The Science Journal of the Lander College of Arts and Sciences

Volume 9
Number 1 *Fall 2015*

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1-10-2015

The Rehabilitative Potential of Auditory to Visual Sensory Substitution Devices for the Blind

Naomi Perl
Touro College

The Rehabilitative Potential of Auditory to Visual Sensory Substitution Devices for the Blind

By Naomi Perl

Naomi Perl graduated in June 2015 with a BS degree in biology and is now attending the Doctor of Physical Therapy program at College of Staten Island.

Abstract

Living with a sensory impairment is challenging, and those who have lost the use of one sensory modality need to find ways to deal with numerous problems encountered in daily life. When vision is lost, these challenges include navigation through space, finding objects, recognizing people or surroundings, reading or even communicating without access to nonverbal signs provided by others such as eye gaze or facial expressions. Nevertheless, the blind manage to function efficiently in their environment, often to a surprisingly high degree. The key to this amazing phenomenon lies in the plasticity of the brain and the connections it makes after loss of a sensory modality. Based off this theory is the idea that the brain's plasticity allows for the effective use of sensory substitution devices (SSD). Sensory substitution refers to the transformation of the characteristics of one sensory modality into the stimuli of another modality. Primarily, this paper will attempt to answer the question of whether or not auditory to visual sensory substitution devices have the potential to be incorporated into long term rehabilitation efforts for the blind. In order to conclusively answer this question, this paper will discuss how effective these devices are in recreating the lost sense, in terms of acuity, pattern recognition, depth perception, SSD based movement, and sensory perceptions acquired from long term use of SSD's by blind patients.

Introduction: Neuroplasticity following blindness

Neuroplasticity describes the brain's ability to change its structure and function throughout the course of a lifetime. The largely differing conditions in the brain following early onset sensory impairments such as congenital blindness or deafness, allow for large scale changes that promote a full reorganization of the brain. This may result in a functional network remarkably different from the one seen in healthy individuals. Accordingly, in a congenitally blind person, despite the lack of visual input to the brain, the visual cortex does not degenerate, but rather it receives input from non-visual functions such as touch and audition (Bubic, et. al., 2010). Functional neuroimaging methods validate these findings by showing that the occipital cortex functionally engages in perceptions such as audition (Gougoux, et al., 2005; Kujala, et al., 2005) and tactile Braille readings (Gizewski, et al., 2003). Studies in which auditory (Collingnon, et al., 2006) and tactile processing (Merabet, et al., 2004) were disrupted via transcranial magnetic stimulation to the occipital cortex confirm the necessity of occipital engagement in these non-visual functions. Recently, anatomical studies in primates indicated the existence of projections from the auditory to the visual cortex (Chabot, et. al., 2007) Furthermore, it is important to realize that the involvement of unimodal brain regions (occipital cortex) in cross modal perception (auditory and tactile stimuli processed by the occipital cortex) is not only limited to individuals with sensory impairments, but can under specific circumstances be identified in the general population. The difference is that the cross modal involvement is much more pronounced in those with sensory impairments, perhaps due to increased neuroplasticity, as sensory areas deprived from their customary sensory input become integrated into other neural circuits, affecting the entire system as a whole (Bubic, et. al., 2010).

Sensory substitution devices/ the human-machine interface:

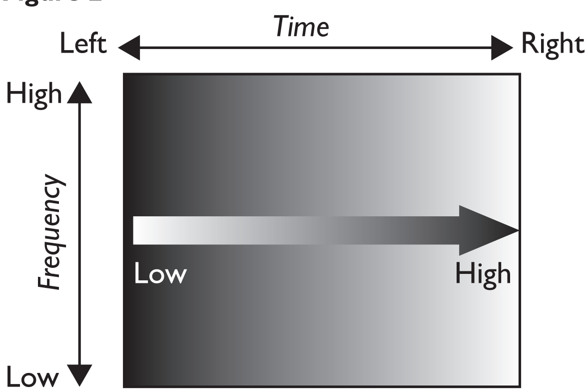
Sensory substitution refers to the transformation of the characteristics of one sensory modality into the stimuli of another modality. For example, it is possible to replace vision with touch or audition, and to replace audition or vestibular sense, with touch. This paper will focus on sensory substitution devices (SSD's) which replace vision with audition, otherwise known as auditory to visual sensory substitution devices. In general, auditory to visual SSD's capture visual information via a video camera, which then transforms the images into auditory input that is conveyed to the user using headphones or an earpiece (Bubic, et. al., 2010). (Figure 1)

Figure 1

The general concept of a sensory substitution device (SSD) and a typical visual to auditory setup. SSD's typically include a visual capturing device, a computational device transforming the visual input into auditory input, and an output device, transforming this information to the user (Bubic, et. al., 2010).

