REVIEW

CURRENT OPINION

The brain as a flexible task machine: implications for visual rehabilitation using noninvasive vs. invasive approaches

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Purpose of review
The exciting view of our brain as highly flexible task-based and not sensory-based raises the chances for visual rehabilitation, long considered unachievable, given adequate training in teaching the brain how to see. Recent advances in rehabilitation approaches, both noninvasive, like sensory substitution devices (SSDs) which present visual information using sound or touch, and invasive, like visual prosthesis, may potentially be used to achieve this goal, each alone, and most preferably together.

Recent findings
Visual impairments and said solutions are being used as a model for answering fundamental questions ranging from basic cognitive neuroscience, showing that several key visual brain areas are actually highly flexible, modality-independent and, as was recently shown, even visual experience-independent task machines, to technological and behavioral developments, allowing blind persons to 'see' using SSDs and other approaches.

Summary
SSDs can be potentially used as a research tool for assessing the brain's functional organization; as an aid for the blind in daily visual tasks; to visually train the brain prior to invasive procedures, by taking advantage of the 'visual' cortex's flexibility and task specialization even in the absence of vision; and to augment postsurgery functional vision using a unique SSD–prostheses hybrid. Taken together the reviewed results suggest a brighter future for visual neuro-rehabilitation.

Keywords
blindness, brain organization, multisensory integration, sensory substitution, vision

INTRODUCTION

Severe visual impairments, varying in cause and severity, affect over 200 000 000 people worldwide, constituting a major clinical and scientific challenge to develop effective visual rehabilitation techniques. One such class of invasive approaches aims at restoring the function of the peripheral visual system, for instance using artificial retinal prostheses ('bionic eyes' [1▪,2▪,3▪▪,4,5]), using gene therapy [6▪▪] or by transplantation of photoreceptors [7▪] (see [8▪,9▪] for recent reviews of the various methods). However, these promising solutions are facing huge challenges as they have not yet achieved sufficient technical capabilities, need to be tailored to the impairments' specific cause, are expensive and invasive and have, at least so far, very low-resolution end-result sight. An alternative and promising direction to follow, which was demonstrated to have a much better functional performance, is the use of sensory substitution devices (SSDs), which offer rehabilitation at the central nervous system level while bypassing the nonfunctioning peripheral components. SSDs are noninvasive human–machine interfaces, which, in the case of the blind, transform visual information into auditory or tactile representations using a predetermined transformation algorithm. Although this is not intuitively thought of as 'real' vision, and usually

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Curr Opin Neurol 2012, 25:86–95

DOI:10.1097/WCO.0b013e32834ed723

KEY POINTS

- Sensory substitution devices (SSDs) encode visual information to auditory or tactile representation, thus enabling the blind and the visually impaired to 'see' in a noninvasive manner with their intact senses, in principle better than any approach available so far.
- Brain areas are highly flexible sensory-independent task-specific operators, and given adequate training are capable of changing the type of sensory input they use to retrieve task-relevant information within a matter of hours to weeks.
- SSDs may be combined in a synergistic fashion with the most advanced retinal prostheses, 'bionic eyes', which currently are still lacking in terms of resolution and rehabilitative power, in order to train the brain to 'see' prior to surgery, and to augment the prostheses' capabilities post-surgery.
- The combination of different visual rehabilitation approaches detailed here may aid the entire spectrum of visual impairments, by tailoring the optimal solution for each individual or group of patients.

lacks visual qualia (though see [10••,11•] for anecdotal results of acquired qualia), if one conceives 'seeing' as the ability to create a mental representation of the shape, surface properties, and location of surrounding objects and to interact with them in a manner comparable to a normally sighted person [12], then SSDs enable the blind to 'see' using their intact senses, similarly to visual imagery or dreaming (for a discussion on this subject see [10••]).

The purpose of the current review is to discuss potential clinical implications of vision substitution, focusing on their use as stand-alone devices, but also suggesting how SSDs might serve in conjunction with the invasive approaches, before or after the clinical intervention, to maximize visual rehabilitation. We will also present an exciting emerging view on the brain's functional organization, which goes against the conventional textbook view, partially based on evidence gained using SSDs; and will outline how this view holds promising prospects for rehabilitation in adulthood despite discouraging past attempts.

