

Vision Restoration to People with Long-Term Blindness Using the Brain-Computer Interface Technology: A Sociotechnical Research Framework to Improve Usefulness for Users

Zdenek Smutny¹, Milan Hudec², Ines Kožuh^{1,3}

¹Centre for Social Informatics, Faculty of Social Sciences, University of Ljubljana, Ljubljana, Slovenia; ²Faculty of Natural Sciences, Matej Bel University, Banská Bystrica, Slovakia; ³Faculty of Electrical Engineering and Computer Science, University of Maribor, Maribor, Slovenia

Correspondence: Zdenek Smutny, Centre for Social Informatics, Faculty of Social Sciences, University of Ljubljana, Kardeljeva ploščad 5, Ljubljana, 1000, Slovenia, Email zdenek.smutny@fdv.uni-lj.si

Abstract: Invasive and non-invasive brain-computer interface (BCI) represent a promising technology for treating various diseases and disabilities. BCI-based invasive solutions also include visual prostheses. Currently, there is rapid development of cortical prostheses and bold statements, eg, about the potential of Neuralink's experimental neuroprosthetic Blindsight to restore vision. However, questions arise about the usefulness of such solutions for people with long-term blindness, considering other compensatory aids and referring to the empirical basis of cases where vision has been successfully restored surgically in the past. These cases reveal that biological restoration of sight does not guarantee functional vision. Moreover, technological limitations, such as low-resolution phosphene-based vision, individual variability or postoperative complications, reduce usability and usefulness for potential users. Therefore, we draw on literature on visual prostheses, documented cases of vision restoration, and employ a sociotechnical approach used in design science to discuss aspects that influence the usefulness of the vision restoration to people with long-term blindness, with emphasis on cortical prostheses. This approach emphasises the need to include or inscribe social values into designed BCI solutions to reveal what people with blindness need and what can be achieved with current technology. Research on user values and needs must shape the visual prostheses design, and their functions must be helpful to the user and synergistically complement his or her sociotechnical context (eg, interacting with other used aids and smart environments, or supporting needed social skills). Sociotechnical research can guide iterative design, improve future user acceptance and adoption, align prosthetic development with real-life needs, and prevent users from reverting to life with blindness due to cognitive overload or poor functional adaptation. Thus, we call for systematic and long-term sociotechnical research, which is lacking in this area. For this purpose, a relevant sociotechnical research framework and future research agenda are presented.

Keywords: BCI, brain-machine interface, design science research, social informatics, user experience, visual prosthesis, cortical prosthesis, transcranial stimulation, sight restoration

Introduction

Estimates of the number of people with blindness in the world have increased from 36 million to 43 million people over the last decade, and another 295 million currently have moderate and severe vision impairment.^{1,2} However, by the middle of the 21st century, it is projected that there could be as many as 115 million people with blindness in the world.³ People can become blind as a result of injury, illness, or are blind from birth. Worldwide, the predominant causes of sight loss include uncorrected refractive errors, cataract, diabetic retinopathy, glaucoma, and age-related macular degeneration.^{4,5}

While in developing countries, there are several problems with the affordability of appropriate aids,⁶ in developed countries, relevant healthcare and aid or assistance systems are available. For example, in the European Union, this is often addressed in parallel with research into population ageing in order to ensure a good quality of life and independence

in later life,⁷ because one of the consequences of ageing is deterioration of vision, which can lead to, for example, a higher risk of falls or social isolation in older people.⁸ Vision impairment and blindness are actively addressed worldwide by designing aids, assistive systems (eg in smartphones or using wearables), smart environments (SmE) (eg intelligent homes) or medical procedures to maintain the quality of life of patients or their partial or complete cure.

In this regard, one of the currently discussed topics is the restoration of vision to people with blindness using the brain-computer interface (BCI), also known as a brain-machine interface. BCI solutions can be invasive (implantation directly on the brain's surface) and non-invasive (based on transcranial communication). In the case of vision restoration, only an invasive variant is experimentally used. This topic is well-established in scholarly literature,^{9–11} where researchers already developed experimental prototypes of other devices implanted on human participants that allow for very limited visual perception. This technology has, however, gained renewed public and scientific interest due to the recent announcement of Blindsight, an experimental neuroprosthetic device developed by Neuralink.¹² The Neuralink's co-founder, Elon Musk, has publicised that it

Will enable even those who have lost both eyes and their optic nerve to see [if] the visual cortex is intact, it will even enable those who have been blind from birth to see for the first time.¹³

It should be noted that no clinical studies or data are currently available on the use of Blindsight in human patients. Even though the statement is optimistic (especially regarding those who are blind from birth) and given the current possibilities of BCI, it is still rather a speculative technology in the case of the complete restoration of vision. It is still in nascent stage,¹¹ which entails many technological, biomedical, sociomedical and sociotechnical challenges.

In the literature, the scholars^{14–17} examined possibilities of current and future restoration of vision from biotechnological perspective, but not from a sociotechnical point of view or perspective of people with (long-term) blindness. Sociotechnical aspects are still not well examined in this area.¹⁸ Accordingly, in our article, we will focus on the sociotechnical perspective of people with long-term congenital or acquired blindness, ie for most of their lives. It entails consideration of several specific neurophysiological and behavioural characteristics, including gradual degeneration of the visual system, no or little visual memory, getting used to their handicap, or primary use of other senses (especially touch and hearing). It is evident that people with long-term blindness are largely underrepresented in current experimental research and other studies. On the other hand, it is understandable that current experimental research focuses on people with short-term blindness or partially preserved vision, because their ability to process visual data has not degraded.^{19,20} In this context, it is relevant to disclose that one of the authors of this article also falls into this category of people with long-term blindness (see Acknowledgement), thereby providing an experimental and unique dimension to our paper compared to the literature.

The aim of this article is to discuss issues of restoring vision to people with blindness using visual prostheses from a sociotechnical perspective (emphasis is placed on the perspective of the long-term blind and cortical prostheses) and how sociotechnical research can help direct research and development in this BCI area, so that the proposed solutions are more useful and contextually relevant for users with blindness and, thereby, increase the potential for adoption and reduce financial costs on design and development. In connection with this aim, a high-level sociotechnical research framework and relevant research agenda are presented.

In the following sections, the article presents current possibilities for restoring vision through visual prostheses and the technological, biomedical, and sociomedical problems related to BCI technology. As this is a viewpoint article, we base our work in the Background section on a narrative (and not systematic) review and draw mainly on current literature from Web of Science and Scopus citation databases. The search used combinations and variants of the following keywords: brain-computer interface, sight/vision restoration, sight/vision recovery, visual prosthesis/prostheses, pseudo-pixelated vision, retinal prosthesis/prostheses, optic nerve prosthesis/prostheses, thalamic prosthesis/prostheses, cortical prosthesis/prostheses, review, problem, issue, SLR, BCI. The starting point for our considerations was review articles published in the last 15 years. Articles were selected based on relevance to the thematic focus of this article at the authors' discretion. Furthermore, we used a snowball approach to identify additional relevant literature.

Specific cases or examples, where the sight was surgically restored, were selected based on the mentioned snowball approach and direct search on Google Search and Scholar using a combination and different variants of keywords: sight/vision restoration, sight/vision recovery, lifetime, people with blindness, blind people. The obtained cases were further

verified by the authors for their credibility in the academic and scientific literature, which was mostly indexed in the above-mentioned citation databases and referred to these cases. For individual cases, it was preferred to use primarily scientific literature if possible. No time restriction was used.

On this basis, a sociotechnically oriented discussion including synergy with existing aids is developed (see section Sociotechnical perspectives on BCI adoption by people with long-term blindness). The penultimate section integrates the above and introduces a sociotechnical research framework for the visual prosthesis research agenda (see section Sociotechnical research framework for the visual prosthesis research agenda), which outlines possible directions and focuses of social and design science research. It offers recommendations regarding the research agenda and related research questions. The Conclusions section presents the article's limitations, the benefits of sociotechnical research for DSR, with reference to prosthesis designers and users, and directions for future research in DSR using the proposed framework.