Different auditory to visual SSD's primarily differ in the conversion algorithm the computer utilizes to transform the visual information into auditory input. To formulate an answer regarding the rehabilitative value of auditory to visual sensory substitution this paper takes into account the following selection of auditory to visual SSD's which are used in the various studies cited later on. The first auditory SSD developed is the vOICe system. The capital letters conveniently stand for "Oh I See". The vOICe utilizes a conversion algorithm in which for every image picked up by the camera, the vertical axis is represented by frequency, the horizontal axis is represented by time and stereo panning, and the brightness of the image is encoded by the amplitude of the sound (loudness). The resulting sound encoding the image is termed a "soundscape" (Bubic, et. al., 2010). (Figure 2) The voice can theoretically generate a resolution up to 25,344 pixels (Striem- Amit, et al., 2012).

Figure 2



A schematic summary of the vOICe algorithm. Time and stereo panning constitute the horizontal axis in the sound representation of an image, tone frequency makes up the vertical axis, and loudness corresponds to pixel brightness (Bubic, et. al., 2010).

Another more recently developed device is the Prosthesis for Substitution of Vision by Audition (PSVA). The algorithm is similar to vOICe, except the PSVA uses a frequency mapping to map horizontal position as well as vertical position. Thus, the frequency associated to each pixel increases from left to right and from bottom to top. Furthermore, in order to enhance the similarity with the human visual system, the receptor field of the PSVA has a higher resolution in the center of the picture to simulate the human fovea (Hanneton, et al., 2010) In contrast, the PSVA has a maximal theoretical resolution of only 124 pixels (Striem- Amit, et al., 2012). Another device known as the Vibe converts a video stream into a stereophonic sound stream. It uses a virtual retina composed of two levels of "cells"; sensors and receptors. Each sensor corresponds to a particular pixel. The activity of the sensor is a function of the coded components of the captured pixel. A receptor has a receptive field determined by a set of sensors. So, a receptor is concerned by a particular area of the captured video frames. Each receptor produces a signal that can be interpreted as a sound. The signals of all the receptors are mixed together to produce a stereo audio output that can be adequately adapted for human perception (Hanneton, et al., 2010). Lastly, Israeli Scientists have come up with a new device called EyeMusic which uses an algorithm that is similar to vOICe algorithm in most respects, except that it also conveys color. It distinguishes color by using different musical instruments for each of the four colors: white, blue, red, and green. Black is represented by silence. In order to increase the pleasantness of the sound the device was created with a relatively low resolution of 24 by 40 pixels, is (Abboud, et. al., 2014)

Occipital Activation through the use of Sensory Substitution Devices

Recent neuroimaging studies have investigated the neural bases of sensory substitution, raising questions about the nature of sensory substitution in blind versus blindfolded individuals. (Poirier, et. al., 2007a) Studies show Occipital activation in both blind and blindfolded sighted subjects while using auditory SSD's. Using Positron Emission Tomography (PET), Arno and colleagues have shown that pattern recognition using the PSVA induced the recruitment of extra-striate occipital areas (BA 18 and 19) in early blinded subjects, and to a lesser degree in blindfolded sighted control subjects (Arno, et. al., 2001). In another study PET was used to show activation of the visual cortex during depth perception using an auditory SSD. In this study blindfolded sighted volunteers used the PSVA to determine depth based on the relative target size, the proximity of the target to the horizon, and the linear perspective. The exercise was found to involve the extra-striate area BA 19 (Renier, et. al., 2005). A study using functional Magnetic Resonance Imaging (fMRI) has shown that pattern recognition through an auditory to visual device can induce the recruitment of striate (BA 17) and extra-striate (BA 18 and 19) areas in blindfolded sighted subjects (Poirier et al., 2007b). These studies show similar occipital activation in the blind and sighted when using these devices, however the basis of the visual activation in each subject group is debated. In general, the use of SSD's seems to induce visual brain areas via two processes: mental imagery and cross modality. Though cross modality, a function of the brain's neuroplasticity, seems to be the primary basis of SSD use, mental imagery may play an important part in the process, especially for blindfolded sighted users. Both blind and sighted people can perform mental imagery. The phenomenon of cross modality, though more significant in the blind, occurs in the sighted too. So, both processes can be performed by either group. In addition, both mental imagery and cross modality are known to activate the visual area of the brain. After reviewing the data a study by Poirier et al proposes that perhaps mental imagery is predominant in sighted subjects, and