THE TRADITIONAL VIEW OF BRAIN ORGANIZATION GOES AGAINST SIGHT RESTORATION

In traditional neuroscience, the common view is that the human brain is divided into the 'visual cortex', the 'auditory cortex' and so on according to the sensory modality which arouse it, and into higher-order multisensory areas integrating information from these unimodal cortices (the sensory division-of-labor principle [13]). Even today the vast majority of textbooks emphasize explicitly and implicitly this organizational principle, in spite of various quite influential studies suggesting this view is not fully correct [14–16].

In the blind, it is well established that the 'visual' cortex has been plastically recruited to process other modalities, and even language and memory tasks (reviewed in [17••,18•]). Many of these changes start to occur within days following the onset of blindness [19], and therefore affect not only the congenitally blind but also, though probably to a different extent, early and late blind individuals. This plasticity may act as a double-edged sword (reviewed in [17••]). On the one hand, it helps the blind to better cope with blindness by supporting compensatory capabilities [20,21,22•,23–25], but at the same time, it might interfere with sight restoration efforts, by disturbing the visual cortex's original functions. Unfortunately, this discouraging forecast for sight-rehabilitation practicability was supported by several cases of medical sight restoration (e.g. by cataract removal) [26,27]. Although visual information was available to their brain, and some visual abilities were restored quite fast (mostly dorsal stream functions such as movement detection and visual localization), these individuals showed very serious deficits in practical visual perception tasks such as shape and face recognition, 3D perception, and figure-background segregation which is critical for accomplishing even the simplest everyday task in natural environments [26–28]. It seems as if the regained visual input was offered to a brain that was wholly unpracticed at analyzing and interpreting it; and visual experience gained at this stage without supervised explicit training may have come too late or too little.

THE BRAIN AS A HIGHLY FLEXIBLE SENSORY MODALITY-INDEPENDENT TASK MACHINE VIEW

However, a growing body of evidence has accumulated in the past decade that casts doubts on the canonical view of the sensory-specific brain. This evidence demonstrates that, in both sighted and blind individuals, the occipital visual cortex is not purely visual and that its functional specialization is independent of visual input (partially reviewed in [29•] and detailed below), leading to the hypothesis that the brain is task-oriented and sensory modality-independent [30•,31••]. Furthermore, recent evidence has shown that in some cases the same specialization emerges even without any visual experience or memories (as assessed by studying the fully congenitally blind; [30▪,31▪▪,32,33,34▪,35,36,37▪]), and that this emergence occurs rapidly once the brain is trained to interpret the relevant information, suggesting that the cortical functional specialization can be attributed at least partially to innately determined constraints [31▪▪]. The task selectivity was demonstrated for various tasks and areas, including selectivity to nonvisual motion in visual middle temporal area [33,34▪,38–41], to tactile object recognition in the lateral-occipital complex (LOC) [14,15,42▪,43,44,45▪,46,47▪,48]; and to sound localization in the middle-occipital gyrus (MOG) [37▪,49▪▪]. These results are summarized in Fig. 1c.

