

# Brain-Computer Interfaces for Vision Recovery in Precortical Vision Loss

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**Introduction:** Precortical vision loss remains a major global health challenge. Advances in brain-computer interfaces (BCIs) offer a new pathway towards restoring functional vision by bypassing damaged structures in the visual pathway.

**Methods:** This narrative review aims to synthesize the current evidence on BCIs for precortical vision recovery, including non-invasive and invasive techniques. Device design, testing, and outcomes are discussed, with an emphasis on developments in technology and engineering.

**Results:** Non-invasive BCIs induce neuroplasticity and may restore vision in conditions of precortical vision loss such as glaucoma and optic neuropathy. Cortical visual prostheses demonstrate the ability to evoke visual precepts and recover functional vision. Integration of artificial intelligence and high-density electrode arrays has improved image encoding and device adaptability to enhance user experience and rehabilitation potential. Patient selection, safety, and long-term outcomes remain active areas of investigation.

**Discussion:** BCIs present a paradigm shift in treating precortical blindness that offers hope for patients with no alternative options. Yet, challenges persist, including surgical risks, durability, and variability in response. Personalization of stimulation protocols and further technical refinement are needed to optimize efficacy and accessibility.

**Conclusion:** BCIs are a promising experimental modality for precortical vision restoration. Continued research and interdisciplinary collaboration are essential to address current limitations.

**Plain Language Summary:** Vision loss has a negative impact on functional independence and well-being. Conventional treatments like medications or surgery cannot always effectively manage vision loss caused by damage to the visual pathway. Therefore, researchers are exploring new ways to treat vision loss using brain-computer interfaces (BCIs) capable of bypassing damaged visual tissue. Studies have shown that BCIs can help people with blindness regain visual function when other treatments are not effective. Moreover, complementary technologies such as artificial intelligence have made BCIs more customizable. This review aims to discuss the theoretical underpinnings, history, progress, and challenges of using BCIs to treat patients experiencing vision loss, with a focus on translational potential.

**Keywords:** brain computer interfaces, neuroprostheses, neuroplasticity, blindness, vision restoration

## Introduction

Vision impairment and blindness are major global health problems that affect the functional independence of billions of people worldwide and impose significant societal and economic costs.<sup>1</sup> Conventional approaches to preventing blindness, such as pharmacotherapy and invasive surgery, are limited by adverse side effects, high costs, and treatment failure. These limitations are especially pronounced in cases of advanced vision loss, where restoration of meaningful vision is often unattainable. For example, patients suffering from disorders of the retina or optic nerve have few effective treatments to choose from. Novel modalities for vision restoration such as targeted gene therapy and optogenetic

approaches have been reported in the literature as theoretically effective treatments for these conditions, but face constraints in immune rejection and limited procedural and surgical access.<sup>2,3</sup>

Recent advances in brain-computer interface (BCI) technology offer a paradigm shift towards a new treatment modality for advanced vision loss that bypasses damaged peripheral visual pathways for direct stimulation of the visual cortex.<sup>2</sup> Although reviews on BCIs have been published,<sup>3</sup> new developments in bioengineering and artificial intelligence (AI) have rapidly accelerated the development of novel visual BCIs. The present review synthesizes the theoretical foundations, history, evidence, risks and benefits, and future directions of utilizing BCIs for vision restoration, with a focus on their translational potential for ophthalmologists managing vision loss.

## Materials and Methods

### Literature Search

A comprehensive search of the current body of peer-reviewed evidence on BCIs for vision loss was conducted on PubMed using PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) keywords. The query utilized the following search terms: “(brain-computer interface) AND (vision) AND ((recovery) OR (restoration))”. Titles and abstracts of articles were independently evaluated by the authors. Final article selection was performed independently by the authors after reviewing full-text files. References cited in articles from our initial query were also manually reviewed. All reviewed articles were evaluated for (I) a clear vision-related indication for BCI use. All reviewed articles were subject to the following exclusion criteria: (I) studies written in a language other than English and (II) studies evaluating non-human subjects. All reviewed articles were subject to the following inclusion criteria: (I) studies written in English and (II) primary clinical studies involving BCI use for visual indications. No restrictions were placed on the included number of patients or patient demographics.