cross-modality is predominant in blind subjects (Poirier, et. al., 2007a). Both populations may fare better in different respects following this proposal. The sighted or for practical purposes late onset blind, who predominantly utilize mental imagery, will be able to better associate the cross-modal input to the properties of vision as they knew it. On the other hand, the early blind who lack such understandings of the visual world, and instead primarily utilize the cross modality of the brain, due to more highly developed cross modal networks and plasticity, seemingly have a larger potential in the realm of sensory substitution.(Bubic, et. al., 2010) In general, this paper will value this proposal, and when analyzing various studies which utilize blind and/or blindfolded participants, it will acknowledge the discrepancy in their use of SSDs, and the effect that these differing modes of use have on the results when applicable, while still focusing on the broader picture. This approach will help when trying to determine an answer regarding the rehabilitation potential of these devices for the blind, as this paper is less concerned with the effects and potential of these devices in regard to sighted individuals.

Methods:

The information in this paper was obtained from Touro College's online database and from various online medical journals. All of the data is experiment based, collected and analyzed to best answer the question of how effective SSD's are and to analyze their potential to be incorporated into rehabilitation efforts for the blind.

Discussion: Acuity

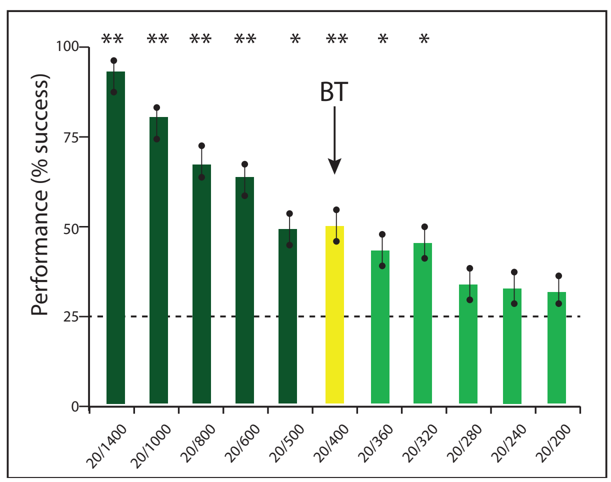
An important factor regarding the usefulness of SSD's is the amount of detail resolvable to the user. To measure this, a study was conducted using the Snellen E- chart visual acuity test. This test, generally used by ophthalmologists, was adapted into an auditory version via the vOICe technology, and used to test the visual acuity of a group of eight congenitally blind, and one early onset blind individual. Each participant was trained for several months in a two hour weekly training session, by a single trainer, on a one by one basis. The training program was composed of two features. One part focused on structured two dimensional training, in which the participants were taught how to process two dimensional static images such as letters, numbers, faces and houses using the vOICe. The second part, live view training, focused on visual depth- perception and training in hand "eye" coordination using the vOICe. The test was conducted by playing soundscape stimuli in a pseudo randomized order of E directions. Patients had to state the rotation of the letter E (up, down, left, right). (Figure 3)

Figure 3

A blind participant perceiving an image of a large Snellen E and identifying its direction (Striem-Amit et. al., 2012).

The results, analyzed on both a group level and on an individual basis, showed that group performance differed statistically from chance level, and individual visual acuity scores varied between 20/200 and 20/600. Five of the nine participants had visual acuity that exceeded the visual acuity threshold for blindness of 20/400 as defined by the World Health Organization (WHO). (Figure 4)

Figure 4



The group performance on the Snellen acuity test, also displayed is the WHO Blindness Threshold (BT) (Striem-Amit et. al., 2012).

The study also showed that participants were able to identify and mimic the body posture of a person standing a few meters away and navigate in crowded corridors while avoiding obstacles. One of the participants was able to identify live three dimensional emotional facial expressions. Capabilities such as these provide a basis for the device to be used in natural settings, which are sufficiently more complex than those present in the study. (Striem-Amit et. al., 2012) Another study also investigated the acuity of users of the vOICe via the Snellen E