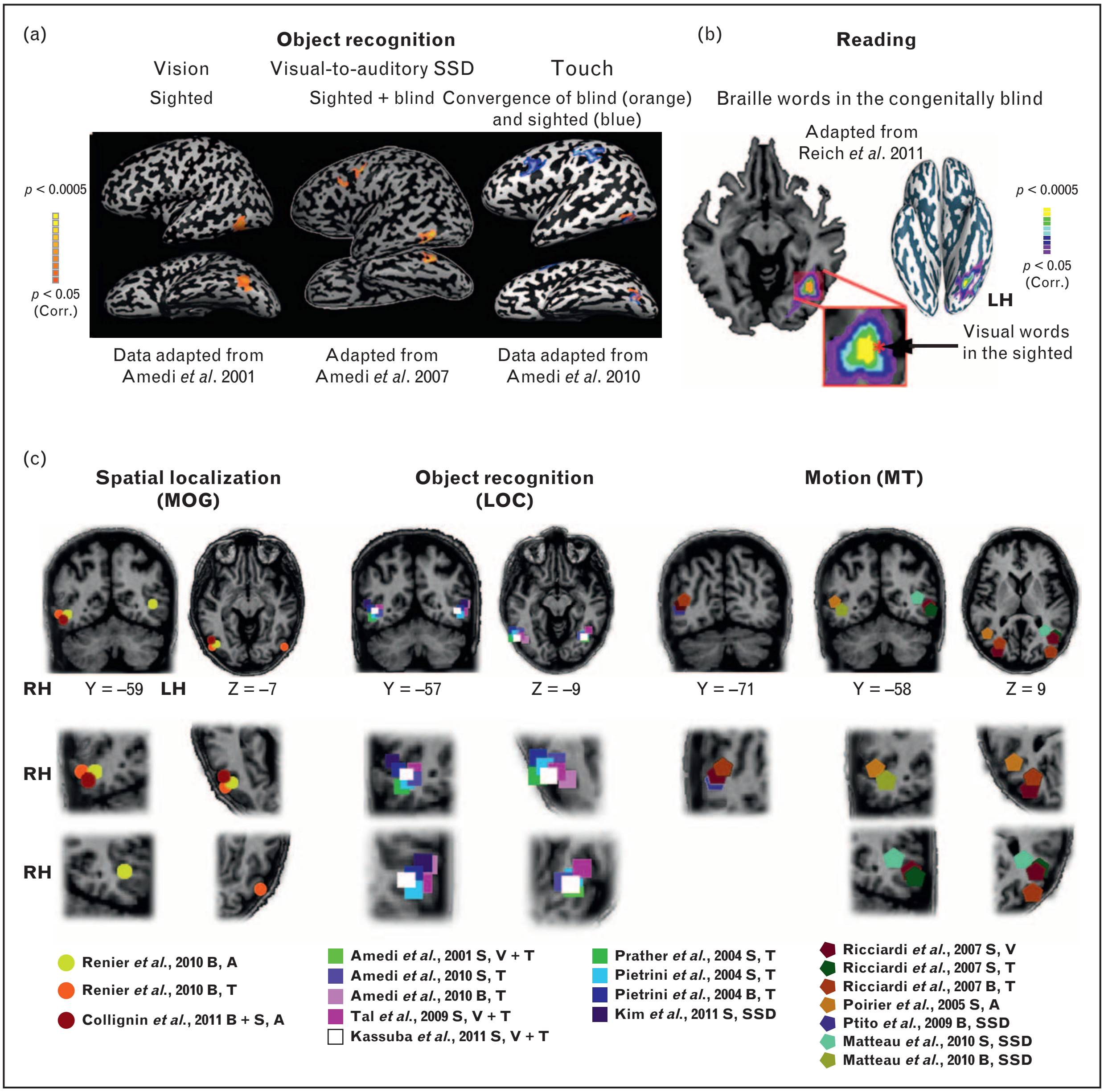

FIGURE 1. Modality-independent task-specific activations in various areas of the 'visual' cortex. (a) Activation of the lateral-occipital complex (LOC) during object recognition using vision, touch and visual-to-auditory sensory substitution. Image adapted from [32]; data adapted from [15,42▪]. (b) Specific activation of the visual word form area (VWFA), the site of activation to visual written words in the sighted, during tactile Braille reading in the congenitally blind. Adapted from [30▪]. (c) Summary of the reported middle-occipital gyrus (MOG), LOC and middle temporal (MT) modality-independent task-specific activations, during spatial localization, object recognition and motion tasks, respectively. Activations are presented on slices of Talairach-normalized brain. Only works that reported group-level coordinates are presented. For each work the participating patients (blind/sighted) and the modality of stimuli used during the experiment is detailed. Abbreviations: A, audition; B, blind; S, sighted; SSD, sensory substitution device; T, touch; V, vision.

Interestingly, even listening to sound echoes activated the visual rather than the auditory cortex in blind echolocation experts [50▪].

A causal support for the hypothesis of the task machine brain comes from the auditory cortex in the deaf as well [51▪▪] (for reviews on this subject see [52▪,53▪]).

