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Is There a Future for Sensory Substitution Outside Academic Laboratories?

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Abstract

Sensory substitution devices (SSDs) have been developed with the ultimate purpose of supporting sensory deprived individuals in their daily activities. However, more than forty years after their first appearance in the scientific literature, SSDs still remain more common in research laboratories than in the daily life of people with sensory deprivation. Here, we seek to identify the reasons behind the limited diffusion of SSDs among the blind community by discussing the ergonomic, neurocognitive and psychosocial issues potentially associated with the use of these systems. We stress that these issues should be considered together when developing future devices or improving existing ones. We provide some examples of how to achieve this by adopting a multidisciplinary and participatory approach. These efforts would contribute not solely to address fundamental theoretical research questions, but also to better understand the everyday needs of blind people and eventually promote the use of SSDs outside laboratories.

Keywords

Sensory substitution devices, limitation, sensory deprivation, rehabilitation, ergonomics, blindness

1. Introduction

In pursuing visual rehabilitation, invasive and non-invasive solutions are explored. Invasive interventions, such as implanted neuroprostheses, rely on the integrity of visual pathways and brain regions. For example, several groups are currently developing artificial retinas aimed at inducing visual phosphenes through electrical stimulation of the remaining retinal cells (e.g., Ohta, 2011; Rizzo *et al.*, 2007). Since such invasive approaches attempt to stimulate the deficient sensory system directly, the natural reorganization processes that oc-

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cur in the blind may interfere with these procedures (Collignon *et al.*, 2011a). As such, these prostheses are intended mainly for late-onset blind individuals, since the development of the visual system and previous visual experience would be a prerequisite to trigger and interpret the visual percept induced by the stimulation of neural tissues. For instance, it has been demonstrated that the optic nerve and optic chiasm of congenitally blind individuals are considerably altered (Levin *et al.*, 2010; Park *et al.*, 2009; Ptito *et al.*, 2008). At the cortical level, a study demonstrated that the ability to elicit phosphenes by applying transcranial magnetic stimulation (TMS) directly over the occipital area is dramatically reduced in subjects with a high degree of visual deafferentation, especially in those without a history of visual experience (Gothe *et al.*, 2002). Similarly, studies exploring visual skills in individuals who have recovered their sight after prolonged blindness (Fine *et al.*, 2003; Gregory, 1963) show that they present with marked visual deficiencies, particularly when interpreting complex visual inputs or scenes. Indeed, the loss of visual abilities following early visual deprivation, and the consequent recruitment of occipital regions by non-visual inputs, may hinder the re-acquisition of the original visual function *via* the prosthetic implant (Collignon *et al.*, 2011a, 2013). It was recently demonstrated that early blind individuals who recovered their sight in adulthood still had robust responses to auditory stimulation in their visual cortex even many years after sight recovery (Saenz *et al.*, 2008). A similar phenomenon can be observed in deaf individuals: visual activation of the auditory cortex has been demonstrated to impair the chances of a successful outcome for cochlear implantation (Doucet *et al.*, 2006; Lee *et al.*, 2001; Strelnikov, 2013).

By contrast, sensory substitution devices (SSDs) are non-invasive aids that can be employed regardless of the different clinical features of blindness as they aim to leverage behavioral compensation and brain reorganization in favor of the spared senses. More specifically, sensory substitution implies the use of one spared sensory modality to supply information normally gathered by the impaired sense (Bach-y-Rita *et al.*, 1969). As is the case for traditional visual aids, with sufficient training some elementary sensory substitution can be achieved through simple tools. For instance, blind people can learn to use the long cane as an extension of their body to perceive tactile information about surrounding surfaces and, in turn, use it to locate objects and obstacles in peripersonal space (Serino *et al.*, 2007). Another example of visual-to-tactile substitution extensively used by blind individuals is Braille reading, in which an experience-dependent enhanced tactile discrimination ability (Wong *et al.*, 2011) is used to fluently read raised-dot patterns substituting for visual letters. Although these aids represent a core component of specific programs of schools for the blind in many countries, there are currently no reliable statistics on their use among the blind population. According to a survey on the use of assistive aids, there are approximately 130 000 white cane users and 59 000 Braille readers in the United States alone (National Health Survey on Disability; Russell *et al.*, 1997).