## Results

### BCIs for Vision Restoration: A Primer

BCIs encompass a wide array of devices used for various clinical indications that can be classified broadly into non-invasive and invasive categories. In simple terms, BCIs connect the electrical activity of the brain to an external device. Commonly known examples of non-invasive BCIs include electroencephalography (EEG) monitors used for the diagnosis of sleep disorders and epilepsy,<sup>4,5</sup> functional magnetic resonance imaging (fMRI) used for functional brain mapping,<sup>6</sup> and transcranial magnetic stimulation (TMS), a non-invasive medical treatment for mood disorders.<sup>7</sup> Known examples of invasive BCIs include deep brain stimulator implants used in the treatment of epilepsy and Parkinson’s Disease<sup>8</sup> and assistive speech generators for patients suffering from aphasia caused by motor neuron disease<sup>9,10</sup> or vertebral stroke.<sup>11</sup>

The first report of the BCI was authored by Berger in 1924, when he described the identification and wake-sleep cycle correlation of discrete alpha and beta waveforms on EEG.<sup>12</sup> Several theoretical papers tabulating the possible applications of BCIs in animal research<sup>13</sup> and human rehabilitation<sup>14</sup> were subsequently published in the late 1900s. The turn of the 21st century brought increased public awareness to the BCI as a clinical tool after several paralyzed patients successfully regained motor,<sup>15–18</sup> communication,<sup>19,20</sup> and even sensory function<sup>21,22</sup> after BCI implantation.

The theoretical basis of using BCIs for vision restoration relies on encoding images of the outside world into excitatory electrochemical signals that stimulate neurons comprising the different components of the visual pathway (retina, optic nerve, optic tract, thalamus, optic radiations, visual cortices, etc.), subsequently generating the sensation of basic visual precepts that patients can perceive without external visual input.<sup>23,24</sup> These stimulated sensations, known colloquially as phosphenes, could feasibly be combined and reagggregated in various ways to construct representations of the external world.<sup>23,25</sup> One major benefit of using BCI technology for vision restoration is it could cure patients suffering from any etiology of vision loss along the entire length of the visual pathway. For example, both optic nerve BCIs<sup>26,27</sup> and cortical BCIs<sup>28</sup> used intraoperatively during stereotactic neurosurgery in the conscious patient have been reported to be effective in eliciting phosphenes.

## Strengths and Limitations of Brain-Computer Interfaces for Vision Restoration

BCIs present many theoretical advantages for patients with vision loss. First, they bypass damaged anatomy, allowing for recovery of visual function even when parts of the visual pathway are focally non-functional.<sup>29,30</sup> As such, they have the potential to restore vision for patients with blindness secondary to pathologies where conventional therapies are ineffective (eg. stroke, phthisis bulbi, enucleated eye). In the example of an enucleated patient, a BCI would bypass the absent eye and convert external visual input processed through a camera into patterned electrical stimulation delivered directly to the visual cortex to generate phosphenes. Second, the possibility of a direct interface between BCIs and cortical visual centers presents the additional benefit of functional neuroplasticity; repetitive excitation of cortical areas responsible for vision necessarily strengthens the networks connecting these regions to the parietal lobe through Hebbian plasticity and cortical remapping. Third, the ability of BCIs to integrate with existing prosthetic frameworks as well as semiconductor and artificial intelligence (AI) architectures provide multiple avenues to enhance resolution, stability, and adaptability for real-time phosphene simulation, thereby reducing cognitive burden.<sup>31,32</sup>