CRITICAL CONVERGING EVIDENCE TO THIS VIEW USING SENSORY SUBSTITUTION DEVICES

An ultimate way to test the highly flexible task-rather-than-sensory-selectivity view is to use SSD approaches. For instance, we recently [30▪] used the tactile Braille script, apparently the most primitive form of vision-substitution transforming solely written letters, to show that the Visual Word Form area (VWFA), a visual area that processes written language in the sighted [54▪▪], is also the peak of selective activation to Braille words in the congenitally blind [30▪,55▪] (Fig. 1b). Thus, the VWFA specializes in the perception of written words, irrespective of the sensory channel through which they are presented, and even regardless of visual experience.

Using advanced SSDs that are capable of transforming more complex visual scenes, it is possible to test the sensory-modality-invariance of other occipital areas dedicated to the processing of more complex visual categories (e.g. selectivity to faces in the fusiform face area). For instance, the lateral-dorsal part of the LOC (LOtv) was shown to be activated by auditory stimuli which conveyed detailed shape information delivered by 'the vOICe' SSD [32,56] (Fig. 1a), but not by the typical sounds which objects produce, without, however, affording any shape information [32,57]. This strengthens the notion that the LOtv specializes in the processing of objects' shape irrespective of the input sense.

Finally, the most fundamental large-scale division of labor of the visual cortex, between the ventral 'what' and the dorsal 'where and how' processing streams ([31▪▪]; Fig. 2a); and the animate–inanimate large-scale segregation of the ventral stream ([36]; Fig. 2b), were also shown, using a visual-to-auditory SSD and an auditory task, respectively, to prevail independently of input modality and visual experience.

If this hypothesis of the highly flexible task-oriented sensory-independent brain applies, the

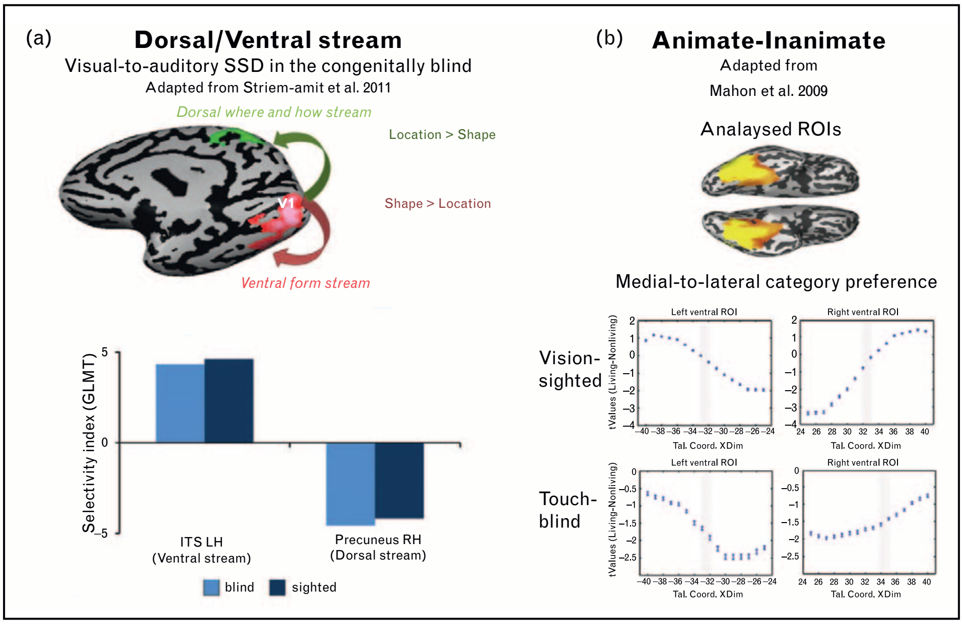

FIGURE 2. The specialization of the cortical 'visual' streams is independent of visual input and visual experience. (a) Upper part: task-specific activation for shape (vs. location, in orange) in the 'visual' ventral stream and location (vs. shape, in green) in the 'visual' dorsal stream using a visual-to-auditory SSD in congenitally blind individuals. Bottom part: selectivity indices (the difference between the T values of the shape task vs. the location task sampled from the peak ROIs of the shape and location activation, demonstrating the task specificity of the visual stream (inferior temporal sulcus, ITS) and dorsal stream (precuneus) in both congenitally blind and sighted patients. Adapted from [31▪▪]. (b) Medial-to-lateral ventral occipito-temporal preference for animate vs. inanimate stimuli, in sighted and congenitally blind individuals using vision and audition respectively. Adapted from [36].

absence of visual experience should not limit proper task specialization of the visual system, despite its recruitment for various functions in the blind, and the visual cortex of the blind may still retain its functional properties using other sensory modalities. This is very encouraging with regards to the potential of visual rehabilitation.