Background

Restoring Vision by Visual Prostheses

The first experiments that focused on investigating the effects of electrical stimulation of the human brain, including the visual cortex, can be found in the scientific literature from the 1920s. These experiments followed on from earlier findings and animal experiments. For example, in study of Foerster,²¹ a patient saw a motionless small spot of light when electrically stimulating a certain part of the occipital pole of one cerebral hemisphere. Visual prostheses developed so far, providing coarse pseudo-pixelized vision, are based on this phenomenon, associated with direct or indirect electrical stimulation of the visual cortex.²² Patients also describe these spots of light as blips on a radar screen.²⁰ A single spot or blip is called a phosphene and can be compared to a blurry pixel. However, unlike pixels on a computer screen, phosphenes are not evenly spaced and do not lie next to each other. They create unique light patterns in each patient, ie discrete, separate visual elements against an unstimulated background.^{9,23} How such an image composed of phosphenes looks like is presented, for example, in studies of Vurro et al, and Sanchez-Garcia et al.^{22,24} Although it is difficult for the patient to interpret these phosphenes (eg reading letters formed from phosphenes), it is assumed that “neuroplasticity triggered by learning and rehabilitation will improve artificial vision over time”.²⁵

The scientific community has been dealing with the issue of vision prostheses using direct stimulation of the visual centre of the brain since the 1960s. For example, Brindley and Lewin²⁶ tested their prosthesis on a patient with blindness who saw phosphenes when stimulated. They already thought that 50 electrodes would be needed to recognize a letter and 600 for smooth reading.²⁶ For example, the second patient operated on could read Braille letters at a speed of 8.5 characters per minute.²⁷ The authors optimistically stated that their “findings strongly suggest that it will be possible, by improving [their] prototype, to make a useful prosthesis”.²⁶ This hope was shared by further developments led by William Dobelle, which continued until the beginning of the 21st century.^{28,29} However, the solutions developed so far have a number of limitations.³⁰ The main advances can be seen in technological miniaturization, material design, and the method of connection to the brain.²⁵

The restoration of sight in a person with blindness depends on the circumstances surrounding the loss of sight. This also determines the potential for his or her sight to be restored. However, due to the focus of this article, in this section we will focus only on functional visual prostheses, which, according to Borda and Ghezzi,²⁵ can be divided into retinal, optic nerve, thalamic, and cortical prostheses.

All of these prostheses provide coarse pseudo-pixelized vision. The choice of the appropriate prosthesis depends on the circumstances of the vision loss, eg, retinal prostheses cannot be used when removing the eyeballs. The implementation of the prostheses is invasive in all of the above types and requires surgery.

All solutions consist of external and implanted components.²⁴ The camera acquires an image of the real world, which is first processed by a portable visual processing unit (external components) and converted into stimulation pulses.³¹ In this way, a simplified image is created, which is transferred to a specific perceptual location, depending on the type of prosthesis, and further processed by the patient's brain. Each prosthesis must be individually calibrated according to the real distribution of phosphenes in the patient's visual field. Image transfer using BCI works as follows for individual types of prostheses:

- Retinal prosthesis: electrical impulses to the retina using implanted electrodes, then the visual data are normally interpreted by the visual cortex as phosphenes.
- Optic nerve prosthesis: electrical impulses via electrodes connected to the optic nerve, then the visual data are normally interpreted by the visual cortex as phosphenes.
- Thalamic prosthesis: electrical impulses via electrodes implanted to lateral geniculate nucleus, then the visual data are normally interpreted by the visual cortex as phosphenes.
- Cortical prosthesis: electrodes are placed directly on the primary visual cortex, where electrical impulses directly affect neurons.

This allows for simple scenes to be displayed. However, advanced features that would actively assist the patient in spatial orientation or identify specific objects require additional devices and applications for voice command recognition and image processing. Current solutions envision that phosphenes could indicate letters, objects in a room, or the direction of movement of objects.²⁰

Retinal prostheses are focused on stimulating retinal neurons,³² and the optic nerve must be fully developed. The eye can move and naturally capture images or scan scenes and fixate objects.³³ The resulting image is significantly limited because it is impossible to separately stimulate each of the 1.1–1.3 million optic axons in the human adult optic nerve.³⁴ The resulting image has low resolution. There are only three regulatory-approved retinal prostheses used by over 500 patients worldwide who have lost their sight during their lifetime³⁵ – it can be assumed that these numbers will be higher in 2026. These prostheses allow users to localize high-contrast objects and assist them in spatial orientation.³⁵ We distinguish three types of prostheses according to implementation location:³⁶ epiretinal, subretinal, suprachoroidal prostheses. These prostheses offer lower surgical risks, as implementation is the easiest of all visual prostheses.²⁵

Optic nerve prosthesis offers a solution if the eye is more severely damaged. The first solution used a self-sizing spiral cuff electrode around an optic nerve,^{31,37} but a later solution utilized direct optic nerve electrode.³⁸ The advantage of this solution is the stimulation of a wide visual field, but with a small number of electrodes, which is associated with a low number of displayed phosphenes. The number of human users is very small due to the surgical location and specific implementation conditions on the patient side.³⁹ In practice, this is more about testing this technological approach than a commonly applied solution.

Thalamic prosthesis is closely linked to advances in deep brain stimulation, as the goal is to stimulate the lateral geniculate nucleus within the brain.²⁵ It can be used in cases of optic nerve damage. The main advantages of this solution are potentially high-acuity artificial vision and it might encode a more naturalistic perception.³⁰ So far, this prosthesis has been investigated in animal experiments as a proof-of-concept.²³

Cortical prostheses have achieved unprecedented development, with the first precursor of these prostheses being implanted in 1967 by Brindley and Lewin.²⁶ Thanks to miniaturisation and new materials, the number of electrodes and, therefore, the number of phosphenes has increased. Cortical prostheses employ two main types of electrode arrays:⁴⁰ those positioned on the cortical surface and those that penetrate the cortex. Until recently, it was believed that retinal prostheses could potentially provide the most electrodes and the number of displayed phosphenes with current technologies. Physiological and technological limitations allow us to display images with a resolution of up to 1500 phosphenes in retinal prostheses,²⁴ which is sufficient resolution for recognising objects and scenes according to Zhao et al.⁴¹ However, the rapid development of cortical prostheses gives us new possibilities and can be demonstrated by developments in the last decade.

In the case of cortical prostheses used in humans, the display of higher tens of phosphenes was recently achieved, eg in study Fernández et al¹⁹ it was 88 phosphenes using 96 electrodes that penetrate the cortex. However, further research on monkeys⁴² used 1024 silicon electrodes, which, with the same success rate as in Fernández et al¹⁹ has the potential to display up to 938 phosphenes. Neuralink's technology consists of 3072 electrodes,⁴³ which could enable even greater resolution for object and scene recognition. The aforementioned solution from Neuralink does not only deal with people with blindness, but also wants to offer solutions in other areas, such as the restoration of motor functions, compensation for neurological and psychological disorders. So far, this solution has been implemented for several first users⁴⁴ and the first user with blindness of this solution will probably be operated on in 2026.^{45,46}

Zhao et al⁴¹ state that the minimum number of phosphenes for object recognition is between 256 and 576, with recognition accuracy exceeding 60% and for scenes between 1024 and 2304. However, other researchers are trying to display objects even with fewer phosphenes. For example, Scialom et al⁴⁷ reported that an average of 21 objects can be displayed with only 65 phosphenes. A limitation of both views is that both studies were conducted on healthy sighted participants who have developed visual memory. Another problem is that phosphenes do not follow a grid, and their display is highly individual, eg, in which part of the visual field are they displayed, how they are spread out in it, and what their number is.

Based on this brief overview, it is clear that visual prostheses can potentially change the lives of people with blindness from the perspective of current and future research, especially concerning the rapid development of cortical prostheses.^{15,17} This development is not driven solely by the effort to restore vision to people with blindness, but the reason for this rapid development is the potential multifunctionality of the invasive BCI solutions, as electrodes implanted on the cerebral cortex can be used to stimulate various areas of the brain and compensate for various disabilities or diseases.¹¹ However, it should be emphasised that BCI technologies are in the nascent stage of the technology life cycle, which raises many questions and problems.^{48,49}

Three main areas are mentioned in the scholarly literature, which bring together individual problems associated with the development of BCI, in our case, with an emphasis on the restoration of vision to people with blindness:

- technological,^{25,42,44}
- biomedical,^{25,30}
- and sociomedical.¹⁴

In practice, individual areas and therefore problems touch and influence each other. In the following text, we want to highlight the most critical problems, especially in connection with the use of BCI in cortical prostheses, which are the focus of greatest hope, because they offer the possibility of connecting the largest number of electrodes and thereby generating more phosphenes.¹¹ The list of problems does not attempt to be complete, but to highlight the main ones.

Problems of BCI Technology Related to Restoring Vision

In this section, we will first focus on technological and biomedical problems. Based on an understanding of these problems associated with the implantation of BCI technology at the personal level, social-related issues that arise in the context of using BCI technology at the societal level can be introduced.

Current cortical solutions use hundreds to thousands of electrodes inserted into the selected brain area, which necessitates the use of surgical robots – the development of these robots is therefore closely linked to the success of the deployment of cortical prostheses. For example, the article⁴³ presents a robot that is capable of inserting up to 192 electrodes per minute in automatic mode. In the surgeries performed so far, there is cooperation between a live neurosurgeon and a specialised robot, a so-called cobot.⁴⁸ The use of cobots is necessary mainly to reduce the time required for the surgery and ensure the accuracy of electrode placement. The initial limitation of the technologies used is the possibility of placing electrodes only on the exposed surface of the visual cortex. Therefore, it is not possible to stimulate neurons located deeper in the visual cortex, ie neurons deeper in the brain are unreachable with current technology. This also limits the quality of the perceived image. The same applies to feedback, where action potential signals are recorded only from small groups of neurons near the electrode.⁵⁰ These technological limits are also related to signal propagation through nervous tissue and unintentional activation of passing axons.³⁰

Any extensive surgery, such as the aforementioned implantation of electrodes and the entire device, is a significant intervention into the user's body.³⁰ Such a surgery aims to connect the human body with an artificial device. This involves problems such as ensuring biocompatibility and survivability of the implemented device.^{30,51} A fundamental problem is, in particular, the separation of technology from the body. An example can be a three-year study⁴² conducted on monkeys, which shows a gradual decrease in signal quality, the number of electrodes generating phosphenes, and increasing current thresholds for initiating phosphenes with increasing time since surgery. Due to the long-term implementation of foreign devices in the monkeys' bodies, encapsulation of arrays and cortical degeneration occurred.

