown, in these plots overall differences in synchronicity as illustrated in A would appear as uniform shifts of all points along one axis relative to the other.

humans, e.g. low heritability [40], high inter-individual variability [41,42], and slow development [43–45], suggest enhanced and prolonged sensitivity to the environment [46]. Further, association areas remain less myelinated than sensory cortices in adulthood [47], a sign that these regions are more flexible given the role of myelin in limiting plasticity [10]. However, a recent study showed that genes associated with the opening and closing of critical periods exhibit similar temporal patterns of expression in visual and frontal cortex, suggesting that the timing of maximal sensitivity may not be all that different between systems [48]. Understanding the developmental trajectory of plasticity in association cortex could be useful for determining the optimal timing of cognitive interventions. Earlier interventions may not always be more effective if they take place prior to the opening of the sensitive period, and it may not be necessary to intervene early on some cognitive skills if the window of peak plasticity remains open into adulthood.

There is limited research on the age-dependence of cognitive plasticity in humans. Studies of international adoption have found that earlier adoption (at less than one year of age) is associated with better cognitive outcomes [49,50]. Many of the most effective educational interventions have been targeted at preschoolers (e.g., The Perry Preschool Program [51], The Abecedarian Project [52], Tools of the Mind [38]), and there is some evidence that long-term curricular changes are more effective in preschool than they are at later ages [54]. To our knowledge, only one short-term cognitive training study compared outcomes across different ages of children. Four-year-old children showed greater behavioral improvements from attention training than did six-year-old children, but both age groups showed brain activity changes consistent with maturation [55]. However, because the training task could have been more appropriate for four-year-olds than for six-year-olds, the differential responsiveness could be attributed to factors other than differential plasticity. This complexity highlights the difficulty of assessing the age-dependency of cognitive plasticity.

3. Different treatments can be tailored for different ages. Like visual abilities, cognitive skills have also been hypothesized to be hierarchical. According to the Developmental Cascade Model [56], processing speed supports working

memory, which in turn supports fluid reasoning. These skills develop at different ages, and longitudinally, gains in a lower-level skill predict future gains in a higher-level skill [57]. Cognitive interventions might be most effective if matched to a child's cognitive skill profile. For example, a younger child, or a child with low processing speed, might benefit more from processing speed training than from reasoning training because deficits in the lower-level skill create a bottleneck for the higher-level skill. Future research is necessary to determine whether there are indeed multiple hierarchical sensitive periods in cognitive development, and whether educational interventions are more effective if tailored to age or developmental stage.

Conclusion

For decades, clinical observations have inspired research in visual neuroscience, and in turn, basic research on neuroplasticity has informed our understanding of visual disorders. We suggest that this bidirectional relationship can serve as a model for the future of cognitive plasticity research. Three specific research avenues stand out to us as analogous across fields: understanding and treating the root cause, defining the optimal timing of interventions, and tailoring interventions to age and developmental stage.

Important differences between fields could potentially limit the usefulness of these analogies. At a cellular level, plasticity in ocular dominance columns is easier to measure than plasticity in association cortex, because the structure of association cortex is not as well understood. However, recent work suggests that there may be maps in association cortex that are analogous to those in sensory cortex, which may make cognitive plasticity research more tractable in the future [58,59]. Behaviorally, animal models of monocular deprivation closely parallel human experiences with amblyopia, but it is unclear whether animal models of cognitive enrichment and social isolation adequately mirror the diversity of human cognitive experiences. Clinically, treatment efficacy is easily defined and measured in vision, e.g., acuity gain per 100 hours of patching [17], but optimal outcomes are more difficult to define in cognitive plasticity research. Most interventions show effects on some cognitive and academic measures but not others and the relative importance of these measures is unclear.

Looking forward, direct comparisons of sensory and cognitive plasticity both in terms of mechanisms and phenomenology will help maximize our ability to translate progress across brain systems. For example, modeling methods used to identify the time course of sensitivity to deprivation in the human visual system via perceptual measurements (e.g., [60]) could be applied to cognitive measurements, allowing for common tracking of plasticity across brain systems. However, clearly defined periods of environmental disadvantage are likely much less common than periods of altered vision. Thus, rather than focusing on susceptibility to deprivation, the same principles could be applied by reasoning that sensitive periods are also marked by maximal responsiveness to experience and training. This would allow for the testing of hypotheses about the time-course of plasticity: Does cognitive plasticity occur together with or lag behind sensory plasticity (**Figure 1A**)? Are there individual differences in the timing of peak plasticity that span sensory and cognitive systems? For this second question, **Figure 1B** illustrates two example scenarios: the peaks of cognitive and sensory plasticity are correlated (upper panel) or uncorrelated (lower panel) across individuals. Note that an overall delay or advance in one system relative to the other (as shown in **A**) would simply be a shift along either axis of the plots. If sensory and cognitive plasticity are indeed correlated across individuals, it would suggest that visual plasticity could be used as a predictor for cognitive plasticity. For example, if a student were identified as an "early developer" based on visual assessments, it would suggest that she would benefit more from earlier cognitive interventions. These questions will be essential to understanding how the human brain is shaped by experience, both in general and in the classroom.

Critically, advances in basic neuroscience have the potential to impact both the treatment of visual disorders and educational efforts to improve cognitive skills. Neuroscientists have discovered methods for restoring plasticity in older animals by altering neurotransmitter levels through brain stimulation [61], pharmacology [62], environmental changes [63,64], and behavioral manipulations to boost attention and motivation [65]. Some of these approaches have been translated, experimentally, to humans to improve both visual perception and cognition [66–68]. However, it is still unclear which, if any, of these approaches are appropriate for children. Altering plasticity during key developmental stages may not be without cost, especially if typical patterns of developmental plasticity are poorly understood. In particular, increased plasticity is associated with both increased treatment efficacy and increased susceptibility to trauma or deprivation (See **Figure 1**). For example, in an animal model of amblyopia, prolonged immersion in complete darkness can restore plasticity and improve vision in older animals that have previously undergone monocular deprivation [63,64], but the same intervention performed in younger animals can result in temporary blindness [19]. More broadly, periods of high plasticity, while essential for tuning brain systems to the demands of their environment, likely also come at a cost in terms of stability and metabolic energy. It is likely that brain development occurs in such a way so as to efficiently learn, consolidate, and exploit predictable aspects of the demands posed by one's environment. Greater knowledge about neuroplasticity, including a better understanding of its variability across brain regions and across individuals, is necessary for the optimal design and timing of interventions to improve both vision and cognition.

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