In recent years, due to the explosion of information technology, several systems have been developed for visual substitution in addition to those described above. Since the seminal work of Paul Bach-y-Rita, who created the first SSD translating visual information into tactile input (Bach-y-Rita *et al.*, 1969), a number of visual-to-tactile (e.g. TDU, Bach-y-Rita *et al.*, 1998) and visual-to-auditory (PSVA, Capelle *et al.*, 1992, 1998; vOICe, Meijer, 1992; VIBE, Auvray *et al.*, 2005; EyeMusic, Abboud *et al.*, 2014) SSDs have been designed. All these systems comprise three main components: (i) a sensor capturing the specific form of energy (e.g., a camera for light), (ii) a transformation algorithm transcoding the acquired information into auditory or tactile patterns, and (iii) a stimulator delivering the conversion outcome to the user.

Besides their potential for rehabilitation purposes, SSDs offer the fascinating opportunity to study the phenomenology of perception in one modality through the stimulation of another sense. Accordingly, these devices have been extensively employed in behavioral and neuroimaging studies of healthy and blind volunteers to investigate a number of fundamental issues in cognitive neuroscience, such as perceptual learning (e.g. Kim and Zatorre, 2008; Levy-Tzedek *et al.*, 2012a), cross-modal plasticity (e.g. Amedi *et al.*, 2007; Collignon *et al.*, 2007, 2009a, 2011b; Ptito *et al.*, 2005) and the 'supramodal' organization of the brain by showing how a region typically considered modality-specific (e.g. visual areas) can be recruited to process the same cognitive operation but from a different sensory domain (e.g., auditory, tactile — see Reich *et al.*, 2012 for a recent review of the literature).

Neuroimaging studies have consistently reported that the use of SSDs massively recruits the occipital cortex in early- (Amedi *et al.*, 2007; Kupers *et al.*, 2010; Ptito *et al.*, 2005) as well as late-acquired (Amedi *et al.*, 2007; Merabet *et al.*, 2009) blindness in a cross-modal fashion. A TMS study showed that a virtual lesion of the extrastriate cortex disrupted performance in a SSD-based shape recognition task in blind individuals but not in sighted controls, suggesting a functional cross-modal reorganization of auditory processing in this brain region (Collignon *et al.*, 2007). SSD studies focusing on concept representation have also provided evidence that some brain regions may subserve a specific type of information processing independent of the input sensory modality, promoting the idea of the brain as a 'flexible task machine' (Reich *et al.*, 2012), organized in metamodal/supramodal functional regions (i.e., analysing sensory information regardless of the input modality; Pascual-Leone and Hamilton, 2001; Ricciardi and Pietrini, 2011).

Despite the breakthrough in fundamental research achieved through SSDs, it is still not clear whether these devices have a bright future outside academic laboratories. In previous behavioral studies employing SSDs, after a sufficient period of training, both blind subjects and blindfolded sighted subjects perform successfully on a number of 'visual' tasks including pattern and object recognition (Arno *et al.*, 1999, 2001; Striem-Amit *et al.*, 2012a), object distance estimation (Renier *et al.*, 2005), localization tasks (Auvray *et al.*, 2007; Kim and Zatorre, 2008), and making reaching movements (Levy-Tzedek *et al.*, 2012b). However, although they have proven somewhat effective within the laboratory environment, SSDs are still not commonly adopted by impaired individuals, who seem to rely more on conventional and familiar aids to cope with their everyday life. In this opinion article, we discuss a number of issues that might be preventing SSDs from spreading further outside laboratories: ergonomic constraints; possible interference on compensatory recruitment of spared sensory modalities; cognitive overload in ecological environments; the relatively poor added value compared to other largely available and well-accepted sensory aids; and the lack of optimized and customized training protocols. We suggest that further consideration of these issues, and integrating laboratory experiments with more ecological case studies, may lead to a better understanding of the specific needs and expectations of blind individuals and, eventually, facilitate the diffusion and use of SSDs outside laboratories.

2. Device Ergonomics and Functionality

Ideally, SSDs should help blind and visually impaired individuals interact with their environment by supplying the missing relevant visual information without hampering the functioning of their remaining senses. In this perspective, ergonomics, as the "fundamental understanding of human behavior and performance in purposeful interacting sociotechnical systems" (Wilson, 2000), play a key role in researching and designing future devices for visually impaired individuals.