SENSORY SUBSTITUTION DEVICES AS STAND-ALONE REHABILITATION DEVICES

The preference for a specific rehabilitation approach depends both on the type and severity of visual deterioration and on the site of the lesion along the visual pathways, and treatment should be tailored specifically to each individual or group of patients. Invasive approaches such as retinal prostheses, which use a signal processor to convert camera-captured visual information into patterned electrical stimulation directly on the retina, are making great progress in dealing with cases in which the visual system is mostly intact but the eye itself is damaged [1▪,2▪,3▪▪,4,58]. However, in cases when the rest of the visual system, past the ganglion cells, is damaged such approaches would not be helpful to sight restoration, leaving SSDs as the main therapeutic approach. For these patients, SSDs can serve as stand-alone aids for daily use, providing otherwise nonexisting visual capacities such as understanding of shape, color and location. Additionally, SSDs can serve as low-cost aids accessible to the vast majority of the world's visually impaired population, who reside in developing countries and have low accessibility to medical treatment [59▪] (WHO fact sheet N282 2011).

Whereas the concept of SSDs has existed for several decades ([12]; see illustration in Fig. 3a), many stumbling blocks stood in the path of their adoption. They were expensive, cumbersome, hard for the blind users to operate and not efficient enough for real world use – and thus to the best of our knowledge no SSD has been adopted as a main tool by a wide blind community. Psychological and social factors, such as reluctance to try new devices, and the lack of supervised training procedures might play an additional main role for this limited adoption of SSDs.

However, recent technological advances have enabled major progress in the abilities of SSDs and removed many of these stumbling blocks for both novel SSDs and improvements in veteran ones. New types of information are easily collected using advanced sensors for surround sound and distance information [60▪]. Miniaturization of components, and especially processors, has enabled SSDs to shrink from closet-size devices [12] into smart phones ('The vOICe' website). Together with the wireless revolution this enables devices to be both more mobile and less obtrusive. The availability of parts and the option of building them into existing devices have dropped the prices dramatically, especially for auditory-based devices – a factor which makes them more easily available to the blind population. Thus, one can now download a program (e.g. 'the vOICe' SSD can be downloaded for free from the internet) and use it with a lightweight inexpensive webcam, a pre-existing smart phone or laptop and simple earphones (a discretely worn mobile set-up is demonstrated in Fig. 3b). Moreover, advances in interface make these devices more accessible to the blind users and enable them to operate the device without the help of sighted.

Valuable experience garnered from the veteran SSDs has led to the attempt to improve the user experience by using more pleasant stimuli and better training programs.

Finally, as computer vision becomes more advanced and applicable, it can be combined with an SSD interface. This will enable a more filtered and relevant version of the scene to be conveyed, and can be particularly useful for tasks such as object identification and scene segmentation.

RECENT BEHAVIORAL ACHIEVEMENTS USING SENSORY SUBSTITUTION DEVICES

Whereas full implementation of new advanced technologies still lies in the future (although novel prototypes are already making their first steps [61–65]), some currently available devices have already proven to provide the blind with various exciting visual capacities (see examples in Fig. 3c).

For instance, following a brief training, blind individuals were able to perform tasks relevant to understanding the traits of objects placed before them: point at targets, recognize patterns [67]; perform motion discrimination and tracking tasks [33,68]; extract depth cues from SSD-conveyed images, estimate object distance [69▪] and even to recognize objects [31▪▪].

Dealing with whole environments, congenitally blind individuals were able to detect and avoid obstacles during effective navigation within a human-sized obstacle course [66▪], and to recognize different virtual routes [70▪].