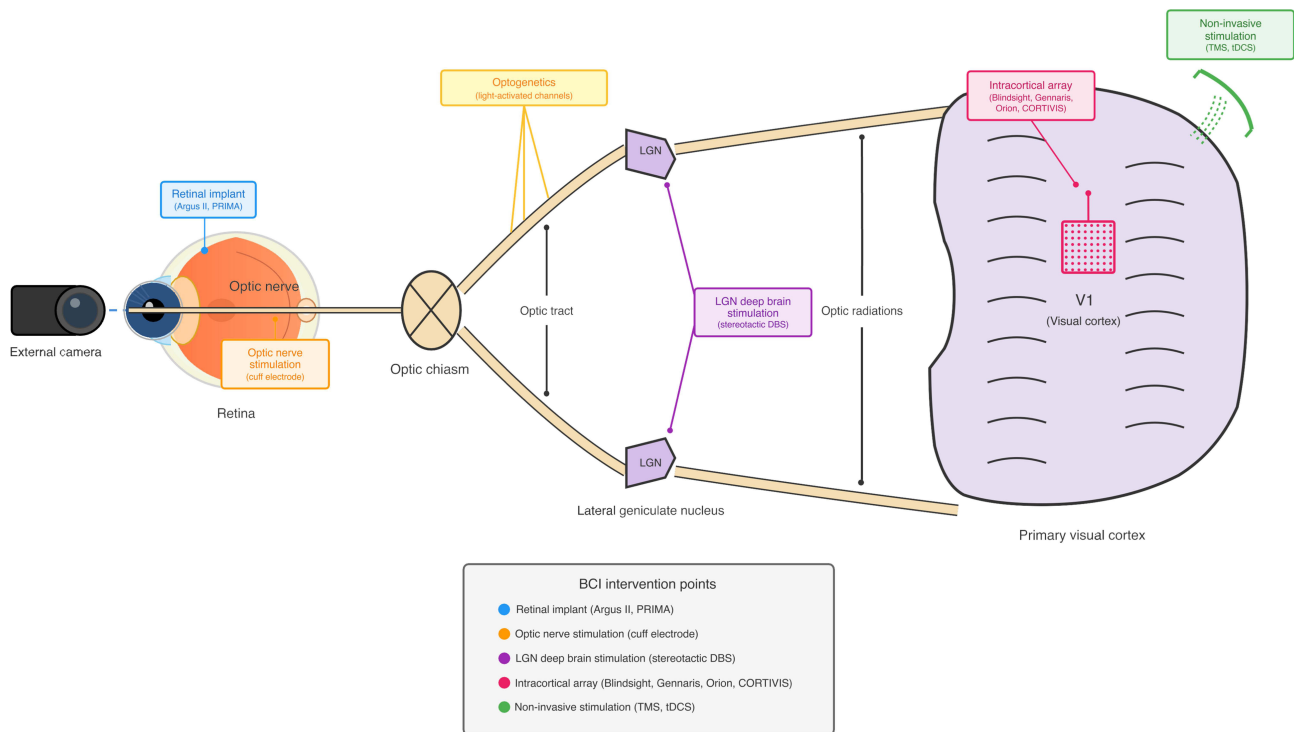
If successfully implemented, BCIs would likely provide patients with more autonomy and functional independence than alternative proposed solutions.<sup>33–36</sup> However, BCIs carry just as many theoretical risks. These include the immediate surgical risks of perioperative infection, hemorrhage, and immune rejection,<sup>33</sup> as well the long-term surgical risks of device-related obsolescence and need for reoperation. Two meta-analyses evaluating the prevalence of surgical site infections for implanted deep brain stimulators estimated a pooled infection risk of 4–5%; this risk is likely similar to that of the theoretical risk of BCIs.<sup>37,38</sup> The potential for maladaptive plasticity and abnormal or unwanted cortical activity, psychophysical and neurocognitive burdens, extensive postoperative rehabilitation, and device maintenance must also be considered, especially in patients who do not achieve satisfactory postoperative visual function. Other important considerations include a limited body of evidence on BCI durability as well as regulatory barriers borne from a scarcity of large-scale multicenter trials evaluating device standardization and long-term safety data.<sup>29,31,34,39</sup> Perhaps most important, however, are the ethical and societal concerns related to patient privacy, autonomy, and inequitable access to a costly novel therapeutic modality. BCIs present a new class of concerns regarding patient privacy. Monitoring neural data may reveal sensitive cognitive and behavioral information vulnerable to misuse or surveillance and could jeopardize patient autonomy through proprietary algorithms that blur the boundaries between user agency and machine influence. Finally, inequitable representation in clinical trials as well as geographic disparities in governance risk incorporating structural bias into BCI development and access.<sup>31,40</sup>

Non-invasive and invasive BCI prosthetics offer distinct strengths and limitations. Non-invasive BCIs, such as sensory substitution devices (SSDs) and superficial cortical stimulators, are safe, avoid the risks of invasive neurosurgery, and are more affordable and accessible. They leverage the cortical adaptive process of “intersensory plasticity”, which allows the brain to process and integrate visual information through the non-visual senses.<sup>31</sup> However, they carry limitations, including reduced spatiotemporal resolution and lower fidelity, that reduce the richness of the restored visual experience.<sup>41</sup> Non-invasive BCIs also require extensive training and adaptation, meaning that patients with altered mentation may not achieve meaningful gains in functional vision. On the other hand, invasive BCIs such as cortical prostheses directly stimulate the visual cortex, enabling the generation of higher resolution phosphenes that bypass damaged visual pathways. However, invasive BCIs also carry clear weaknesses, including the aforementioned surgical risks and long-term concerns related to biocompatibility and ongoing neuropsychological assessment.<sup>3</sup> To aid comparison, [Figure 1](#) outlines key differences between non-invasive and invasive BCIs.