Studies in physical and rehabilitation ergonomics may also help address functional issues such as wearability, hygiene and aesthetics (Lenay *et al.*, 2003). For instance, all components should be small in size in order to be as unobtrusive as possible, and the hardware robust but light so that the SSDs can be carried for long time periods. Similarly, battery life should be optimized, since the autonomy of portable devices relies on how long they can be used without being plugged in. In addition, the appeal of a device's exterior design should not be neglected, since users of wearable assistive aids often deem cosmetic acceptability as more important than the technology's potential benefit (Golledge *et al.*, 2004).

A major but often underestimated problem with SSDs is the obtrusive interference with the spared senses. It is therefore crucial to design SSDs that are able to transmit information to the remaining senses without interfering with their functionality. For instance, instead of delivering information through conventional headphones, auditory information may be conveyed to the cochlea *via* bone conduction. Bone conduction delivers auditory stimuli without obstructing the external ear, allowing the user to also hear surrounding sounds (MacDonald *et al.*, 2006; Walker *et al.*, 2005). Although studies explicitly assessing possible interference between substituted information delivered *via* bone conduction and the surrounding sounds are required, the use of this technology appears promising.

Current devices substituting vision with tactile or auditory experience are likely to interfere, at least to some extent, with individual coping strategies and adaptive information processing. Since congenitally blind people may have developed adaptive strategies and behavioral compensation in their spared senses (Collignon and De Volder, 2009; Collignon *et al.*, 2006, 2009b; Gougoux *et al.*, 2004; Lessard *et al.*, 1998; Lewald, 2013; Wong *et al.*, 2011), it should be carefully investigated whether an auditory or tactile stimulation might produce cognitive overload or interfere with these 'augmented' senses.

A number of studies have evaluated the success of SSDs implementing such resolution levels by means of standard visual tests (Haigh *et al.*, 2013; Sampaio *et al.*, 2001; Striem-Amit *et al.*, 2012b). When measured as visual acuity, the performance with SSDs exceeded the WHO blindness acuity threshold (WHO, 2001). However, discussing visual acuity with reference to SSDs may be only marginally appropriate: the device's camera can be used as a zoom to capture a finer image, therefore the maximal distance for an observer to recognize a shape in front of him/her is only limited by the zooming capability of the system. More importantly, the user's experience and performance depends on how this information is perceived and used. As previously pointed out (Giudice and Legge, 2008; Loomis *et al.*, 2012), the devices' coarse resolution is mainly due to differences in sensory bandwidth among substituted and substituting modalities. Since vision spatial bandwidth largely exceeds that of the other senses, a simple isomorphic vision-to-touch or vision-to-auditory translation degrades and loses the information that is gathered through the camera. Thus, an important step would be to find more efficient and intuitive ways to map different modalities, rather than quantifying pseudo-visual acuity.

Although these resolution levels might perform well in laboratory settings, they are likely to fall short when dealing with the complex and rich visual information that is typical of ecological environments (Collins, 1985). Therefore, a fundamental question is the amount of information that should be selected and encoded from vision to the substituting modality, and whether this information should be simply translated or considerably pre-processed and simplified during the encoding. The conversion and transmission of each piece of information captured by the camera has the potential to create a noisy, unpleasant and overwhelming stimulation.

Cognitive ergonomics may help solve these issues. Since perception can be thought of as an inferential process (Heekeren *et al.*, 2008) where the perceiver has to make sense of the environment by interpreting and organizing the sensory information collected, the question is, what kind of support should the SSDs provide in order to maximize the decision process without overloading the cognitive system? Current SSDs encode the information present in the environment in the form of semi-abstract features (e.g., sound pitch for elevation) that the user should be able to use to recognize a structure in the world. For instance, an SSD may code ‘a vertical line and horizontal line’ into sound, enabling the user to infer that ‘there is an edge’, and to categorize the stimulus as an ‘L’. This approach has certainly proved useful in performing ‘visual’ tasks such as pattern recognition (Poirier *et al.*, 2007), distinction of two-dimensional shapes (Arno *et al.*, 1999, 2001), and object discrimination and localization (Auvray *et al.*, 2007; Kim and Zatorre, 2008; Proulx *et al.*, 2008; with blind individuals: Renier and De Volder, 2010; Striem-Amit *et al.*, 2012c).