Over time, scar tissue will develop around the implants, making receiving signals from surrounding neurons impossible.²⁰ As can be seen, “the long-term effects of neural implants are not yet fully understood, and close monitoring of any adverse effects will be essential”.¹⁷ The Neuralink device also had problems with the biocompatibility and survivability of the implemented device, where 85% of the electrodes stopped working a month after the surgery.⁴⁴ Given that invasive BCI solutions are implanted in various brain centres (not just the visual cortex), such solutions may also bring other related neurological and psychiatric problems, as the implemented device directly or indirectly causes organic changes in the brain, which can cause organic disorders of the nervous system and related mental disorders.¹⁴

After surgery, a rehabilitation phase is required,¹¹ which includes optimising stimulation parameters, calibrating the device for the patient, and learning to recognise shapes and displayed scenes,^{15,19} before the patient can use the artificial vision. Each implementation of even the same type of cortical prosthesis is unique, as each patient sees a different number and distribution of phosphenes in the visual field.⁴⁰ The area of the visual field where phosphenes are seen is still small because the area where the electrodes are implanted is also small.⁹ Researchers want to solve this problem by spreading electrodes throughout the visual cortex.²⁰ This solution could produce more phosphenes across a larger visual field, but it also means a more invasive surgery. Another problem is spontaneous phosphenes that occur in people with blindness and need to be distinguished from electrically induced visual perceptions.¹⁹ However, the frequency of spontaneous phosphenes decreases with time since surgery.

These problems affect the length of calibration of the implanted solution within a given instance, the ability to render objects or scenes, and the patient’s ability to interpret them. This rehabilitation phase is currently long and highly individualised. The challenge for researchers is to find ways to reduce calibration time and move closer to a plug-and-play design.¹¹

It is assumed that brain plasticity will help with rehabilitation,⁵² but this is a double-edged sword. On the one hand, the patient gets used to new sensations and learns to interpret them adequately.^{25,52} On the other hand, if technical difficulties occur after a longer period of time and, eg, electrodes start to disconnect or the layout of phosphenes changes due to technical difficulties, this negatively impacts the patient, as he or she has to adapt to the new conditions.

The ability to interpret objects or scenes is linked to the circumstances of the loss of vision and the duration of a person’s blindness, as it affects the preservation of visual memory and imagination. It is therefore very individual. We know that the brain’s visual system degenerates after just a few years of blindness.²⁰ On the other hand, there is a case where a person with blindness mentally trains his imagination and can draw complex 2D drawings even decades after losing his sight, see eg technical schemes prepared by author with blindness in studies of Hudec and Smutny.^{53,54} Cortical prostheses have been tested primarily on people who lost their sight in later life, so it is a big question how it would be possible to usefully restore vision in people who were born blind and never used the visual cortex in the same way as a healthy person.²⁰ Brain plasticity, ie adaptation to blindness and the failure to realise visual learning during childhood, plays an important role here. It is one thing to have biologically restored sight, and quite another to have functional vision to be able to interpret and use these visual perceptions in a similar way to a sighted person as presented in subsection Cases where sight was restored to people with long-term blindness.

In the remaining text of this section, we will focus mainly on socially relevant aspects that relate to the use of BCI technology not only by people with blindness. This perspective brings a broader scope, including issues generally associated with BCI technology arising at the societal level, ie in the future massive sociotechnical interaction. At the social level, people with blindness become one of the social categories of possible users of this technology. It can be assumed that widespread adoption will not only be for medical but also non-medical use, ie human enhancement and cyborgisation. Therefore, the following text has a broader focus, touching on general BCI problems.

An important starting point for considering the implementation of BCI technology could be cost-benefit and risk-benefit analyses reflecting the individual user context.¹⁴ Given that current cortical BCI solutions are not dependable, require invasive surgery, and the consequences of long-term use are unknown, current users of cortical prostheses are mainly altruists because BCI solutions do not bring them a fundamental improvement in their quality of life. These people themselves admit that they do not do it for the primary purpose of improving their condition and abilities, but to help in research and future generations.²⁰

The aforementioned individual risk-benefit analysis and the potential user's awareness are also associated with ethical aspects related to his or her initial health condition. It is worth remembering that the BCI technology

Has the potential [...] [to bypass] a diseased body or treat cases of certain brain diseases like motor neuron disease, amyotrophic lateral sclerosis, spinal cord injuries, Parkinson's disease, epilepsy, depression, blindness, deafness, and chronic pain.¹⁶

Potential users, therefore, include people with limited expressive abilities, eg locked-in syndrome. Even in these cases, it is necessary to ensure that people are aware of the risks and benefits of the solution in their individual case before implanting a BCI device.¹⁴

Other issues that have both a technological and social dimension include privacy concerns and ensuring security. BCI enables two-way communication, so there is a risk of attack and misuse of BCI devices, which could have life-threatening impacts on its users.⁵⁵ New security risks that need to be addressed are emerging, as security is not just a technological issue but is closely linked to user behaviour. An example is the Internet of Brains security,⁵⁶ as BCI technologies will be wirelessly connected to other technologies and directly or indirectly to the internet.⁵⁷ Thus, privacy concerns and security need to be addressed not only technologically but also legislatively (setting norms) and by educating users. An example is the need for a new approach to the protection of human rights, as they will need to be reconceptualised to include both the physical and mental dimensions and new ways of communication, eg issue of neuro-rights.⁵⁸ Furthermore, the two-way communication of BCI devices is related to the possibility of specific cyborgization of humans. For example, extension of the mind, which can have further transformative impacts on the entire society, especially in the case of BCI application on a broad scale, also on the healthy part of the population, ie non-medical use.⁵⁹

Cases Where Sight Was Restored to People with Long-Term Blindness

The vast majority of scholarly literature on visual prostheses addresses the restoration of visual perceptions, see eg review articles,^{11,25} but less is addressed regarding their further processing by other brain parts to restore a person's full cognitive abilities. Scholars are primarily concerned with the processing of visual stimuli and visual perception. In research on people with visual impairments, the emphasis is not only on visual perception (visual processing across various brain regions), but also on visually guided actions and behaviour, as well as behaviourally guided vision, which involves interaction with other senses and the motor system.^{60–62} The aim of these researches is to improve a person's abilities to use (artificial) vision to perform everyday tasks. In the context of understanding the consequences of restoring vision to people with long-term blindness (which can be congenital or acquired, eg in childhood), it is also necessary to understand visual processing and its possibilities and limits. Although there is a scholarly literature on visually guided actions of people with visual impairments, little of it focuses on people who were long-term blind.

Questions arise regarding the consequences of restoring vision to a previously blind person:

- Can we, based on other medical experiences, estimate what will happen if an individual with long-term blindness regains his/her sight?
- What impacts does such restoration of vision have on the individual, and what consequences does it bring?

The reason why designers or researchers, and therefore the literature on visual prostheses, do not deal with these questions much is that they focus on helping patients who had vision in childhood (at least up to the age of 10) and are blind for a short time.²⁰ In other words, it can be expected that the visual cortex is learned from childhood, fully developed, and the visual system has not yet degenerated (visual imagination and memory are preserved). Below we have selected several cases where vision was restored in patients who were either blind from birth or for a long time (decades). This perspective has a fundamental limitation that needs to be noted. According to Haynes' pyramid,⁶³ case studies provide the weakest scientific evidence for the phenomenon under study. However, systematic reviews focusing on the abilities and behaviour of patients after vision recovery are lacking. Although these are only individual cases, they allow us to estimate the usefulness of our efforts to design future BCI solutions to restore vision for this type of user.

Restoring vision to a person who was long-term blind means entering *terra incognita*. This is illustrated by Molyneux's problem, which reads:⁶⁴ Is a person who was born blind and whose sight was restored later in life able to recognize objects by sight that he previously recognized very well by touch? The answer to this question, based on empirical research Held et al⁶⁵ is likely negative. He or she would not recognise them immediately after regaining his or her sight, but he or she would learn to do so through learning. In Molyneux's problem, we see that restoring sight is not a return to something familiar that a person who has been blind since birth has lost, but it is access to a completely new ability that they have yet to learn to work with. And another problem is that a newly sighted person will not achieve the same abilities as a normally sighted person. Because this person has already somehow come to know the world differently (through other senses and their interconnection) and is used to working with it in their own way.

Patients who experience dramatic recovery from blindness experience significant to complete visual agnosia (severe confusion in visual perception) and may become dysfunctional in both the social and physical worlds, compared to when they were blind. Ackroyd et al⁶⁶ present the case of a woman who became blind at the age of 3, and whose sight was restored surgically 24 years later. Although her vision was almost completely restored from a biological perspective, her functional vision was still poor six months after the surgery. She could only detect large objects, had very limited spatial vision, and was unable to learn to recognize visual patterns. Seven months after the surgery, she voluntarily returned to a life of blindness. This is also highlighted in a paper Dickens et al⁶⁷ which reports that a patient who was severely visually impaired and later long-term blind voluntarily returned to a life of blindness after successful surgery and restoration of sight for various reasons, eg psychological issues like low mood and depressive symptoms.

