Sensory Substitution and Augmentation – What's Happening "Under the Hood" in Our Brain

Maidenbaum Shachar
IMRIC, ELSC
Hebrew University,
Jerusalem, Israel
Shachar.Maidenbaum@gmail.com

Amedi Amir
IMRIC, ELSC
Hebrew University,
Jerusalem, Israel
Amira@ekmd.huji.ac.il
Brain.huji.ac.il

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Abstract

Sensory substitution devices (SSDs) are non-invasive human-machine interfaces which sense information via one modality and transform it into another, in which it is transmitted to the user. SSDs hold great potential for assistive augmentation goals such as substituting impaired senses and adding new ones. But how is this information processed in our brains? This is especially important as according to traditional neuroscience it should be severely limited by the existence of critical periods in brain development and the view of brain regions as rigid and sensory based. Here, we will use the example of visual-to-auditory sensory substitution devices for the blind to discuss what happens "under the hood", how the use of sensory substitution actually appears to work and what this has revealed about our brain organization in general, leading to theories such as the view of the brain as a task machine. Finally, we will attempt to outline some implications of this theory for the potential for visual rehabilitation in particular and for sensory augmentation in general.

Author Keywords

Sensory substitution; blind; visual rehabilitation; brain organization; Design; Human Factors

ACM Classification Keywords

B.4.2; H.1.2; H.5.1;

1. Introduction

Sensory substitution devices (SSDs) are non-invasive human-machine interfaces which sense information via one modality and transform it into another in which it is transmitted to the user. The main goal of SSDs has been visual rehabilitation for the blind by translating visual information into other senses. Starting with the work of Bach-y-Rita, first with a tactile array and later on an array of electrodes placed on the tongue (BrainPort [2]), through the work of Meijer who created the visual-to-auditory SSD in widest use (The vOICe [4]), many attempts have been made to achieve this goal. However, despite these efforts SSDs are still only in very limited use (reasons for this and some possible steps for returning part of the spotlight to practical rehabilitation reviewed in [3]).

As visual SSDs have seen the most research, we will use this sub-group of as our main example here. It should be noted though that SSDs have also been used successfully for other goals, such as using the Brainport to restore balance in cases of bilateral vestibular damage (BVD) and a tactile-to-tactile translation to enable tactile sensations in leprosy afflicted limbs [2].

Additionally, there have already been several attempts to augment senses using SSDs. For example, Alsberg [1] attached a hyperspectral camera to the vOICe SSD, enabling sonification of chemical compounds and auditorilly distinguishing visually identical substances (sucrose vs. potato powder). The FeelSpace team used a magnetic sense for improved spatial orientation [6].

Thus, SSDs offer a fascinating potential for human augmentation in general and for assistive augmentation in particular.

2. Under the hood

How do these devices really work? What is happening in our brains when we use them? Do they integrate into our regular sensory space?

These questions have practical implications to the potential for these devices in complex tasks and in integration into our perception of the world, as according to traditional neuroscience the potential for these devices is strictly limited, especially for restoring a sense damaged from birth. In this work we will explain these theoretical limits and show how the theories they are based upon are challenged by recent results which offer significant potential for visual rehabilitation and assistive augmentation.

3. The traditional models

We will begin by presenting two of the basic theories of traditional neuroscience. (A) **The sensory brain**: The common view was that the human brain is divided into a “visual cortex”, “auditory cortex” and so on by the sensory modality that elicits it, and into higher-order multisensory areas integrating information from these unimodal cortices. (B) **The rigid brain & Critical periods**: In early childhood there are "critical periods" in which the brain is particularly plastic, and during which lack of sensory information may prevent the proper functional specialization and development of regions normally involved with that sense. Once development has passed these critical periods the human brain becomes fixed and there is little or no plasticity in adulthood.

These theories forecast a pessimistic outlook for sensory rehabilitation. If the brain is truly sensory-based & rigid after critical periods, then learning new senses should be impossible. Once a sensory input channel is lost, so is access to brain regions linked to it, and critical periods prevent their use even if we restore function to them later in life. This was supported by the disappointing results of sight restoration attempts, in which even patients whose vision was fully restored failed to gain many visual functions [9].

4. Plasticity and Cross-Modal Plasticity

One of the first changes to these established theories was the discovery of adult plasticity, and compensatory cross-modal plasticity - the ability of sensory regions whose input channel was lost to be plastically recruited for other purposes even in adulthood. E.g. it is well established that the 'visual' cortex of the blind is recruited to process other modalities and even cognitive tasks such as language and memory [5].

On the one hand, this plasticity enables sensory regions to be recruited for other tasks, and aids coping with the sensory loss by boosting compensatory capabilities [5]. But at the same time, it may interfere with sensory restoration and augmentation efforts by altering the visual cortex's original functions. Even if we could return the vision-deprived regions to process visual input, it might impair their use for functions for which these areas were cross-modally recruited, like memory.

5. Cracks in the traditional theories

It is well established that the visual cortex is comprised of different functional areas, each processing different aspects of vision. E.g. the FFA shows preference for faces, VWFA for visual representation of language etc. Surprisingly, several of these basic brain regions which were once considered "visual" were recently shown to retain their function even without visual experience despite missing the critical periods. Thus, the LOC for tactile & SSD object location and perception, the VWFA for reading braille or reading via the vOICe, MT for non-visual motion (reviewed in [3,7]). Even non-traditional senses such as echolocation were able to activate the visual rather than the auditory cortex [8]. These results show that **the visual information is processed also in the traditional "visual" areas even when received via other senses with SSDs**.

6. The brain as a task machine

These results have led to the hypothesis of the brain as task-oriented and sensory-modality independent, or in other words a "task machine" [3,7]. The brain regions can still perform their specific task if they receive the relevant information, regardless of the sensory channel in which it was sensed. Thus, the lack of visual experience should not limit the task-specialization of the visual system, despite its use for various functions in the blind, and may still be able to retain its functional properties via other sensory-modalities. This is very encouraging for the potential for visual rehabilitation.

7. Beyond vision

The implications of this view for assistive augmentation go far beyond the examples we just discussed from vision. According to this theory, if we have a region devoted to shapes, it does not matter what sensory channel the shape information came from, or even if it is one of the "classical" sensory channels available to humans, as long as the information is contained within the signal. This in turn offers us a great flexibility in how to convey information, and will potentially enable us to process input which is normally not available.

8. Shared sensory space

A critical step for augmenting human senses is the ability to integrate this new information with existing senses. For example, CC, a low vision vOICe SSD user reported the ability to integrate information coming from the vOICe with her residual vision [10]. Others have recently shown evidence of a shared sensory workspace using vision and auditory-to-vision rotation and mismatch [11] paradigms. This enables the user to integrate input from several different input channels in parallel creating supra-additive effects [3].

9. The importance of training

One of the clearest insights from this approach and from our experience with SSD users is the importance of training. While even an hour of SSD training is reflected in the brain, true mastery of these devices takes a lot of time and work. One does not learn to see in a day. The brain must learn to properly process the information it is offered before it can truly make full use of it (See [10] for good examples of this).

Conclusions

We suggested here that the theory of the task-machine brain offers a potential neural basis for processing augmented sensory information and integrating it into our regular sensory perception. This optimistically affects the potential limits of assistive augmentation, and understanding of these organizational brain principles may help us optimize future assistive tools. At the bottom line, the theoretical potential for sensory augmentation is there – now we need to learn to tap it.

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