However, given the structural complexity of the real world, such direct mapping of the visual environment into ‘one-to-one’ corresponding auditory or tactile information is likely to result in overly complex and noisy stimulation that is difficult to interpret. Even though some highly experienced, well-trained individuals have succeeded in using current SSDs in real-world situations (see supplementary video in Striem-Amit *et al.*, 2012b), the effort required to interpret the perceived information is likely to result in cognitive overload. Therefore, despite the fact that ‘parallel’ whole-object level processing is possible, it may not be optimal. New substituting devices may benefit from selecting only a subset of predetermined useful information in a preliminary step aimed at finding a simplified structure within the environment. These systems may deal more effectively with complex tasks, such as discrimination between two items of the same category or recognition of texture changes, by implementing computer vision algorithms such as figure/background segregation, selection of relevant pieces of information, and basic categorization. For example, future SSDs may benefit from the implementation of algorithms enabling the user to recognize a person before he/she talks, or to find a specific piece of furniture in a room depending on the specific needs of the moment. The idea of a system designed to provide rich and well-processed information to the user, acting as a smart and informed guide through the world, resembles more closely augmented reality, defined as “all cases in which the display of an otherwise real environment is augmented by means of virtual objects” (Milgram and Kishino, 1994), than the current concept of sensory substitution.

Drawing on cognitive ergonomics, we suggest that successful rehabilitation and prosthetic devices should provide, according to the specific task or situation at hand, either a relatively unprocessed and reduced amount of information, as traditional aids do, or rich and highly pre-processed information. While assistive devices offering simplified cues about the environment are already available and appreciated by the blind community, devices exploring the potential of augmented reality are still limited. There are some interesting attempts by private corporations at leveraging computer vision to create augmented reality platforms. A current example is the Google Glass (Google Inc., www.google.com; a wearable device that can be used with voice commands), which can connect to the Internet and is equipped with an integrated GPS system. Recently, a research consortium headed by the Polytechnic University of Turin, Italy has proposed a Google Glass' application for the deaf, GoogleGlass4Lis, translating online content provided in Italian into Italian Sign Language (LIS, Lingua dei Segni Italiana). An interesting attempt to compensate for visual impairment using computer vision is represented by the OrCam sensor (OrCam Technologies Ltd, www.orcam.com), a camera mounted on one's own glasses that is able to read printed text and recognize specific objects. In the future, the device's developers plan to equip the camera with features such as face and place recognition. This technology points in the direction we deem as more beneficial for the visually impaired, and supports the idea that augmented reality applications for the blind may be a promising avenue for future development and research.

In summary, although current SSDs poorly address some ergonomic constraints (Lenay *et al.*, 2003), it seems likely that further technological progress, perhaps achieved by collaboration with private entities, may lead to advanced devices more suited to meet physical, rehabilitation and cognitive ergonomic demands. At a time of exponential technological innovation, with private corporations making considerable investments in the development of human interface devices, more efforts should be dedicated to strengthening the links between the private sector, academia and the sensory deprived community in order to achieve synergy in the development of truly effective and commercially available sensory aids.

3. Accessibility of SSDs and Alternative Sensory Aids

When evaluating which specific device to use, people are likely to consider the relevance of its features to their individual needs, existing alternatives, and cost and availability.

Although SSDs are designed to help visually impaired individuals interact with their environment, other available aids may already meet their needs. Thus, considering some of the existing alternatives and comparing them to

SSDs might help address why the new systems have not been largely adopted. A broad coverage of the available assistive devices specifically designed for blind people can be found in Velázquez (2010).

A first core feature of current SSDs is that they enable blind people to access and read printed text by recognizing two-dimensional shapes, e.g., lines and edges. Although a growing number of books and popular magazines are available in alternative formats, including Braille and audio records, the vast majority of common print materials (e.g., correspondence, product labels or bills) are not yet easily accessible to the blind. At present, blind people can choose from a wide range of automated optical character recognition (OCR) systems, which scan print materials and either save it or read it aloud. Blind people can also read what is displayed on a screen or operate a computer using screen-reading software, and either speech synthesizers or electronic refreshable Braille displays (www.afb.org/prodmain.asp). One of the most prominent examples of this kind of technology is VoiceOver (Apple Inc., www.apple.com) — screen reading software that allows blind users to interact with a computer without seeing the screen, and supporting refreshable Braille displays. Given the number of OCR systems available, the advantage of using SSDs as a support for reading is therefore not so obvious. In fact, OCR technologies have been developed specifically to achieve this relatively standard task, resulting in an intuitive and simple solution. On the contrary, SSDs encode information about single letters' shape, providing a time consuming and potentially cognitively overloading experience.