A similar case was described in paper⁶⁸ of a man who was able to distinguish only light from dark from the age of 10. His sight was restored surgically at the age of 51. Although he had had vision for part of his childhood, after its restoration he was overloaded with visual sensory data and was unable to connect what he saw with his earlier visual memory. He had to relearn how to recognize objects, people (faces), and understand spatial vision. He was "able to see but not to decipher what he was seeing".⁶⁸ He was able to recognize letters, but was unable to read a word, although he could read Braille and English in raised or inscribed letters.

There is also a well-known case of a patient⁶⁹ who was blind from birth and regained his sight at the age of 52. After the surgery, he could not functionally see perspective and depth of space. He had problems identifying objects that he could not previously recognise through other senses. On the contrary, he was able to estimate the size of objects that he previously recognised by touch, but had difficulty estimating the height of large objects. He was taught to read upper English in raised or inscribed letters by touch at school. After the surgery, he could identify some letters similar to the case in paper⁶⁸ and later learned to write. He worked as a cobbler his entire life, and even after regaining his sight, he preferred to work with tools blindly, as he had been accustomed to all his life.

Another case⁷⁰ shows the importance of visual learning in childhood. A woman who was blinded from an early age but could see light throughout her childhood had her sight restored at the age of 23. After the surgery the patient was behaviourally blind, eg she could not avoid people and objects while walking. She underwent 1.5 years of visual rehabilitation, during which she learned, for example, to recognise objects. The results of the rehabilitation show that "binocular deprivation during the critical period of development causes behavioural blindness, which is partially recoverable".⁷⁰

There are other sources in the scholarly literature^{71–73} describing sight restoration in people with long-term blindness. These cases suggest that the effects of vision restoration are individual and that some vision-related skills can be learned. Other abilities probably do not. Visual rehabilitation and learning improve abilities even in people who have been blind since birth or for most of their lives, which is positive from the point of view of the usability of visual prostheses. On the other hand, coping with newly obtained visual sensory data is highly individual. It is difficult to break habits and certainties from the period when the patient was blind. Therefore, rehabilitation and psychological support are very important after vision is restored.

Sociotechnical Perspectives on BCI Adoption by People with Long-Term Blindness

The article aims to examine issues of restoring vision in people with blindness from a sociotechnical perspective, emphasising those who are long-term blind, and to show how a sociotechnical approach can help guide research and development to increase usefulness for users and future adoption. Therefore, following subsection first presents the initial sociotechnical perspective and its focus on the usefulness of the proposed solution for its users. The second subsection discusses the use of sociotechnical research to increase the potential for adoption and usefulness for people with blindness. In addition to the direct focus on visual prostheses, the last subsection also presents alternative technological approaches and the advantages of integrating visual prostheses with existing solutions in terms of the current sociotechnical context in which people with blindness live.

Sociotechnical Perspective

A concise definition of the sociotechnical perspective is presented in Sarker et al⁷⁴

Sociotechnical perspective considers the technical artifacts as well as the individuals/collectives that develop and use the artifacts in social (eg, psychological, cultural, and economic) contexts. This perspective privileges neither the technical nor the social, and sees outcomes as emerging from the interaction between the two. Further, it espouses a focus on instrumental outcomes such as efficiency and productivity as well as on humanistic outcomes, such as well-being, equality, and freedom.

In our case, we will consider a specific type of sociotechnical perspective⁷⁵ associated with design science research (DSR), which deals with the design of artifacts in engineering and information systems, and therefore also the design of aids and SmE for people with blindness.^{53,76–79} DSR builds on a sociotechnical perspective and emphasizes user values, which are reflected in the solution.⁷⁵ In this view, social starting points (eg need, implementation context, normative aspects) shape the initial design of the artifact, which is further improved in iterative DSR cycles based on feedback from (potential) users until the production phase.⁸⁰

Sociotechnical research takes into account both the social and technological components of a sociotechnical system in its analytical investigation. It can be carried out independently as primary research, or as part of design science methods that focus on the design and development of solutions. Within DSR, according to Wieringa,⁸⁰ sociotechnical research either precedes the design phase as problem context investigation or is part of the validation/evaluation of the solution's usefulness in the post-design phase (eg research on acceptability and acceptance of the treatment/solution). DSR is focused on pre-adoption research and from an engineering perspective the main goal is to propose a solution. The results of pre-adoption analytical research are immediately applied in design and development, because it is part of DSR. Such research is specific in that potential users and other stakeholders express their opinions on the solution's usefulness, which further enables the analysis of sociotechnical interaction in a problem context. It follows that analytical (socio-technical) research has a mainly supporting role in design science. However, the pre-adoption research (including acceptability and acceptance) can also be conducted as separate social research outside of DSR. Adoption research is linked to a perspective in the social sciences, where the main goal is analysis. This research is conducted on a production version, and its conclusions influence a new version or future solutions.

Sociotechnical research supporting solution design can be divided into four types:

- Problem context investigation – It is exploratory research focused on understanding the problem context into which the solution will be proposed. This research precedes the construction of the prototype.
- Acceptability – It is research into the potential user's perceived acceptability of a solution design before they can try it out in practice (eg description of functions, presentation of principles).
- Acceptance – It is research into the user-perceived acceptance of a functional solution based on practical testing (eg testing a pre-production version; experiences are based on short-term use of the solution).
- Adoption – It is research into a multi-phase process that begins with the user's decision to use a solution (eg, purchase or commitment to use the solution) and continues with long-term use of the solution from which his or her experiences are derived. The research has an explanatory character rather than an exploratory one.

The goal of DSR is to find out how to include or inscribe social values and needs into designed solutions.⁷⁵ In other words, it focuses on the solution's usefulness for users⁸⁰ and thus increases the likelihood of users accepting the solution or rather reduces their resistance when implementing a new solution in practice. This is not primarily about ensuring functionality and testing functions (technological perspective), but the emphasis is on evaluating the usefulness of the solution for users. The above implies, among other things, that more important than using the latest technologies supporting many new functions is whether the solution meets instrumental and humanistic outcomes, eg affordability, efficiency when using the tool, or ensuring user privacy.⁷⁴ When designing, researchers must balance between partial technological alternatives and usefulness for the target user, while also keeping in mind other contextual specifics of implementing this mutuality in practice.

Given that this article aims to support the design of cortical prostheses in particular, which are at a nascent stage of technological development, we classify acceptability and acceptance only under DSR and not as separate research in the social sciences, as adoption. It can be assumed that sociotechnical research at the nascent stage will primarily be qualitative, with a small sample of participants. It is not yet possible to fully use the research potential of acceptability, acceptance and adoption using quantitative approaches such as structural equation modelling and related models (eg theory of reasoned action, technology acceptance model, unified theory of acceptance and use of technology) used in the human-computer interaction area.⁸¹

Using Sociotechnical Research to Increase Adoption Potential

By focusing on the real users, DSR solves the problems caused by the fact that some proposed aids for people with blindness are directly designed by sighted researchers based on their idea of what these people need and evaluated by sighted people whose natural cognitive abilities are limited (eg blindfold; altered perception using virtual or augmented reality). Although such solutions make functional sense, they do not have to be based on the values, needs, abilities and possibilities of people with blindness and can therefore be rejected by them in practice.⁸² The main reason is that the mental model of the world is completely different for them. However, it makes sense to test a particular technology using sighted participants in the case of technological concept verification, eg, using phosphenes to generate objects and scenes.^{24,47} However, the final solutions that could be used in practice by people with blindness must be built and evaluated in close cooperation with them (and their families). In visual prosthesis development, research has often prioritised technological and biomedical dimensions, while sociotechnical aspects (eg, acceptability, evaluation, and broader social context) have received comparatively less attention, as also mentioned in studies of Lane et al, Karadima et al, and Dagnelie.^{18,83,84}

Designers may argue that a technological solution must first be available and only then should we consider implementing it at a personal or social level. This is certainly true, but sociotechnical research on future users and technological possibilities can show us what people with blindness would need and what can be achieved with a particular state of technology. This can speed up the development of useful solutions for a given problem context. Designers can focus on ensuring the most critical needs (cost-benefit analysis), proceed iteratively, and more quickly fine-tune a helpful solution that will be available sooner and will be in line with the needs, capabilities, abilities, and mental model of people with blindness. This is a more relevant approach than trying to find sophisticated solutions that potentially enable more extensive functions, which, however, will be useless for someone who has been blind for a long time (eg due to visual agnosia or the compensatory aids used to meet the need). In other words, while the development of visual prostheses is mainly based on a sequential approach, the sociotechnical perspective in DSR^{75,80} and experience with the development of aids for disabled people show that a parallel or iterative approach is more appropriate.⁸²

It has been almost 60 years since we verified the principles that would allow the restoration of vision in humans using coarse pseudo-pixelized vision,^{26,27} yet most of the research conducted to date has been technologically and biomedically oriented. Even William Dobelle,⁸⁵ who had been conducting research since the mid-1970s, never published a sociotechnically oriented study (focused on patients' attitudes or experiences with his solution) until his death and the termination of the project in 2005.¹⁸ Only later preliminary research¹⁸ as part of their project at the Illinois Institute of Technology brings interviews with participants from Dobelle's research. This preliminary research and the recent study⁸³ are exceptions in this respect. The latest one in particular study,⁸³ which focused on three visual prosthesis approaches (retinal, thalamic, cortical), brings interesting conclusions from a sociotechnical point of view. This study, using

interview methods, shows the levels of expectation and acceptance as well as the perceived risk-benefit balance of Greek respondents with blindness. The study also shows that potential users of visual prostheses are least afraid of retinal and most afraid of cortical prostheses. The number of respondents who declared their willingness to use them before learning about the consequences of implementing prostheses decreased after this learning, while the number of those who were completely against it increased. Among the most important abilities that they would like to ensure from these prostheses are face perception, movement perception, light perception and localization, and activities of daily living. The main required capability is to ensure greater independence. The perceived risks by potential users continue to outweigh the perceived benefits.

