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Review

Sensory substitution: Closing the gap between basic research and widespread practical visual rehabilitation

Q1 Maidenbaum Shachar[a], Abboud Sami[a], Amedi Amir[a,b,*]

[a] Department of Medical Neurobiology, The Institute for Medical Research Israel-Canada, Faculty of Medicine, The Hebrew University of Jerusalem, Jerusalem 91220, Israel
[b] The Edmond and Lily Safra Center for Brain Sciences (ELSC), The Hebrew University of Jerusalem, Jerusalem 91220, Israel

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ABSTRACT

Sensory substitution devices (SSDs) have come a long way since first developed for visual rehabilitation. They have produced exciting experimental results, and have furthered our understanding of the human brain. Unfortunately, they are still not used for practical visual rehabilitation, and are currently considered as reserved primarily for experiments in controlled settings.

Over the past decade, our understanding of the neural mechanisms behind visual restoration has changed as a result of converging evidence, much of which was gathered with SSDs. This evidence suggests that the brain is more than a pure sensory-machine but rather is a highly flexible task-machine, i.e., brain regions can maintain or regain their function in vision even with input from other senses.

This complements a recent set of more promising behavioral achievements using SSDs and new promising technologies and tools.

All these changes strongly suggest that the time has come to revive the focus on practical visual rehabilitation with SSDs and we chart several key steps in this direction such as training protocols and self-train tools.

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* Corresponding author at: Department of Medical Neurobiology – The Institute for Medical Research Israel-Canada, Faculty of Medicine, The Hebrew University of Jerusalem, Jerusalem 91220, Israel. Tel.: +972 2 675 7259; fax: +972 2 675 8602.
E-mail address: amir.amedi@ekmd.huji.ac.il (A. Amir).
URL: http://www.brain.huji.ac.il/ (A. Amir).

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1. Introduction

In this review we describe approaches to using sensory substitution devices (SSDs) to help the visually impaired. Section 2 introduces the problem of visual rehabilitation in general, attempts to deal with this problem, and in particular experiments involving sensory substitution devices (SSDs). Section 3 briefly discusses the reasons for the limited adoption of SSDs. Section 4 presents recent theoretical, practical and technological advances. Section 5 puts forward some practical steps to bridge the gap between the use of SSDs for research and their applicability for practical visual rehabilitation in everyday use by the blind community.

2. The challenge of blindness, and visual rehabilitation approaches

In this section we describe the goals of visual rehabilitation (Section 2.1), current and near-future approaches (Section 2.2) and sensory substitution devices (Section 2.3), and explore whether “seeing” via sensory substitution devices counts as vision (Section 2.4).

2.1. Goals of visual rehabilitation

Over 285,000,000 people worldwide are affected by severe visual impairments, of whom nearly 40 million are blind. This constitutes both a clinical and scientific challenge to develop effective visual rehabilitation techniques (WHO, 2012). These visual impairments arise from a wide variety of etiologies, and in many cases require completely different types of treatment. Additionally, the vast majority of the visually impaired live in developing countries and in harsh economic conditions, such that any comprehensive solution must be both relatively cheap and easily available (Held and Ostrovsky, 2011; WHO, 2012).

2.2. Current and near-future invasive methodologies

There are a number of current approaches to visual rehabilitation (see Striem-Amit et al., 2011 for recent reviews of these and other methods). Invasive approaches aim at physically replacing or restoring the function of the peripheral visual system, for instance by using artificial retinal prostheses (Ahuja et al., 2011; Chader et al., 2009; Collignon et al., 2011a; Djilas et al., 2011; Humayun et al., 2012; Rizzo III, 2011; Wang et al., 2012; Zrenner et al., 2011), gene therapy (Busskamp et al., 2010) or transplantation of photoreceptors (Yang et al., 2010). However, while in the long term these solutions hold great promise, they still face huge hurdles in terms of technical capabilities, ability to customize to specific etiologies (the type and severity of visual deterioration and the site of the lesion along the visual pathways), are extremely expensive, and only provide very low-resolution end-result sight (Humayun et al., 2012). In addition, even these limited results still require a very long and arduous visual rehabilitation process.

2.3. Sensory substitution devices (SSDs)

A different approach, known as Sensory Substitution, is designed to convey visual information to the visually impaired by systematically substituting visual information into one of their intact senses. Sensory substitution devices (SSDs) are non-invasive human–machine interfaces which, in the case of the blind, transform visual information into auditory or tactile representations using a predetermined transformation algorithm (see Fig. 1 for illustration).

The first such structured substitution system is probably Braille reading. This technique, developed originally by Barbier as a means for writing and reading in the dark for the French military in the Napoleonic era, was later revised by Louis Braille to enable the blind to read by substituting visual letters with tactile ones. This was further developed in the early 1950s with the development of automatic text-to-braille converters such as the Optacon (Goldish and Taylor, 1974).

A highly interesting effort which is often neglected historically, was the Elektroftalm that attempted to electronically transform a visual image into auditory (late 1890s) and tactile (1950s) stimulation (Starkiewicz and Kuliszewski, 1965) using one or several sensors.

These early attempts led to the more organized and methodological attempts of Paul Bach-y-Rita in the 1970s, which positioned him as the pioneer of the extensive use of sensory substitution for research. Bach-y-Rita focused on tactile devices and specifically a prototype device he named the “*Tactile Vision Sensory Substitution*” (TVSS) which blind users could use for tasks such as recognizing large letters, catch a ball tossed at them and so on (Bach-y-Rita, 1972).

The work of Bach-y-Rita suggested that these devices could serve as stand-alone aids for limited daily use, providing otherwise non-existing visual capabilities such as perception of shape, color and location. Additionally, as SSDs are relatively low-cost they could be made accessible to the majority of the world's visually impaired population, who as mentioned above primarily reside in developing countries and have limited access to advanced medical treatment (Held and Ostrovsky, 2011; WHO, 2012).

SSDs have enormous potential for non-invasive rehabilitation for the majority of the blind. In over 95% of all cases of blindness, the problem is not in the visual/occipital parts of the brain but rather in the eye, retina or the visual pathways (WHO, 2012). In addition, in the subset of cases where the visual pathways between the ganglion cells and the visual cortex is damaged, approaches that repair the retina would not be able to convey the information from there to the brain, leaving SSDs as the main potential therapeutic approach. However, despite of several decades of research, the use of SSDs has hardly exploited this vast potential. Before we explore the reasons for this relative failure, and how this might be remedied in the near future based on recent theoretical practical and technological advances, it is worth inquiring how ‘seeing’ using SSDs compares to natural vision.

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