A second main feature of current SSDs is that they allow detection of distal information and distance estimation, facilitating spatial navigation. Nevertheless, blind people can move sufficiently well on their own with the support of a long cane, though this aid mostly provides them with an extended representation of their peripersonal space. Blind individuals could benefit from a device combining the potential of current SSDs and the handiness of long canes to navigate more safely in space. Smart canes seem a promising answer to this issue, as they represent an evolution of the simple cane (Kim and Cho, 2013). For instance, the recently developed EyeCane can supply further information about objects within a 5-m range *via* simple auditory cues (Maidenbaum, 2012). This device is also more useful than the traditional long cane, since it is less obtrusive and noticeable. By providing additional and useful information about the surrounding environment, SSDs may reduce uncertainty and distress in long cane users. However, distress and fear can also be relieved by guide dogs, which are excellent navigation aids. They can guide people through crowded environments and around obstacles otherwise difficult to detect with a cane, learn habitual routes, and even be trained to recognize specific objects. From a psychosocial perspective, guide dogs can also contribute remarkably to the well-being of their owners. While the long cane and the guide dog are useful mainly in detecting and avoiding obstacles, blind people can rely on modern GPS-based navigation systems for orientation in outdoor spaces (Loomis *et al.*, 2001). GPS systems can also allow the user to explore a new environment offline before actually navigating through it (Petrie *et al.*, 1996). Crucially, GPS technology is easily accessible, inexpensive, cross-platform, rapidly improving, and it offers a growing number of applications. GPS-based devices are also highly appreciated in the visually impaired community because they aid navigation by providing verbal directions, which are less intrusive and overwhelming than constant auditory/haptic feedback (Loomis *et al.*, 2012). GPS technology represents the best outdoor navigation aid currently available, and visually impaired people can choose from several commercial devices (e.g., StreetTalk, Freedom Scientific Inc., www.freedomscientific.com; Trekker Breeze, HumanWare Inc., www.humanware.com). However, GPS technology is not suitable for indoor navigation, because of the attenuation of the signal and its insufficient localization precision. Thus, wayfinding in unfamiliar buildings may result in difficult experiences for those who do not have access to orienting information such as signs and building maps. Non-visual orienting information may be provided using Braille signs, talking signs, talking lights, or RFID tags (see Tjan *et al.*, 2005 for a description). Nonetheless, these represent non-flexible solutions since only fixed information on the environment is provided. To ease indoor navigation, new assistive technologies try to provide the person's position, useful contextual information, and directions by using either indoor tracking systems (e.g. Ultra-Wideband technology, Riehle *et al.*, 2008), or location determination and indoor guidance systems (Tjan *et al.*, 2005). However, such indoor navigation technologies are limited or still in the prototype phase. Current SSDs are also not optimally suited for assisting indoor navigation in unfamiliar buildings. Even though they facilitate walking through corridors and open doors, they do not guide the user, or identify useful orientation landmarks. Still, it is possible to imagine how this technology might evolve to serve this function. A system capable of performing visual processing such as those described above may locate and identify hallways, doors, signs, room numbers, and more general useful landmarks within a building, detect obstacles, and recognize objects and people. Thus, a possible future application for SSDs is represented by indoor navigation, for which current available alternatives are at an early stage of development and not yet integrated with outdoor navigation devices in an integrated system (Giudice *et al.*, 2010).

Cost and availability have represented a major obstacle to the adoption and diffusion of SSDs among blind people. At present, mobile SSDs are neither easily available nor cheap. For instance, AuxDeco FSRS is a rather expensive forehead display distributed only in Japan (EyePlusPlus, Inc., www.eyeplus2.

com), and BrainPort V100 vision-tongue display (Wicab, Inc., www.wicab.com/index.html) has just become commercially available in Europe, although the cost of the device and the relevant training required are still unknown. A notable exception is vOICe, an auditory algorithm coding visual information, since the software is freely available on the Internet and strikingly easy to install, even on a mobile phone or a tablet (www.seeingwithsound.com). Since large-scale manufacturing might help mitigate these limitations, partnerships with the private sector may be worth considering. This sort of collaboration might prove effective; private companies are able to mass manufacture devices, and may also introduce relevant online modification (e.g. level of performance or costs) of the hardware. However, such devices must prove useful before going commercial.