Given the tremendous technological progress not only in the possibilities of miniaturisation and new materials, but also in software processing of visual data, we believe that it is an ideal time to carry out a greater degree of sociotechnical research focused on the acceptability, acceptance and adoption of proposed and used solutions and approaches. We are currently seeing rapid technological and biomedical developments, especially in the development of cortical prostheses, which further increases this need.^{11,20,42,43,46}

Sociotechnical research can accelerate the practically oriented development of aids, including those for (partial) restoration of sight, and offer options for balancing the benefits of solutions and the concerns of people with blindness, including the risks they are exposed to (eg surgery and post-surgery problems). For example, if Karadima et al⁸³ show that the perceived disadvantages outweigh the advantages (especially with cortical prostheses), further research should ask why and under what circumstances people with blindness would reconsider their position. It means, in cooperation with designers, presenting use cases demonstrating the current technological possibilities of cortical prostheses, eg design of various use cases on how to navigate in space in multiple ways using artificial vision, from a directional arrow with a few phosphenes to rendering a scene with hundreds of phosphenes. Such research can identify circumstances under which people with blindness would be more willing to undergo the risks of surgery, rehabilitation, and other post-surgery problems. More complex research could focus on alternatives to artificial vision that enable people with blindness to perform the same or similar tasks by compensating for their disability. Such results could also help designers focused on aids or SmE to offer relevant non-invasive alternatives. Based on such research, a person with blindness can responsibly decide what solution(s) he or she would be interested in, given their condition.

Visual prostheses do not exist in a vacuum. Alternative technologies enable a wide range of capabilities – spatial orientation, identification of approaching people, greater social inclusion, navigation, and others.^{53,86,87} Therefore, visual prostheses should be placed in this sociotechnical context of people with blindness. The goal of visual prostheses should be to support the already existing abilities and possibilities of people with blindness, including those provided by (some of) previously used aids. It should be remembered that visual prostheses currently do not allow to restore vision in the strong sense of the word, on the contrary, it is a specific type of coarse pseudo-pixelized vision. It is not about replacing all other solutions (ie compensatory aids and SmE) for people with blindness with one solution offering full restoration of human vision, but on the contrary, it is about complementing existing solutions and their positive synergy with visual prostheses.

In terms of the potential adoption of visual prostheses, referring to experiences from cases where sight was restored to people with blindness, the new solution should not force a person with blindness to fundamentally and immediately change approach to the world, which is especially true for people with long-term blindness,^{66,69} in order to avoid rejection of artificial vision. The transition should be individual and gradual, and the rehabilitation should focus on those skills that the patient needs first and cannot be provided with the previously used aids. Such an approach aims to gradually supplement the mental and cognitive model of the world in a person with blindness, see gradual progress in drawing in study of Gregory and Wallace,⁶⁹ with relevant learning. It means that a person with blindness will have different needs in the short term and others in the long term and at the same time, a person with long-term blindness will have different needs than a person with short-term blindness. For example, a person with short-term blindness will have fewer abilities related to self-care or spatial orientation.

Especially for people with long-term blindness, the goal should not be to suddenly destroy their mental model of the world and the experienced procedures that they have created for many years and which provide them with a certain sense of safety, see cases in subsection Cases where sight was restored to people with long-term blindness. On the contrary, for

people with long-term blindness, the goal should be to support them ideally where their compensation with other perceptions or aids is insufficient. It should not be a revolution, but rather a gradual transition with the possibility of future individual expansion of the functions of the prosthesis and the associated multi-phase rehabilitation.

The sociotechnical approach in DSR, with its iterative approach,^{80,88} shows that it is not always appropriate for potential users for the designer to focus on the main ultimate goal (restoration of vision in the strong sense of the word), but rather to focus on simpler approaches/solutions and sub-goals solving problems that people with blindness encounter and where alternative solutions are not as good. And in this way, to supplement the possibilities and abilities that a person with blindness already has. In other words, designers can focus on purposeful solutions to the pressing problems that people with blindness face (eg problems with orientation in an unfamiliar environment, reading information, social isolation) rather than on the general goal, which is very far away – restoring sight through coarse pseudo-pixelized vision while minimizing known negative impacts and ensuring that the BCI user can fully use it similarly to a sighted person. For example, an overly sophisticated solution may be less valuable than simpler approaches to displaying an event. Instead of displaying a scene with objects using hundreds of phosphenes, which requires the user to interpret them, a few phosphenes can display the direction or approximate position in the visual field, accompanied by a voice command or notification describing the situation. For people with long-term blindness, less can sometimes be more.⁸⁹

The cases where sight was restored to people with long-term blindness are not just about the biological functional restoration of sight but also the usefulness of such restoration for people with long-term blindness. After all, even a person with blindness with the right aids or SmE can be fully competitive with a sighted person in some types of work,⁷⁸ thanks to the virtualisation of society and the creation of environments accessible via computer, where the cognitive abilities of a healthy and disadvantaged person are erased or minimised. From the point of view of usefulness, it is essential whether new solutions in the form of cortical prostheses will enable people with long-term blindness to perform activities that they are currently unable to perform or only to a very limited extent. Or whether these activities can already be performed with the same quality, if not better, with current compensatory aids. In the second case, the benefit of such a solution for people with blindness is negligible, and it can be assumed that adoption will also be low (concerning the need for surgery and possible post-surgery problems).

It can be likened to the idea of wanting a healthy person to expand their abilities with echolocation, which bats and cetaceans use. If we ignore the biotechnological solution to such a problem, the benefit of such an expansion of the senses for everyday life would be minimal, because humans detect obstacles visually. The benefit to the quality of life would be minimal, and therefore, the adoption of such a solution would be low. In other words, even if the solution would bring a new function and possibilities, the usefulness of the solution for the everyday life of a modern healthy person is small.

In this context, reading letters, words, and sentences is an interesting skill and a need. Reading is often mentioned as one of the abilities that researchers have focused on since the beginning, in connection with restoring sight in people with blindness.^{20,26,68,69} In today's era of extensive digitalisation and virtualisation of society, we have aids that can be connected to computing devices that allow people with blindness to write and read as quickly as the sighted.⁷⁸ The current problem is only identifying and reading text outdoors – there is room for new, more useful universal solutions. In this case of possible use of visual prostheses, it is necessary to ask whether a solution based on displaying letters using phosphenes and requiring their interpretation by a person is practical. This is a mentally demanding task, possibly more difficult than for people who have regained full sight after surgery, as a person with blindness and restored vision must fully concentrate (phosphenes are not aligned pixels) and the ability requires extensive learning. That this is a difficult task is shown by a patient operated on in 1972 who was able to read one Braille letter every 7 seconds.²⁷ This is approximately 15 times slower than the average speed of tactile reading. A much faster communication option with preserved hearing (combined disability is rare) is to use speech synthesis to read text. The ability to identify letters is, therefore, interesting from the point of view of functional verification of the solution. Still, from the perspective of practicality for people with blindness, it is not important to be able to use artificial vision to read words, as it can be provided by other aids depending on the situation.

Despite the benefits of sociotechnical research and the expected future development and improvement of cortical prostheses, we must not forget that some people with long-term blindness will never want to use them.⁸³ Whether

because of possible complications (they will not be convinced by the benefits and they will be afraid of possible negative consequences) or because they are satisfied with their established life in blindness, which they know well and is safe and familiar to them. For these reasons, it is necessary to further develop common compensatory aids and SmE to ensure their greater independence, because this is the most important need and value for people with blindness.^{83,90} For this purpose, further sociotechnical research on aids and SmE needs to be conducted in parallel with the sociotechnical research on visual prostheses.