test. This time, however, all the participants were blindfolded sighted vOICe users who received no training prior to experimentation. In this way the study aimed to provide a benchmark measure of acuity, because in the previous study it is unclear whether the acuity levels achieved are due primarily to the resolution of the device, or rather the compensatory neural plasticity of the blind participants, combined with their expertise in using the device. The participants included 26 adults all of whom reported normal vison. The participants completed two experimental procedures using the Snellen E test. In the first test scores of 20/2464 and 20/4682 (in comparison with normal vision: 20/20) were achieved by the highest number of participants. In the second test a score of 20/2464 was achieved by the highest number of participants, showing a marked improvement from the first test. In general, the acuity results from this study are much lower than those of the previous. However, the participants in this study received less than 1% of the training received by participants of the previous study. In addition, since all the participants of the previous study were blind this was probably a factor in their high performance. Nonetheless, these results are significant, because they show that very little training or explanation is required to carry out this task using an SSD (Haigh, et. al., 2013). This study is important because it helps to define the minimum capability of the device. The participants were both blindfolded and received no training and still managed to extrapolate results, showing the even greater potential of the device with blind users who will use the device after many hours, days or even years of practice, and who may also have developed compensatory neuroplasticity. In addition, these studies of acuity along with future studies of acuity using auditory SSD's, are important in providing a standard measure of acuity for comparing sensory substitution algorithms, and individual differences in sensory substitution acquisition. Furthermore, a standard measure of acuity might be helpful to test the resolution and precision of synesthetic experiences described by long term users of SSD's as described below.

Pattern Recognition

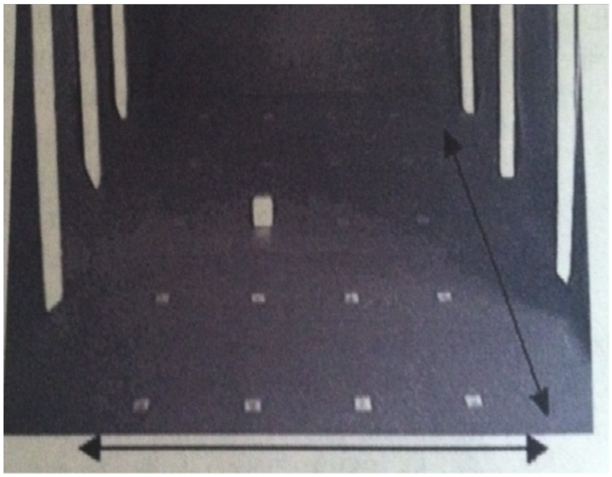
One of the most important developments in information technology is the graphic user interface (GUI). However, the GUI has presented a new challenge for blind people given its inherent visual nature, with icons, multi windows, and mouse-based command structure. Similarly, in the current world of communication, graphics play an increasingly important role. Numerous graphs, charts, diagrams and other forms of visual communication are included in documents intended to be read by sighted people. Thus, blind people remain at a great disadvantage for graphical information access. In a study by conducted pattern recognition in a computer environment was investigated in six early blind and six blindfolded sighted subjects using the PSVA. By comparing performance of both groups, the study aimed to investigate the effect of early visual deprivation on recognition of visual patterns. Subjects were trained during twelve, one hour sessions. During training the subjects learned how to recognize patterns displayed on a PC screen by exploring the graphics tablet with a pen. Subjects heard sounds related to their hand movements and had to recreate the pattern in a frame using aluminum dots and strips. At the end of training, learning was tested by having the subjects recreate patterns which they had encountered during training. Performance was evaluated on the basis of response accuracy and processing time needed to answer. Accuracy was assessed by finding the number of common points between the subject's recreated pattern and the actual pattern. The results showed that early blind and blindfolded sighted subjects are able to recognize patterns from auditory feedback related to hand movements, but the early blind scored better in both accuracy and processing time. This suggests that mental imagery is not a prerequisite for the development of these representations. The results are encouraging from a rehabilitation point of view by showing that pattern recognition in a computer environment is possible using a vison to audition coding scheme without previous visual experience. (Arno, et. al., 2001)

Depth Perception

Sighted people use depth perception for many applications such as obstacle avoidance, navigation, object localization, and grasping. A study investigated how early blind subjects interpret visual depth cues and use them to locate objects using the PSVA SSD, and how sensory substitution can contribute to the development of depth perception and visual perspective in early blind subjects through interactions with the environment. The participants included twenty blindfolded sighted volunteers and ten early blind individuals. All received training in recognizing 2D shapes with the device. None of the participants had previously used the SSD to localize objects, or to explore a 3D environment. The experiment was divided into a pre-test, a practicing session, and a post test. Results from the pre and post-test were compared to see the effect the practicing session had on each of the subjects groups. During the pre-test subjects explored a three dimensional set up via a head mounted camera. The set up consisted of a black table surrounded with six white poles with twenty preselected positions on the table for a white cube. (Figure 5).