In summary, even though current SSDs might benefit blind and visually impaired people, in the absence of a clear demonstration of their advantages relative to reliable, familiar and tested aids, such as the long-cane or Braille, the blind community may opt for the status quo (Samuelson and Zeckhauser, 1988). We argue that the degree of real and perceived complexity in understanding and using SSDs contributes to explain why they have so far failed to spread among the blind community. In innovation adaptation literature, innovation is described as a learning process (Clark, 1995; Mokyr, 1990; Rosenberg, 1982), involving researchers developing the new technology alongside the people who might benefit from it (Douthwaite *et al.*, 2001, 2002). Usually, potential SSD users are minimally involved; they may either adopt or reject the technology, but not change it (Rogers, 1995), and their role is mainly limited to ‘spread the message’ (Ruthenberg and Jahnke, 1985). However, SSD development could largely benefit from visually impaired people’s contribution, since they may embed their experiences in the new technology while using it in their daily life (Rogers, 1995).

4. Training Programs

Visually impaired individuals benefit from training programs aimed at enabling them to live more independently and safely. These programs cover different aspects of daily life, from learning Braille, to communication and social skills development, to the ability to be autonomous. For example, an important module in these programs is sensory training (Campbell, 1992), which helps develop compensatory skills by gathering perceptual information from the immediate environment through the spared senses, especially haptic and auditory information. Another fundamental module is Orientation and Mobility (O&M), which helps blind people acquire spatial mapping skills, usually with traditional navigation aids such as the white cane.

The adoption of SSDs as rehabilitation devices might hinge on the quality of the learning phase. Research evidence on cognitive processes, such as information seeking, attention, and memory, can inform educational researchers on how to improve teaching and learning models, especially those for the disabled (Hardiman, 2001). In turn, research protocols and rehabilitation programs with SSDs can benefit from the experience of well-established teaching and learning frameworks.

4.1. Multisensory Learning Strategy

Models translating knowledge about cognition and learning into practical strategies (Dimensions of Learning Model; Marzano, 1992) may be inspirational for researchers in planning SSD training programs. For instance, evidence that new information is best acquired in the context of prior knowledge (Perry, 2000) suggests the idea of 'visually' presenting SSD content that has been previously learned through a spared sense. Furthermore, studies on perceptual learning promote the use of multisensory-training protocols. Since we are immersed in a rich environment, and objects are fully characterized by redundant information coming from all senses, a multisensory procedure would facilitate more effective and stable learning (Shams and Seitz, 2008). Thus, SSD training might take advantage of a blind person's prior tactile and auditory knowledge to better consolidate the newly acquired percepts. While training with SSDs mainly focuses on learning to handle new sensory information in isolation from other sensory experiences, and often in a controlled laboratory setting, specific multisensory training (audio/tactile SSDs) offers a comprehensive rehabilitation approach, which aims to promote the integration of device use with users' experience of the environment with the preserved senses.

The multisensory learning approach is partially supported by research focusing on sight restoration that seeks to solve Molyneux's Problem: would a blind person be able to visually recognize an object previously known by touch? (Molyneux, 1688). Early works on surgical sight restoration (e.g., cataract removal) showed that blind people who regained vision had major deficits when presented with complex objects, depth cues or visual illusions (Gregory, 1963; Von Senden, 1960). Nonetheless, some of the newly sighted patients were able to visually recognize a known object after touching it (e.g. Von Senden, 1960). More recent evidence (Held *et al.*, 2011) suggests that, although not immediate, the matching between new visual and prior tactile knowledge occurs quite rapidly (Sinha *et al.*, 2013). Indeed, a review on the efficacy of visual prostheses (Merabet *et al.*, 2005) proposed to exploit this capability to map the new visual percept onto the already existing tactile, possibly also auditory, information to guide rehabilitation with visual prostheses. From a perceptual learning point of view, regaining sight and starting to use an SSD might be similar conditions: in both cases there is new sensory (i.e., visual or sensory substituted) information that needs to be integrated in the individual's world-knowledge to create a coherent and unified representation of the environment. Thus, a multisensory learning strategy could prove as useful for SSD training as for rehabilitation in sight restoration.