Alternative Technological Approaches and the Benefits of Connecting Visual Prostheses with Existing Solutions

Despite current enthusiasm surrounding visual prostheses,⁴⁶ they should not be regarded as a replacement for existing aids for people with blindness, as they currently provide only limited, coarse pseudo-pixelized vision. Rather, they represent one component within a broader ecosystem of compensatory solutions whose potential synergistic effects remain insufficiently explored in the literature. If we leave aside the topic of visual prostheses and focus on alternative solutions that deal with compensation for the handicap and not directly restoring sight, these technologies can be divided into single-purpose aids^{86,87,91} and complex SmE including intelligent buildings with an ambient intelligence (AmI) system.^{53,77,78}

The development of these non-invasive and long-term proven compensatory approaches with a high degree of usefulness for people with blindness allows us to think about use cases for how to integrate visual prostheses into the current sociotechnical reality. This also gives us the time we need to improve cortical prostheses, in particular, so that the perceived benefits of potential users outweigh the disadvantages or risks. An example of a possible connection of a home ambient system with a cortical prosthesis can be demonstrated at the RUDO AmI system⁵³ installed in an intelligent building. The visual prosthesis can display status information obtained from the RUDO AmI system, which is currently only communicated to person with blindness through audio messages or notification sounds, and which can disturb sighted people (eg the movement of recognised person to another room, change in the weather outside, the need for intervention by the RUDO system administrator). This can be achieved by displaying specific symbols composed of phosphenes through a visual prosthesis. The person with blindness can respond to them or request detailed information from the RUDO system via available aids (eg smartphone, keyboard, refreshable Braille display, speech synthesis). In the same way, it is possible to draw attention to obstacles or dangerous places in a building (eg stairs). Another example could be enhanced navigation in the building, where the direction in which a person with blindness should go can be indicated through displayed symbols. Similarly, thanks to the camera, it can be recognised a particular object that he or she is looking for and display its approximate location in the room. Or, using artificial intelligence approaches, it can be vocally described a (complex) scene in front of a person with blindness. He or she can ask about the details of the scene. The synergistic connection would increase the usefulness of both solutions for a person with blindness.

In addition to existing solutions, sociotechnical research can focus on technologies and approaches applicable in the future and the attitude of people with blindness towards their use – acceptability research. If we skip the advanced possibilities of tissue engineering in the distant future and the associated cultivation of organoids,⁹² where the connection of the cultivated organoid with the body remains a big question, another direction of research is also offered. This direction may be transcranial non-invasive stimulation of cells in the brain's visual cortex.⁹³ To stimulate individual parts of the brain or even neurons, a combination of signals from the entire electromagnetic spectrum, from units to hundreds of GHz, would be used. Functional magnetic resonance imaging can be used to localise targeted neurons precisely, or the localisation of neurons can be determined during calibration tests, similar to what is done with current visual prostheses. This is only a conceptual design that incorporates available technologies.⁹⁴ However, a number of pressing issues, starting with the selection of appropriate frequencies, still need to be resolved.⁹³ The above technological approach, which is patented, complements current non-invasive BCI solutions based on electroencephalography.⁹⁵

Sociotechnical Research Framework for the Visual Prosthesis Research Agenda

This section presents a high-level framework for sociotechnical research in the area of visual prostheses. It offers researchers a basic orientation in preparing their own research design. Such a high-level perspective allows the framework to be used in the future as new technologies and challenges arise. The framework also simplifies scholars' orientation in interdisciplinary research at the boundary between engineering and the social sciences. The introduction of the conceptual framework is followed by a discussion of the current sociotechnical research agenda.

Orienting Sociotechnical Research on Visual Prostheses

Based on the considerations from previous sections, we have prepared a sociotechnical research framework that outlines the aspects to be investigated from the perspectives of engineering and the social sciences, enabling designers to develop useful visual prostheses. The framework is presented in Figure 1 and research agenda in the next subsection.

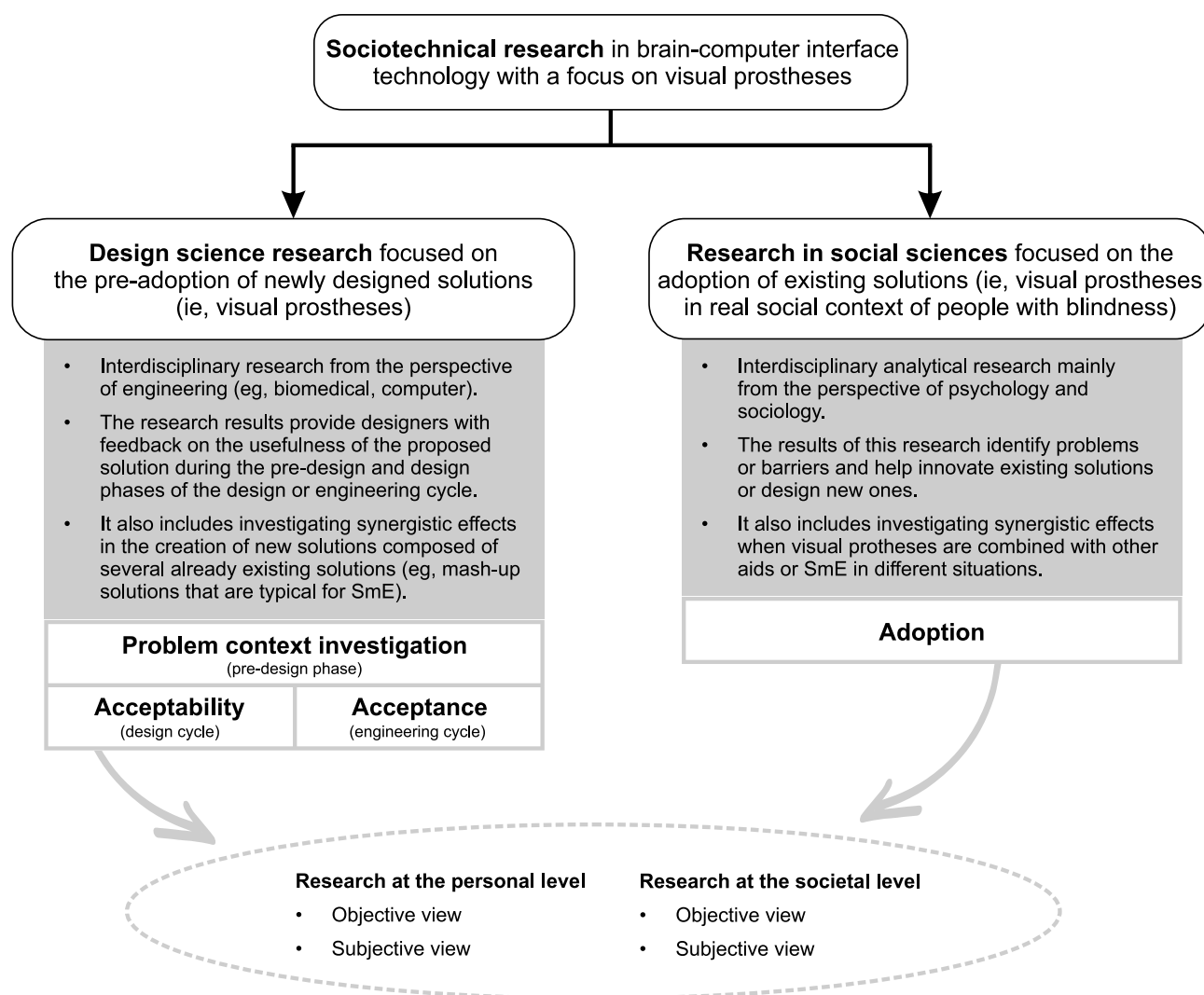


Figure 1 The sociotechnical research framework for the visual prosthesis research agenda offers a general division of sociotechnical research that helps increase the usefulness of visual prostheses and fulfil their goals. The view on DSR is based on Wieringa.⁸⁰ Design cycle consists of (1) Problem investigation > (2) Treatment (solution) design > (3) Treatment validation > go back to (1) or (2). Engineering cycle consists of (1) Problem investigation > (2) Treatment (solution) design > (3) Treatment validation > Treatment implementation > Implementation evaluation > go back to (1) or (2).

Figure 1 presents a high-level view of the basic orientation of sociotechnical research. Pre-adoption research (usually short-term and exploratory) occurs when designing a solution (synthesis), and adoption research (usually long-term and more often explanatory) occurs as part of research in social sciences (analysis) focused on the solution used in practice. Analytically oriented research in social sciences always complements DSR⁸⁸ and helps identify new problems with existing solutions and allows other designers to propose more useful solutions.

Design Science Research: Pre-Adoption Research of a Designed Solution

Sociotechnical analytical research is an important part of some research phases within different design science methods,⁸⁸ where it helps understand the problem context and examine the acceptability and acceptance of the proposed solution. The design of a solution takes place iteratively within the design or engineering cycle to achieve the most relevant solution.⁸⁰

Figure 1 shows the pre-adoption research conducted as part of the DSR. This research reduces the risk of future users rejecting the proposed solution and improves designers' understanding of the problem context. It includes three types of research (see also subsection Sociotechnical perspective):

- Problem context investigation,
- Acceptability (from a DSR perspective, this is research relevant to validating the proposed solution before it is implemented),
- Acceptance (from the perspective of DSR, this is research relevant for the evaluation of the implemented solution).

Although this sociotechnical research is part of the DSR, its results can be published separately, which allows other designers to learn and propose more relevant solutions.