## Challenges of Existing Approaches to Vision Restoration

Of the existing therapeutic approaches to restoring vision, there are three that have been extensively studied: behavioral rehabilitation techniques designed to harness the plasticity of the visual cortex, such as vision restoration therapy (VRT); non-invasive electromagnetic stimulation of the visual pathway; and regenerative genetic and prosthetic interventions that replace irreparably damaged visual parenchyma.

VRT is a non-invasive computer-based vision rehabilitation modality designed to treat visual field deficits secondary to pathologic insult posterior to the retina. The theoretical basis of VRT is that surviving neurons adjacent to the neurons



**Figure 1** Visual pathway and BCI intervention points.

comprising the damaged part of the cortical visual tract have preserved perceptual potential, and this potential can be activated with repetitive visual stimulation. This repetitive stimulation is thought to activate neuroplasticity, strengthen synaptic transmission, and synchronize the partially injured parenchyma as well as downstream neuronal networks, thereby enhancing visual function.<sup>42</sup> The theoretical benefits of VRT are that (I) it is non-invasive and hence presents minimal risk to the blind patient; (II) it can be done at any time after the visual tract is damaged; (III) it is broadly applicable to all types of vision loss, including but not limited to glaucoma, amblyopia, stroke, and trauma. Its limitations include (I) a high treatment burden with sustained improvement only attainable in patients who adhere to regular treatment;<sup>42</sup> (II) difficulty in obtaining a precise prognostic timeline given the heterogeneity of visual pathway injury; (III) a requirement for good cognitive function and mental arousal for treatment adherence, which is often suboptimal in patients with severe vision loss.<sup>43</sup> Several Phase II studies investigating the efficacy of VRT in patients with visual field deficits stemming from different etiologies have been conducted. Sabel et al found that a three-month course of daily VRT led to significant gains in visual function on perimetry testing in a small sample of patients with severe glaucoma.<sup>42</sup> Jung et al found that a three-to-six-month course of VRT caused a trend towards improved visual function in a sample of ten patients with anterior ischemic optic neuropathy.<sup>44</sup> Plow et al found that a three-month course of VRT in combination with low-power transcranial direct current stimulation (tDCS) of the occipital cortex led to improvement in visual function compared to controls.<sup>45</sup> Despite these findings, interpretation of these studies is confounded by small and heterogeneous samples with inconsistent VRT regimens and incongruent statistical methods (Plow et al conducted a per-protocol analysis whereas Sabel and Jung conducted an intention-to-treat analysis). As the quality of evidence on VRT remains poor, larger trials studying more clearly defined VRT regimens on patients suffering from a wider breadth of etiologies of vision loss are warranted.

Non-invasive electromagnetic stimulation (ES) of the visual pathway has emerged as a promising minimally-invasive approach to restoring visual function for all forms of vision loss. The scientific basis of ES relies on artificial induction of visual neuronal activity with an external electromagnetic current. ES was first conceptually reported in 1755 by French academic Charles LeRoy, who generated a perceptible phosphene in a patient blinded by bilateral cataract via application of a low-power transcorneal electrical current.<sup>46</sup> In the following centuries, academicians throughout Europe