These results are reinforced by results in similar tasks (object recognition; size, orientation and location detection; reaching; scene recognition; etc.) from larger groups of blindfolded sighted patients [31▪▪,71–73], and in actual behavioral tasks (e.g. finding an object in a room, following a twisting line on the ground, pairing socks, differentiating

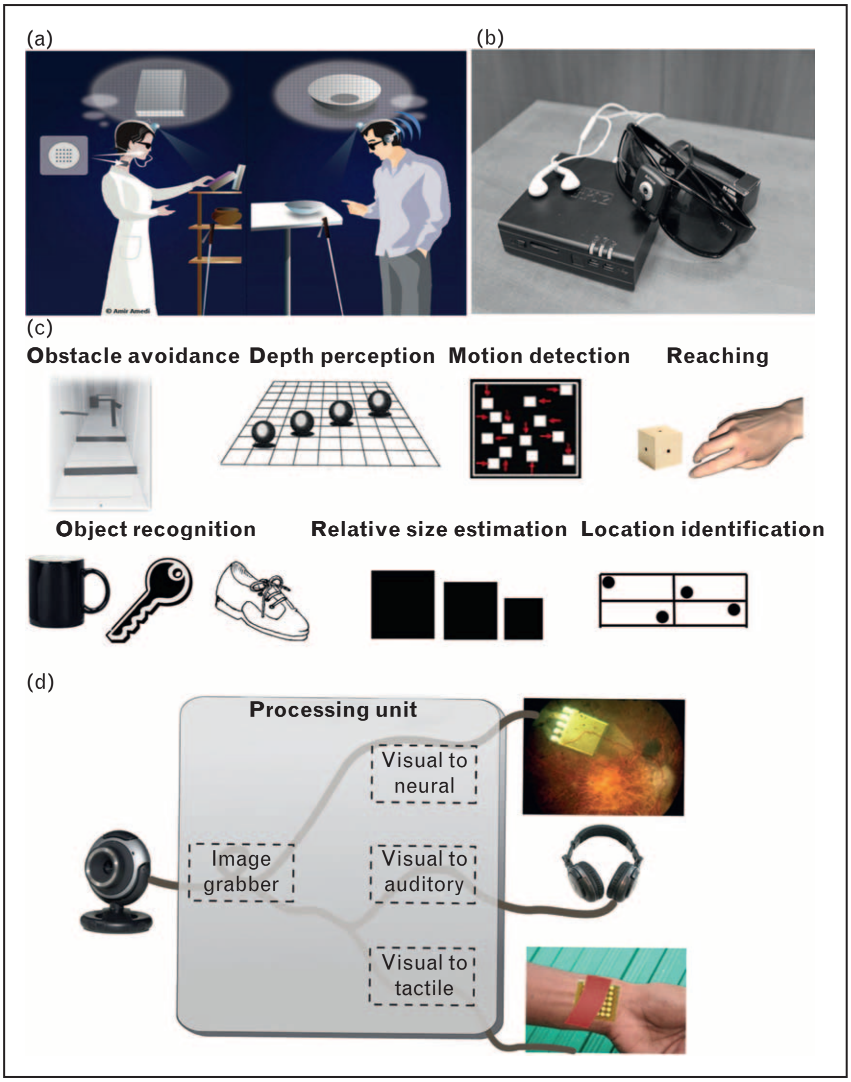

FIGURE 3. Visual rehabilitation using sensory substitution devices (SSDs). (a) Illustration of visual-to-auditory and visual-to-tactile SSDs, used to convey visual information to the blind through their intact senses. Adapted from [9▪]. (b) A mobile kit for visual-to-auditory SSD usage includes a lightweight inexpensive webcam worn on eyeglasses, computing device such as a laptop, and earphones. (c) Examples of tasks which were successfully performed using SSDs. 'Obstacle avoidance' is adapted from [66▪]. (d) Visual rehabilitation device combining retinal prostheses and SSDs. The system includes a camera consistently capturing images of the surroundings; a processing unit which converts the visual information into auditory or tactile sensory substitution representation and neural stimulation conveyed by the retinal prosthesis electrodes. The system can be used as a 'sensory interpreter' postsight-restoration to help teach the cortex how to see after prolonged blindness or for visual perception augmentation.

between different types of fruit, locating light sources, playing tag) performed as a demonstration by single users or small groups [31▪▪,60▪,61,74,75].

Anecdotal testimonies about SSD usage in everyday life can be found in the The vOICe User Group and in user blogs such as 'The Darkness Escapee'. An exciting anecdotal demonstration of congenitally blind individuals recognizing facial expressions from our group can be found here.