4.2. Flexibility in Learning Situations

Since repetition is fundamental to consolidate knowledge (Sprenger, 1998), it would be important to provide portable support materials for blind users to practice with SSDs, perhaps on smartphones or tablets, whenever and wherever they want. The user should also be able to select which information is most relevant among a constantly growing body of materials, customizing the learning experience and redefining his/her goals.

4.3. Community Learning

In SSD training, a trusting relationship should be encouraged not only between the new user and the researcher/instructor, but also between the users themselves, perhaps pairing them together so that they can help each other. A new SSD user may benefit from interacting with experts in the use of the device, who may initially be the researchers and then other blind people already skilled in using it as both could suggest effective strategies. Indeed, several studies (see Del Marie Rysavy and Sales, 1991) pointed out that collaboration among learners results in clear educational advantages. Moreover, creating such a supportive environment may also prevent potential causes of stress and improve learners' attitudes toward the SSD. Within a community, SSD training may indeed benefit from programs designed to promote and sustain the sharing of knowledge and individual experiences among learners and users, whereas individual SSD users would have to face the learning challenge alone. This process could potentially lead to the development of new skills (Ponea and Sandu, 2010a, b) and even to the emergence of specific jargon to better describe the unique form of perception elicited by the device.

4.4. Tailored Training

During the training, the researcher/instructor should be a present observer, ready to offer support when necessary, without intervening too much in the exploratory and learning process (Learner-Centered Approach; McCombs and Whisler, 1997). The researcher should also provide the new SSD user with a customized program tailored to his/her needs and potential (McCombs and Whisler, 1997; Reigeluth, 1999). In particular, special emphasis should be placed on the centrality of the specific needs of each new user. This is a fundamental point to be made when planning training and rehabilitation programs for visually impaired individuals, since they all have different personal histories and conditions that influence the pace of learning and the chance of succeeding in mastering an SSD.

4.5. Ecological Training

SSD training is mostly provided to blind individuals as part of specific research programs. In this context, training procedures can ensure a sufficient level of performance for the purpose of testing relevant experimental hypotheses. However, the new sensory-motor loop trained in experimental laboratories may not necessarily generalize to more ecological contexts. Participants are usually taught how to use the device individually in a one-to-one relationship with the teacher–researcher and the training is conducted in laboratory settings with impoverished materials resembling the test stimuli (typically high contrast 'white on black' 2D patterns). This results in a controlled experience that is quite distant from real life situations. The focus appears to be mostly on the specific experimental results and only marginally on the perceptual learning process itself. Since SSDs are quite complex systems, it has been suggested (Loomis *et al.*, 2012; Merabet *et al.*, 2012) that a steep learning curve is necessary to master the new sensory-motor loop at the proficiency level needed to accomplish specific real-life tasks, such as perceiving depth or recognizing objects. However, this requirement may hold back the spreading of SSDs among the visually impaired. Ideally, training programs should take place in a rich, lifelike environment, since learning will be significantly effective only if it occurs in the authentic social and physical context within which it will be used (Situated Learning; Brown *et al.*, 1989). Yet, it might prove difficult to conduct the training in the real world due to the limitations of the current SSDs discussed above. Nevertheless, the above-mentioned constraints could be addressed by complementing real-world training with the use of realistic computer-based environments. One interesting opportunity that has been recently explored is the use of virtual environments (VEs) to support the development of navigation skills in the blind, and the extent to which such an acquired ability can be applied in the physical environment. Indeed, learning as well as applying orientation and mobility strategies requires both cognitive and psychological efforts, since exploring a new environment can produce anxiety and fear, which in turn can negatively affect concentration. VEs provide relaxing and safe learning environments to practice orientation tasks and increase self-confidence, while allowing the user to explore a new space in advance, reducing the stress of facing an unknown situation.