corroborated similar findings. Today, there are multiple established ES modalities, including but not limited to repetitive transorbital alternating current stimulation (rtACS),<sup>47–49</sup> transdermal electrical stimulation (TdES),<sup>50,51</sup> and transcorneal electrical stimulation (TcES).<sup>52–54</sup> The parameters for each of these modalities vary, but all involve week-long courses of low-frequency electrical current applied at the milliamp scale. Randomized studies have reported good efficacy of these modalities in improving visual function in patients with optic neuropathy<sup>47,49</sup> and stabilizing electroretinogram degradation and retinal vascular perfusion indices in patients with retinitis pigmentosa (RP),<sup>51–54</sup> an incurable inherited retinal dystrophy characterized by progressive photoreceptor degradation. Despite the promising body of evidence surrounding ES as a non-invasive modality for treating vision loss, there remain challenges related to targeted stimulation of damaged visual neurons. For instance, the studies cited above only evaluate ES in patients with defects of the retina or optic nerve, but not of the cortical visual pathway. This is presumably due to limitations in penetrance, which makes the process of selective neuronal activation difficult.<sup>55,56</sup> Accurate retinotopic mapping of the neurons of the cortical visual pathway is also difficult due to the small size of the lateral geniculate nucleus and optic tracts, their anatomical depth, and complex laminar structure. When applied to the cortices, the electromagnetic signal generated through ES accumulates in the superficial gyri and underlying white matter, with rapid attenuation in deeper cortical regions. This is due to the intrinsic resistive properties of cerebral tissue and known inverse relationship between electromagnetic field strength and distance from the generator coil.<sup>57</sup> As with VRT, despite an abundance of small trials reporting positive changes in physiologic parameters reflecting visual function, the quality of evidence surrounding ES-based approaches for vision restoration remains poor, with most of these studies conducted on small cohorts with varying degrees of disease severity.

More robust evidence on regenerative interventions for vision loss is emerging, with most published studies being early Phase I or II trials investigating gene therapies for inherited retinal dystrophies. The most significant data in support of gene therapy for vision loss was reported in 2017 in a large multicenter Phase III trial assessing functional visual improvement after intravitreal administration of an adenoviral vector targeting mutations of the *RPE65* gene in patients with Leber congenital amaurosis (LCA) and RP.<sup>58</sup> In this study, clinically significant improvements in visual function were seen over a three year follow up period.<sup>59</sup> Subsequent meta-analyses corroborated these findings in larger patient cohorts,<sup>60,61</sup> establishing gene therapy as a viable and durable treatment option for repairing damaged retinal tissue in select inherited retinal dystrophies mediated by mutations in the *RPE65* gene. On the other hand, evidence surrounding tissue-based and prosthetic interventions for vision loss is more nascent. Two Phase I/II trials assessing the feasibility of transplanting retinal pigment epithelium (RPE) cells derived from differentiated human embryonic stem cells (hESC) into the subretinal space in eyes with age-related macular degeneration (AMD) demonstrated good viability at 12 months and 4 years after transplant, respectively;<sup>62,63</sup> a follow up study of hESCs derived from autologous marrow is currently underway in China.<sup>64</sup> A separate Phase I study assessing transplantation of an RPE “patch” derived from hESCs in eyes with advanced AMD demonstrated good viability and improved visual function at 12 months after transplant.<sup>65</sup>

Retinal prosthetic devices, colloquially known as “bionic eyes”, offer an alternative approach to vision loss caused by photoreceptor atrophy. These commercially-available devices are, in essence, BCIs that capture images of the external world and convert them into electrical signals detectable by surviving inner retinal neurons, leading to activation of the surviving retinal neural network.<sup>66,67</sup> (Figure 1 and Table 1) Multiple prospective trials have demonstrated that the Argus<sup>®</sup> Retinal Prosthesis System, one such device manufactured by American company Second Sight<sup>™</sup>, durably improves light perception and object recognition at two to five years after implantation.<sup>68–71</sup> However, these devices offer only limited functional vision gains, with many patients achieving best-corrected visual acuity (BCVA) in the range of 20/1000 to 20/400.<sup>72,73</sup> It is also important to note the adverse events associated with these prosthetic interventions, including but not limited to conjunctival erosion, retinal detachment, need for revision surgery, and immunosuppressive risks. Given that most evidence on prosthetic approaches to vision loss demonstrates marginal functional benefit, continued clinical trials focused on improving functional visual outcomes are warranted for this class of therapies.

**Table 1** BCI Subtypes for Vision Restoration. Darkness of Red Background in the “Invasiveness” Column Highlights Degree of Invasiveness