The most striking demonstration of restored advanced functional 'vision' using SSD is the case of P.F. [9▪], a late blind woman who uses the vOICe visual-to-auditory SSD proficiently on a daily basis. She describes her ability to 'see shapes and placements of the objects'; she can 'tell eye sockets, brows and can tell if they have long hair, curly hair'; at first she had only 'flat' visual experiences of edges and shading but following prolonged experience with the device she developed depth perception; she has a visual qualia using the device and she emphasizes that 'there is true light perception generated by The vOICe' [9▪]. Notably, P.F.'s ability to 'see' with the

SSD was temporarily disrupted by a transcranial magnetic stimulation applied to her occipital lobes, providing causal support to the hypothesis of the brain's task specificity [76]. In line with this, a few late blind individuals have reported the emergence of subjective visual qualia using a visual-to-tactile SSD, and this sensation correlated with activity of the occipital cortex [10▪▪].

SENSORY SUBSTITUTION DEVICES CAN BE USED FOR VISUAL TRAINING PRIOR TO SIGHT RESTORATION

According to the hypothesis of the highly flexible task machine brain, with adequate explicit training any brain area can change the type of sensory input it uses to retrieve task-relevant information within a matter of hours to weeks. Therefore, by taking advantage of the occipital cortex's stronger connectivity to other modalities in the blind, SSD-conveyed visual information can theoretically 'reopen' critical periods and induce adult plasticity to revert the visual cortex from performing compensatory tasks (e.g. memory and language; [19,21]) back to performing computations required for visual tasks, and therefore can be used to visually train individuals before sight restoration.

COMBINING SENSORY SUBSTITUTION DEVICES WITH RETINAL PROSTHESES AS A VISION REHABILITATION DEVICE

Following the success of our training program in enabling complex high-resolution 'visual' tasks based on sounds and touch, we suggest a postoperation system combining an SSD with retinal prostheses ('vision rehabilitation device'; VRD, illustrated in Fig. 3d). Such a system will include a camera consistently capturing images of the surroundings and a processing unit. This unit converts the visual information into auditory SSD representation and neural stimulation conveyed by the prostheses' electrodes. Information about the surroundings would thus be received in parallel from the prosthesis as well as from the SSD. In such a device, the SSD would serve as a 'sensory interpreter' providing explanatory input to the visual signal arriving from the alien invasive device. We believe this dual, synchronous information is expected to significantly increase the speed of rehabilitation. At a later stage, the SSD can be used to provide input beyond the maximal capabilities of the prostheses. However, whereas this approach has a great rehabilitation potential, it still requires validation in controlled experiments with implant patients using such a hybrid approach.

VISUAL PERCEPTION AUGMENTATION USING SENSORY SUBSTITUTION DEVICES

Sensory substitution devices can additionally be used for visual perception augmentation for either individuals who have impaired natural vision or those who use retinal prostheses (demonstrated in Fig. 3d). For instance, the resolution of 'the vOICe' SSD stimulation [55▪] can be up to two orders of magnitude higher than that of the currently available neural stimulation [2▪,4]. This possibility is supported by the subjective descriptions of C.C., a woman who has residual eyesight and uses a visual-to-auditory SSD on a daily basis: she claims that her SSD perception and her visual perception share a single space, but with the SSD providing more details such that a more complex perception of the scenery is generated [9▪]. Additionally, SSDs can augment residual low vision resulting from decreased visual field by adding peripheral information. Complementary color (which is particularly important for figure–ground segregation) and depth information, which are currently not conveyed through retinal prostheses, might be also provided by future SSDs.

Importantly, at any time point, and according to the specific task and environment, the blind user can choose the optimal combination of the available means of delivering information. For instance, a tactile SSD might be useful for detecting movement and speed; an auditory SSD for detailed shape information and extraction of high-resolution features; and the prostheses can provide vivid visual sensation.

OUTSTANDING ISSUES

The described high-level functional abilities using SSDs, as well as reported evidence that the adult brain retains an impressive capacity for visual learning [77], encourage the further development of advanced devices. Especially important are the use of more pleasant stimuli, the delivery of complementary color and depth information, the combination of computer vision techniques to ease the stimuli interpretation and comfortable ergonomic design that will fit daily use. It will be fascinating to see what level the users will be able to reach with further prolonged experience, with technology opening more and more doors. From a scientific perspective, it will be especially valuable to assess the level of acquired visual abilities in the congenitally blind despite what is considered to be an irreversible critical period. The delivery of color through SSDs would be of particular interest in this regard, as this feature is unique to the visual modality and thus considered as a concept that could not be understood or perceived by the congenitally blind.