Since there was evidence supporting the transfer of navigation skills from virtual to real situations (Lahav and Mioduser, 2008; Reardon, 2011), a case study on a newly blind individual (Lahav *et al.*, 2012), and a group study with both blindfolded sighted and congenitally blind participants (Maidenbaum *et* *al.*, 2013), inquired into the potential of VEs for training navigation skills. In these studies, subjects were able to navigate through VEs after receiving only very brief training. Moreover, the single-case patient improved her exploration strategies, spatial learning experience, confidence and relaxation. She was able to translate the navigation strategies learned during traditional training in the VEs and apply them back in the real world to better perform her orientation tasks. The potential of such systems is clear: they can be run on normal computers, without needing sophisticated aids or hardware, and can be used while comfortably sitting on the couch, eliminating the risk of getting hurt or lost when learning to navigate in the real world (Manduchi and Kurniawan, 2010).

An additional finding in the group study (Maidenbaum *et al.*, 2013) was that participants regarded the experiment as a game, and therefore they all enjoyed it. The pleasantness of game-based learning suggests that it might improve the rehabilitation of blind individuals by easing the challenges of real-world training and, in turn, reduce the distress potentially resulting form it (Lahav *et al.*, 2012; Maidenbaum *et al.*, 2013; Merabet *et al.*, 2012). Merabet and colleagues (2012) trained early blind participants in wayfinding skills using a custom designed virtual environment called Audio-based Environment Simulator (AbES), either simply exploring the layout of an existing building, or completing the task through an action video game. The authors found that while all the subjects created an accurate map and were comparably able to transfer it to the real world, participants who experienced the game-based learning could better manipulate their mental representation of the building. These results suggest that in designing a virtual system for supporting O&M training for the blind, the gameplay dimension (i.e. the casually linked series of challenges the player-learner will face; Rollings and Adams, 2003) should not be neglected since it increases engagement and motivation (Costkyan, 2002), and thus the effectiveness of learning. Indeed, additional research with AbES software showed that the ludic-based approach of this VE resulted in a particularly engaging experience for blind people, and that this greater involvement facilitated the acquisition of navigational and spatial cognition skills in both adults (Connors *et al.*, 2013) and adolescents (Connors *et al.*, 2014).

5. Conclusions

In this opinion paper, we introduced and examined a number of issues potentially hindering the diffusion of SSDs as assistive and rehabilitative devices for visually impaired people outside research laboratories.

We suggested that research in cognitive ergonomics may prove very informative for the implementation of devices capable of meeting the user's demands. Importantly, the compensatory recruitment of spared sensory modalities must be taken into account in order to minimize interference with adaptive strategies. In addition, the amount of information provided by SSDs should be carefully evaluated in order to prevent sensory and/or cognitive overload for the user.

We discussed how SSDs' low accessibility and affordability may affect their appeal to impaired individuals. Their small-scale manufacturing and high pricing barely compete with the more common and convenient aids. In our opinion, a closer collaboration between researchers and private companies may improve their commercial attractiveness.

We also proposed that models on the diffusion of innovation, developed within other research fields, may prove useful in better characterizing the spreading of SSDs. Specifically, such approaches might be adopted in order to allow end users to participate, thereby collecting their insightful and unique feedback.

Finally, in practicing with an SSD, the new user has to learn a new sensory-motor loop for interacting with the environment. This perceptual learning might prove particularly difficult if not adequately supported, especially since SSDs are complex systems. We proposed that well-established teaching and learning models may inspire researchers interested in designing rehabilitation programs using SSDs. Specifically, in designing SSD training programs the following strategies could prove effective: exploiting a multisensory approach; providing a flexible learning experience; promoting the growth of a community of users; creating individually tailored programs; and providing a rich, ecological training environment. Moreover, we foresee promising avenues for the use of VEs in SSD training. Previous research showed that the gain of a virtual reality experience compared with real-world training results in finer performance and a more pleasant experience. These benefits were even more significant in game-framed situations.

In conclusion, SSDs are non-invasive aids that have the potential to significantly improve the life quality of blind people, but remain mostly confined to research laboratories. We proposed that in addition to the investigation of fundamental research questions, future studies on sensory substitution would benefit from a multidisciplinary approach, and a better understanding of the ergonomic, psychosocial, and neurocognitive issues that may be responsible for the minimal diffusion of current SSDs. This approach seems to be crucial for the purpose of advancing scientific knowledge, translating it into meaningful clinical and rehabilitative applications, and ultimately taking SSDs outside of academia.

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