Research in Social Sciences: Adoption Research of an Existing Solution

Sociotechnical analytical research focused on adoption helps not only identify barriers and problems with a solution in practice, but also understand changes in its use over time. This allows new use cases and problems to be discovered, or functional gaps to be identified that need to be addressed by proposed solutions in the future.

Since visual prostheses are not easy to “try out” and everyone who tries them becomes active user, the distinction between acceptance and adoption blurs. The main difference between these types of research in BCI is the length of time the user uses the prosthesis, and the impact of sociotechnical research on the design of a given prosthesis version. In the case of acceptance, this is weeks and in the case of adoption, months. As previously described, cortical prostheses, in particular, are unreliable and their parameters can change during use (eg, electrode disconnection or encapsulation, cortical degeneration), which affects the prosthesis's usable lifespan.

Levels of Research

If we delve deeper into the sociotechnical research, it can be divided into two levels – personal and societal, as presented in Figure 1:

- Research at the personal level focuses on individual problems and abilities of person with blindness (eg independence in hygiene or dressing; combination of other disabilities) as well as psychological aspects (eg personality traits) influencing the use of visual prostheses.
 - o Objective view – Research into the objective needs associated with visual prostheses in the social context of their use.
 - o Subjective view – Research into subjective needs and values associated with visual prostheses in the individual social context of their use.
- Research at the societal level focuses on social inclusion, problems and abilities of people with blindness and other stakeholders (eg recognizing people, interacting with other people) and social constructs (eg perceived usefulness, perceived interactivity) influencing the use of visual prostheses.

- o Objective view – Research into the objective needs and normative values associated with visual prostheses in the social and cultural context of their use.
- o Subjective view – Research into subjective needs and values associated with visual prostheses in the individual social and cultural context of their use.

We were inspired by a similar division in social informatics, which is focused on sociotechnical interaction research.⁹⁶ This research uses methodological approaches from sociology and (social) psychology. Research at these levels helps us understand people with blindness's attitudes towards the use of visual prostheses. Cost-benefit and risk-benefit analyses can be carried out, and proposals should be made on how to (positively) change their attitudes and improve the technology.

In both personal and societal research levels, the objective and subjective views can be emphasised. These views are important for designers. The objective view includes the main problems being solved and the needs of people with blindness, which results from the handicap and are universally valid for all users. On the contrary, the subjective view also includes other needs or secondary aspects related to the main problems being solved (often very individual). A subjective view may be associated with a very limited context of use, eg a person with a unique disability, or the activities they perform. This allows designers to focus on addressing the most pressing needs or to create a very specific solution for a particular person with blindness or a narrow group.

A Sociotechnical Research Agenda on Visual Prostheses

Stakeholders of the Research Agenda

When the development of vision restoration using BCI is in question, it is necessary to design and implement a comprehensive sociotechnical research agenda. In this section, we consider how research in social sciences can help identified stakeholder groups. Our considerations suggest that future studies could target at least five primary stakeholder groups: people with blindness, informal caregivers, clinicians and rehabilitation specialists, technology developers (or designers), and regulators.

For people with blindness, the research agenda could focus on their needs and values. Namely, it is important to employ a user-centred approach, which will result in intuitive and effective devices adapted to user needs.⁹⁷ The literature also revealed that the most important value, according to which people with blindness will evaluate the proposed solution, is independence.^{83,90} Based on such research, it is possible to better understand users' attitudes towards various technological solutions and the reasons behind them.

Regarding informal caregivers, our considerations suggest that the research agenda focuses on how the implementation of visual prostheses may affect long-term caregiving workload and household routines. The existing research shows that depression and burden are common among informal caregivers of people with blindness,⁹⁸ while the literature emphasises a lack of studies that would examine how new technologies may reduce stress among caregivers and thus calls for more research on how they can facilitate daily activities.⁹⁹ Such research would allow us to understand the effects of BCI on social interaction in the specific environment of people with blindness.

Further, when involving clinicians and rehabilitation specialists, the research agenda could focus on the effectiveness of BCI technology in restoring vision and rehabilitation activities after surgery. Rehabilitation is especially important for the proper and effective functioning of the visual prosthesis and its active use, as shown by studies.^{11,15,19}

For technology developers, the research agenda could focus on structured feedback on reliability problems, unmet functional needs, and contexts of use. Existing research demonstrates that it is necessary to refine BCI to achieve faster, more accurate communication and control, which would open new realms of human-computer interaction and would expand their clinical use.^{100–102}

Finally, the research agenda could provide regulators with robust, safety-related, and long-term risk data to evaluate authorisation decisions for invasive BCI. According to Zhu et al¹⁰³

China's medical BCI governance is state-led, prioritizing safety; the United States features innovation-driven flexibility; the European Union uses an empowerment model to strictly mitigate risks.

It is necessary to find an intersection between these approaches and identify basic regionally universal norms. Based on comparisons of experiences from these parts of the world, this should lead to the development of flexible yet safe regulatory models.

Research Agenda and Approaches

Considering the design process and device lifecycle, specific study designs and methods can be employed at different phases (presented in subsection Orienting sociotechnical research on visual prostheses). Given that social informatics also deals with research on sociotechnical interaction, we can estimate which study designs and research methods will be most suitable for sociotechnical research in the field of visual prostheses based on the social informatics thematic-methodological framework.¹⁰⁴ Review articles and meta-analyses can then be created from the established empirical base. We consider the following study designs and methods to be the most appropriate for individual types of sociotechnical research:

- Problem context investigation – surveys, field studies (eg observation, contextual inquiry, ethnography), interviews, focus groups and mixed-methods studies,
- Acceptability – interviews, focus groups, experiments, case studies and mixed-methods studies,
- Acceptance and Adoption – it can be assumed that case studies, action research, field studies, experiments and mixed-methods studies will be most frequently used, which will be based mainly on qualitative methods due to the very limited sample of participants (individuals). See also subsection Sociotechnical perspective.

To make the proposed sociotechnical framework more actionable, we first supplement it with general research questions that sociotechnical research in connection with DSR should address. We will then expand this view by presenting thematically structured research questions arising from the previous sections of this article, which provide an overview and discuss BCI problems with an emphasis on cortical prostheses. Table 1 presents the research agenda topics concerning sociotechnical aspects. Research questions are classified according to the aforementioned framework.

General sociotechnical research questions related to DSR in cortical prostheses and focused on people with long-term blindness:

- Problem context investigation – What activities should artificial vision support and what should it enable? Additional question on understanding problem context can be How do people with blindness interact with other people and the environment in which they live, what aids do they use, and what activities do these aids cover?
- Acceptability – What values, needs, risks, benefits, and everyday contexts shape potential users' attitudes toward becoming users of visual prosthesis?
- Acceptance – How do users experience the usefulness, burden, and learnability of phosphene-based artificial vision in concrete everyday activities? Additional question on sociotechnical integration can be How does artificial vision interact with existing compensatory aids, SmE, routines, and social practices?

In conclusion, the presented framework is a useful guide for future sociotechnical research, helping increase the usefulness of visual prostheses to users and reduce their resistance or refusal to use them. At the same time, it allows designers to save financial resources, as preparing a solution proposal costs more resources than conducting research among respondents.

Table I Research Agenda Topics and Relevant Research Questions Concerning Sociotechnical Aspects, Classified According to the Aforementioned Framework. The View on DSR Is Based on Wieringa⁸⁰

Research Agenda Topics/Research Questions	Type of Research Question	Where Can the Sociotechnical Research Help DSR? (Engineering Cycle Phase Number)	Type of Sociotechnical Research	Level of Research
Technological constraints and perceptual experience				
How do users with long-term blindness describe, interpret, and make sense of phosphene-like visual information in relation to everyday tasks such as orientation, object localization, and recognizing spatial change?	Empirical	Requirements analysis (1, 2), Solution/treatment validation (3), Usefulness evaluation (3, 5)	Acceptability, Acceptance	Personal
Which perceptual limitations (eg, low resolution, instability, ambiguity, or variability of phosphene perception in time) are experienced by users as merely inconvenient, and which prevent functional use?	Empirical	Design requirements (2), Usefulness evaluation (3, 5, 6)	Acceptability, Acceptance, Adoption	Personal
How do calibration needs influence perceived burden, trust, and willingness to continue using a BCI-based visual prosthesis?	Empirical	Usefulness evaluation (3, 5, 6)	Acceptance, Adoption	Personal
Functional usefulness and technical capability				
What should count as “usefulness” in BCI-based vision restoration if implementation success does not necessarily translate into functional vision for users with long-term blindness?	Conceptual	Usefulness definition (1), Solution/treatment validation (3)	Problem context investigation, Acceptability	Personal
Which everyday activities do people with long-term blindness identify as worth supporting through artificial vision, and which activities are already sufficiently supported by existing nonvisual strategies or aids?	Empirical	Requirements analysis (1, 2)	Problem context investigation, Acceptability, Acceptance	Personal, Social
In which task contexts does artificial vision provide perceived added value over existing compensatory aids, and in which contexts does it introduce additional burden or uncertainty?	Empirical	Problem context analysis (1, 6), Solution/treatment validation (3), Usefulness evaluation (3, 5, 6)	Acceptance, Adoption	Personal, Social
How can iterative cycles of user inquiry, prototype assessment, redesign, and contextual evaluation reveal whether technical improvements actually improve perceived usefulness?	Conceptual / Empirical	Evaluation criteria definition (2), Usefulness evaluation (3, 5, 6)	Acceptability, Acceptance, Adoption	Personal
What factors lead users to accept or reject BCI-based visual prostheses after experiencing their actual usefulness and burden?	Empirical	Solution/treatment validation (3), Usefulness evaluation (3, 5, 6)	Acceptance, Adoption	Personal
How do users prioritize functional outcomes — independence, safety, speed, confidence, reduced cognitive effort, or social participation — when judging whether BCI-based vision restoration is useful?	Empirical	Evaluation criteria definition (2)	Acceptability	Personal