In order to quantitatively evaluate different SSDs, especially the new emerging ones, and compare SSD vision to 'real' eyesight, standard visual tests should be performed. For instance, it was shown using the 'Snellen' standard test that users of a visual-to-tactile device had relatively poor 'visual acuity' [78]; however, this can be attributed to the low technical resolution of that device and it will thus be interesting to test the functional acuity with visual-to-auditory SSDs with greater technical resolution.

Importantly, we do not claim that SSDs are the optimal rehabilitation method and that they should receive precedence over others. Rather, we suggest that it holds the potential to aid specific sub-groups among the blind and stress the importance of combining the various methods. For instance, the suggested combination between SSDs and retinal prostheses should be thoroughly evaluated in the future, to test whether SSDs indeed facilitate and improve the practical vision.

Critically, one must remember that even with the technologically-wise best rehabilitation technique, individuals are not expected to spontaneously acquire high-level vision following prolonged blindness. Therefore, a special emphasis should be given to the development of training methods, and for assessing their efficiency [74,79]. A good training would have to be gradual, based on constant explicit feedback, personally tailored to fit the individual's specific needs, and provide also psychological and motivational support. In the case of the early blind, a unique challenge would be teaching them visual principles (e.g. point of view, shading, perspective) that are required to understand visual scenes and are not familiar to them.

We believe that the combination of explicit supervised training and technical improvements will lead to widespread use of visual rehabilitation approaches among the blind population.

Finally, before any rehabilitation approach can be used on a wide scale it will also be important to investigate whether the recruitment of the occipital cortex of the blind back to processing visual information would cause reduction in its processing of high-order functions such as language and memory; and whether it will lead to decreased behavioral abilities in these tasks.

CONCLUSION

We review here compelling veteran and novel evidence, using visual impairments as a cognitive model, that counters the canonical sensory-specific view of the brain and suggests instead that the visual cortex's functional specialization emerges regardless of visual input or experience. This is encouraging in terms of the potential to restore vision following prolonged blindness. Indeed, we highlighted the capability of SSDs as stand-alone devices to help the blind, even congenitally, to 'see'. However, whereas both SSDs and neuro-prosthetics are commonly discussed as distinct approaches [3■■], we suggest that their combination will most probably dramatically enhance neuro-rehabilitation and augment the partially restored vision in a synergistic fashion. Pending further research, these approaches might hold great potential also for other neurological impairments [80■,81■].

Acknowledgements

The work was supported by a career development award from the International Human Frontier Science Program Organization (HFSPO); Israel Science Foundation (grant number 1530/08); a European Union Marie Curie International Reintegration Grant (MIRG-CT-2007-205357); James S. McDonnell Foundation scholar award (grant number 220020284); the Edmond and Lily Safra Center for Brain Sciences Vision center grant (to A.A.); and by the Samuel and Lottie Rudin Foundation support (to L.R.).

Conflicts of interest

There are no conflicts of interest.

REFERENCES AND RECOMMENDED READING

Papers of particular interest, published within the annual period of review, have been highlighted as:
■ of special interest
■■ of outstanding interest
Additional references related to this topic can also be found in the Current World Literature section in this issue (pp. 101–102).

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In this study on one of the largest groups of visual prosthesis recipients to date, it was shown that artificial vision via the Argus-2 retinal implant indeed augments information from existing residual vision in a spatial-motor task. The task included locating squares on a surface in front of the patient with and without the device to asses the level of improvement.

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This study presents an updated status report on the various attempts to create retinal implants and the currently unsatisfying behavioral achievments acomplished with them, while focusing on the next stage for one of the implant groups (The Boston Retinal Implant).

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7. ■ Yang Y, Mohand-Said S, Léveillard T, *et al.* Transplantation of photoreceptor and total neural retina preserves cone function in P23H rhodopsin transgenic rat. PloS one 2010; 5:e13469.

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