Device Class	Target Tissue	Mechanism of Action	Invasiveness	Examples with Commercial Status	Resolution and Performance	Primary Challenges
Epiretinal prostheses	Retinal ganglion cells (inner retina)	External camera captures images; processor converts to electrical patterns; electrode array on retinal surface stimulates remaining RGCs	High (Vitreoretinal surgery)	Argus II (Second Sight) Discontinued 2020 ~550 patients implanted	<ul style="list-style-type: none"> <li>60 electrodes</li> <li>BCVA of ~20/1260</li> <li>Largely limited to light perception</li> </ul>	<ul style="list-style-type: none"> <li>Requires viable RGCs</li> <li>Limited resolution</li> <li>Retinal detachment risk</li> <li>Company bankruptcy (Second Sight)</li> <li>Complex surgery</li> </ul>
Subretinal prostheses	Bipolar cells (outer retina)	Photovoltaic or electronic implant placed beneath retina; replaces photoreceptor function; stimulates bipolar/horizontal cells	High (Vitreoretinal surgery)	PRIMA (Pixium/Science) CE mark pending as of 2025 Alpha AMS (Retina Implant AG) Discontinued 2019	<ul style="list-style-type: none"> <li>378-1600 electrodes</li> <li>BCVA of ~20/460</li> <li>Letter recognition possible</li> </ul>	<ul style="list-style-type: none"> <li>Requires intact inner retina</li> <li>Heat dissipation concerns</li> <li>Limited field of view</li> <li>Power delivery challenges</li> <li>Long-term biocompatibility</li> </ul>
Optic nerve stimulation	Retinal ganglion cells (optic nerve)	Cuff or penetrating electrodes around/within optic nerve; direct electrical stimulation of RGC axons	High (Orbital surgery)	AV-DONE (China) Preclinical OpticSELINE (Belgium) Animal studies	<ul style="list-style-type: none"> <li>4-8 electrodes</li> <li>Phosphene generation only</li> <li>No form vision yet</li> </ul>	<ul style="list-style-type: none"> <li>Complex nerve fiber organization</li> <li>Difficult selective stimulation</li> <li>Risk of nerve damage</li> <li>Limited electrode contacts</li> <li>No successful human trials</li> </ul>
LGN deep brain stimulation	Lateral geniculate nucleus (thalamus)	Stereotactic electrode placement in LGN; electrical stimulation of thalamic relay neurons	Very high (Craniotomy)	Experimental only Research phase <i>No commercial development</i>	<ul style="list-style-type: none"> <li>Theoretical only</li> <li>Complex retinotopy</li> <li>Limited access</li> </ul>	<ul style="list-style-type: none"> <li>Deep brain location</li> <li>Small targets</li> <li>Complex anatomy</li> <li>Hemorrhage risk</li> <li>Precise mapping required</li> </ul>
Intracortical arrays (V1)	Primary visual cortex	Microelectrode arrays penetrate cortex; direct stimulation of V1 neurons; phosphene-based vision via AI-processed camera input	Very high (Craniotomy)	Blindsight FDA breakthrough 2024 Orion (Second Sight) Development halted		

## Translating Cortical Stimulation into Vision Restoration

The conceptual foundation of using cortical BCIs for vision restoration emerged from decades of academic investigation. Brindley<sup>74</sup> and Dobbelle<sup>75</sup> were the first to report that electrical stimulation of the visual cortex could evoke phosphenes in humans during the 1960s and 1970s. This seminal discovery established the basis of cortical stimulation for vision restoration and the foundation for all subsequent research on cortical stimulation in patients with vision loss. Since their discovery, there has been a clear paradigm shift towards development of BCI-based cortical approaches for patients with damage to the visual pathway.<sup>2,76,77</sup> The United States Food and Drug Administration (FDA) has played a central role in this process through consistent regulatory engagement, yielding a robust ecosystem for expedited device development while ensuring adherence to safety standards. Today, there are several ongoing trials investigating cortical BCIs for vision restoration, including Blindsight<sup>®</sup>, manufactured by Neuralink;<sup>78</sup> the PRIMA subretinal implant designed for central vision loss caused by AMD, manufactured by Science Corporation;<sup>79,80</sup> the Gennaris<sup>™</sup> Bionic Vision System<sup>®</sup> which utilizes nanowire technology to generate uniquely high-resolution phosphenes;<sup>81</sup> and the Orion<sup>®</sup>, manufactured by Second Sight.<sup>82,83</sup> The investigators overseeing the PRIMA subretinal implant trial recently published a 2025 Quarter 4 report demonstrating durable restoration of functional vision in a cohort of 38 patients with geographic atrophy, the most advanced form of dry AMD.<sup>84</sup> Notably, all cortical BCIs designed to treat vision loss are experimental at this time, with no comprehensive published data from large-scale randomized controlled trials. A comprehensive list of the different BCI subtypes is listed in [Table 1](#).

## Technical Advances in Brain-Computer Interfaces for Vision Restoration

Recent technical advances in the development of BCIs intended to restore vision have centered on high-density electrode arrays and the integration of bioengineering and AI to enhance performance.