User adaptation, cognition, and neuroplasticity				
How does long-term blindness reshape the meaning of “restored vision” when users may have developed nonvisual cognitive, spatial, and practical strategies (with other aids) over time?	Conceptual	Problem context analysis (1, 6)	Problem context investigation, Adoption	Personal
How do users with long-term blindness learn to associate artificial visual signals with objects, space, movement, or action possibilities over repeated use?	Empirical	Usefulness evaluation (5, 6)	Acceptance, Adoption	Personal, Social
What cognitive effort, confusion, fatigue, or sense-making strategies emerge when users attempt to translate artificial visual input into meaningful action?	Empirical	Usefulness evaluation (5, 6)	Acceptance, Adoption	Personal
How do differences in blindness history, prior visual experience, and established nonvisual routines shape requirements for training, calibration, and interface design?	Empirical	Usefulness evaluation (5, 6)	Acceptance, Adoption	Personal
Rehabilitation, training, and learning				
Which forms of training help users move from detecting artificial visual stimuli to using them for meaningful everyday action?	Empirical	Usefulness evaluation (5, 6)	Acceptance, Adoption	Personal, Social
How do users’ support needs change across initial exposure, calibration, learning, routine use, and long-term maintenance?	Empirical	Usefulness evaluation (5, 6)	Acceptance, Adoption	Personal
What indicators should be used to evaluate rehabilitation success (eg perceptual accuracy, task performance, confidence, reduced dependence on others, integration with existing aids, or perceived quality of everyday functioning)?	Conceptual	Problem context analysis (1), Evaluation criteria definition (2)	Problem context investigation, Acceptability	Personal, Social
Risk, trust, and risk-benefit perspective				
Under what conditions can invasive BCI-based vision restoration be considered acceptable when potential benefits are uncertain and risks include surgery, long-term device degradation, and ongoing maintenance?	Conceptual	Usefulness definition (1)	Problem context investigation	Personal
How do potential users with long-term blindness evaluate trade-offs between surgical risk, uncertain functional vision, calibration burden, possible device degradation, and expected everyday benefits?	Empirical	Requirements analysis (1, 2), Usefulness definition (1)	Problem context investigation, Acceptability	Personal
How do trust and willingness to use change when users encounter instability, recalibration needs, limited perceptual output, or mismatch between expected and actual usefulness?	Empirical	Solution/treatment validation (3), Usefulness evaluation (5, 6)	Acceptability, Acceptance, Adoption	Personal
Integration with existing aids and practices				
How should BCI-based vision restoration be designed as part of a broader ecology of existing compensatory aids, skills, routines, and social support rather than as a standalone replacement for blindness practices (or unfunctional biological sight)?	Conceptual	Problem context analysis (1)	Problem context investigation	Personal, Social
Where do BCI-based visual prostheses create synergy with existing aids, and where do they create interference, redundancy, cognitive overload, or practical incompatibility?	Conceptual / Empirical	Problem context analysis (1), Solution/treatment validation (3), Usefulness evaluation (3, 5)	All	Personal, Social

Notes: Engineering cycle phase numbers are (1) Problem investigation > (2) Treatment (solution) design > (3) Treatment validation > (4) Treatment implementation > (5) Implementation evaluation > go back to (1) or (2). Additional phase is Solution adoption (6) that complements DSR.

Conclusions

First, we would like to emphasise the limits of this article. These limits are connected to the article's conceptual character and to the use of a narrative approach to familiarise the reader with the topic and to build our argument on case studies, given the lack of other theoretical bases. This limits the possibilities of higher-level generalisation. If we have tried to generalise in some parts, this must be taken into account. The findings and arguments in this paper derive from a limited set of case narratives and should thus be interpreted cautiously as exploratory rather than confirmatory.

Vision restoration is a multifaceted problem. Over the last hundred years, we have moved from the question "Can we restore visual signals?" to "Will restored visual signals, thanks to BCI technology, meaningfully improve the lives of people with long-term blindness?", as this narrative overview shows. Visual prostheses do not offer real vision like a healthy person has, but only its replacement, which, in the case of cortical prostheses, is based on the use of an incomplete visual nervous system. Current invasive BCI solutions involving visual prostheses have a number of unresolved technological and biomedical questions and problems.^{25,51} There are also sociotechnical aspects that fundamentally influence the practical use of technologies. Technologies are useless to humans if they cannot be placed in the user (social and cultural) context of the time in which they live, and if a person is not able to use them with their skills and knowledge. Similarly, restored vision was useless in the case presented in Ackroyd et al.⁶⁶ This article justifies the importance and benefits of sociotechnical research in the nascent stage of visual prosthesis development, which is currently very rapid, especially in cortical ones, and we call for this research, as it is minimal in this area.

We have shown how sociotechnical research can increase the usefulness of the proposed solution and thus also the future potential adoption among users. Thus, sociotechnical research is important for DSR and the continuous innovation of visual prostheses within innovation cycles.⁴⁹ Such research can help the main involved persons or roles:

- Designers better understand the user perspective, focus on developing useful functionalities, and thus reduce users' perceived risks and the likelihood of rejection of the technological solution. Designers can use cost-benefit analysis and focus primarily on functionalities that users need most and that are not expensive to implement (eg, financial and time costs of development, rehabilitation and maintenance).
- Users and potential users can understand the various technological and biomedical aspects of the solution related to their particular life context, as well as the attitudes of other people with blindness. This allows them to better evaluate risk-benefit analysis and consider pros and cons.

Because of bold statements and enthusiasm in invasive BCI solutions,^{12,46} our article underscores the importance of including people with long-term blindness in experimental research related to visual prostheses and their usefulness. Their inclusion will not only enhance the ecological validity but also the relevance of research findings, where design and development of new technologies will be grounded in the real-world experiences. For this purpose, the sociotechnical research framework for the visual prosthesis research agenda was introduced, which allows researchers to methodologically justify and design their sociotechnical research.

From a practical point of view, this article highlights the importance of integrating user-centred validation during testing and development of new technologies as currently there is a lack of focus on user attitudes, experiences and their contextual needs, especially among people with long-term blindness. Sociotechnical research among respondents can save financial resources by ensuring greater usefulness of the solution and reducing the possibility of rejection of the proposed solution, as sociotechnical research is cheaper than design research.

People with blindness must have the freedom to make an informed choice about the solution that is most appropriate, given their physical (biological) and psychological capabilities, and social support (eg from family), which differ between short- and long-term blindness. Researchers must not ignore the possibility that for many people with long-term blindness, continuing to live with blindness – that is, a life supported by other than invasive BCI-based technology – may be a suitable solution.

In conclusion, we present three suggestions for future research using presented framework. First, the emphasis should be placed not only on ensuring high-quality visual perception and its practical application in the case of cortical

prostheses, but also on visually guided behaviour, respectively, behaviourally guided vision. As mentioned, restoration of sight does not guarantee functional vision that a person can use as a healthy person would. For example, Dickens et al⁶⁷ point out that restoring vision can paradoxically also bring depressive behaviour, as it is not only about the physical restoration of vision. It is also about the processing of perceptions and visually guided behaviour, where there is a cooperation with other senses and the motor system.¹⁰⁵ Further research in this area will be welcome as the number of cortical prostheses implanted increases.

Given that people with blindness are accustomed to using other senses such as hearing and touch, it is appropriate to consider the mutual synergy between using visual prostheses and available aids or SmE, routines, and social practices. This could improve the attitude of people with blindness, as new solutions will build on something familiar. Visual prostheses can complement (and vice versa) the functions offered by aids or SmE. Especially in the case of intelligent building, its sensors (and voice input and output) can be used not only to present reality more relevantly, but also to augment it. This can bring new employment opportunities for people with blindness and new benefits. Working in augmented reality thanks to being connected to building sensors can be seen as a work advantage if a person with blindness and a cortical prosthesis, for example, works as an administrator of an intelligent building.⁷⁸ Similar socio-technical research on this synergy is currently lacking. This perspective can include capability approach, sociotechnical fit and technology appropriation research. The last, and no less important, aspect is the need to prepare new norms and policies (technical and legal) that these BCI technologies, their producers, and users must follow to ensure their safety and security.

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The author (M.H.) is a person with long-term blindness (a user of ocular prostheses) who has a PhD in the field of informatics and works as a university researcher focused on developing aids and smart environments for people with blindness.

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Disclosure

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