Technical advances in the research and development of high-density electrode arrays have allowed for acquisition of greater anatomic and spatial resolution, enabling more precise and durable BCI-mediated cortical stimulation for phosphene evocation.<sup>2</sup> These arrays are often invasively implanted, which allows complex and nuanced visual information to be delivered directly to the visual cortex. Commercial examples of BCIs utilizing high-density electrode arrays include the Orion<sup>®</sup> Visual Cortical Prosthesis System,<sup>2,85</sup> which utilizes a subdural grid of 60 surface microelectrodes aggregated on a millimeter-sized semiconductor chip; ([Table 1](#)) the Blindsight<sup>®</sup>, an investigational cortical BCI designed by Neuralink with advanced robotic and AI capabilities that recently acquired “breakthrough device” designation by the United States FDA after demonstrating durable vision restoration in primate studies;<sup>7,86</sup> and the flexible thin-film Layer 7<sup>®</sup> cortical interface manufactured by Precision Neuroscience<sup>™</sup>, the most clinically advanced BCI currently in the early stages of clinical development.<sup>87,88</sup>

Many of these new-age BCIs incorporate AI to supplement the user experience. For example, the CORTIVIS<sup>®</sup> was designed in parallel with Neurolight<sup>®</sup>, a powerful deep learning model that improves information transfer rates by performing object detection tasks that enhance encoding of electrical input by retinal ganglion cells.<sup>30</sup> ([Figure 1](#)) Other examples of AI integrations include the generation of auditory descriptions of visual scenes to enhance rehabilitation by inducing intersensory plasticity<sup>31,32</sup> and image preprocessing and segmentation to enhance phosphene fidelity and object recognition in the profoundly blind.<sup>29,32,33,89,90</sup>

Novel bioengineering techniques have also been increasingly incorporated into BCI systems to enhance translational potential. Optogenetic techniques that directly activate surviving neurons using visible or infrared light have undergone intensive study<sup>91–93</sup> due to their ability to provide greater spatial resolution and more natural-appearing vision than traditional electrode-based systems. ([Figure 1](#)) However, technical challenges exist in delivering adequate amounts of light to deep cortical structures. Magnetic stimulation and magnetically-responsive nanoparticles have also undergone scrutiny as non-invasive alternatives to selective stimulation of BCI-connected neurons,<sup>94,95</sup> though these approaches are still considered experimental. Multisensory paradigms have perhaps seen the most empiric study for BCIs-mediated vision restoration; visual-to-auditory<sup>96</sup> and visual-to-tactile<sup>97,98</sup> systems that transform external visual input into auditory or tactile sensations have been shown to successfully activate the visual cortex in blind patients, demonstrating good functional repurposing of visual cortical areas for the processing of non-visual input.<sup>99–101</sup>

## Clinical and Translational Potential of BCIs

In the realm of clinical ophthalmology, BCIs expand the therapeutic landscape beyond the eye and offer a potential strategy for patients with precortical blindness who are not candidates for gene therapy, stem cell transplantation, or traditional medical or surgical approaches to vision loss. By bypassing damaged ocular structures and directly stimulating cortical visual pathways, BCIs challenge the long-held anatomic constraints of ophthalmic intervention. Future research is necessary to understand the complete spectrum of clinical use cases for this new class of technology. As larger clinical trials investigating BCIs progress and these devices become integrated in ophthalmologic care, clinicians will play key roles in both selecting and counseling patients as well as monitoring long-term functional outcomes.

## Conclusion

BCIs represent a transformative approach to vision recovery that offers new hope for patients with blindness due to irreversible precortical disease. While significant progress has been made in BCI device design and clinical translation, challenges remain in optimizing safety, efficacy, and accessibility. Long-term outcomes, ethical considerations, and regulatory frameworks will require ongoing effort and attention. Continued research and clinical trials are essential to realize the full potential of BCIs for vision restoration.

## Data Sharing Statement

All data reported in this study are publicly available.

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## Author Contributions

All authors made a significant contribution to the work reported, whether that is in the conception, study design, execution, acquisition of data, analysis and interpretation, or in all these areas; took part in drafting, revising or critically reviewing the article; gave final approval of the version to be published; have agreed on the journal to which the article has been submitted; and agree to be accountable for all aspects of the work.

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## Disclosure

The authors report no conflicts of interest in this work.

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