The cube was placed pseudo randomly at different positions during the experiment. After exploring a specific set up, the PSVA was turned off, the cube was removed, and the subjects had to replace it by hand in its initial location. Scores were calculated by finding the difference between the correct position and the position the subject placed it in. Each participant completed 20 set ups. In sighted subjects the mean error score was

Figure 5



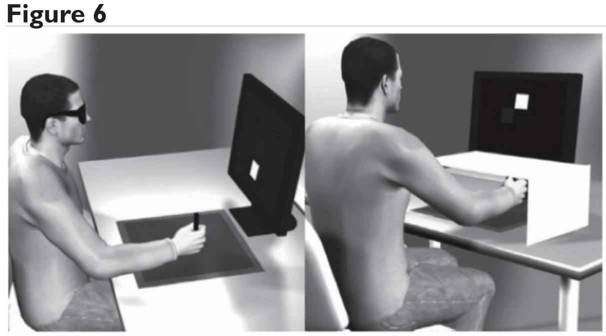
View of the 3D display used in the experiment. The perceived size, height in the field view and the geometrical perspective induced by the poles can be used as depth cues to estimate the egocentric distance of the white cube. The arrows indicate the width and depth axes of the scene. (Renier, et. al., 2010).

about 11 cm for the depth and about 5.5 cm for the width. In early blind subjects, the error score was about 19 cm for the depth and 5 cm for the width. These results show better performance in sighted subjects for the depth and little difference for the width. These results are explained due to the fact that sighted subjects used their knowledge about visual depth to perform the task with the PSVA, in other words using a form of mental imagery, while the early blind subjects were affected by their lack of visual experience. Then, during three 45 minute practicing sessions, subjects got to practice with the PSVA in the 3D display. All subjects had the same number of trials to practice with the PSVA. The post-test following the practicing session consisted of the same procedure as the pre-test. When comparing the scores, significant improvement was seen in the early blind subjects for determining depth, while on a whole there was no significant improvement in the sighted subjects. Only those in the sighted group who were the least accurate in the pre-test showed an improvement in the post test, seemingly representing a ceiling level for accuracy in sighted subjects. However, the improvement seen in the early blind was probably due to enhanced tactile and auditory abilities which contributed to an optimization of the learning process, thus enabling them to learn how to correctly use visual depth cues. With a longer practice period it is likely that early blind subjects would outperform the sighted subjects. These results suggest that visual experiences via an SSD can help blind people learn visual perspective and pictorial depth cues both of which are key for depth perception. (Renier, et. al., 2010)

Fast accurate reaching movements with a visual to auditory SSD:

Previously this paper has discussed acuity, pattern recognition, and depth perception using auditory SSD's. A further study discusses SSD's in regard to sensorimotor integration, which is critical in the effort to make SSD's relevant for everyday tasks, including making accurate reaching movements toward objects, and interacting with people and objects. The purpose of the study was to test the use of auditory SSD's to guide a fast reaching movement. This study utilized the EyeMusic SSD device, and involved 18 sighted participants who were naïve to the use of SSD's. The experiment consisted of a familiarization session and a test session. During the test session participants used a pen shaped stylus to perform 2D reaching movements with their dominant hand on top of a digitizing tablet. Movements were made from a center location to one of four 2 cm radius targets, represented by a white square located 6 cm from the center. In the testing session, participants performed two blocks of trials, which differed by the type of feedback provided: either auditory (SSD) or visual (VIS). During the SSD block participants were blindfolded, while during the VIS block, the participants' arm was placed under an opaque cover, such that they did not have direct visual feedback of their hand. (Figure 6)

Figure 6



The experimental setup: A participant performing the SSD block blindfolded (on left). A participant performing the VIS block, with his forearm hidden from view by an opaque cover (right) (Levy-Tzedek et. al., 2012).

Participants did not receive feedback on their movement path, but received feedback on the location of their hand at the end of each trial. If the endpoint location was within 2 cm of the center of the target the trial was considered successful and only feedback on the location of the endpoint was given in the form of a blue square. However, if the end location of the hand was farther than 2 cm away from the center of the target, feedback on the location of both the target square (white), and endpoint (blue) was given, such that participants could use their end position relative to the target to correct future movements. During the SSD block the participants did not see the squares when receiving feedback, but could distinguish between the

target and the endpoint square because of special eye music algorithm which allows for color incorporation, piano for white and marimba for blue. The following measures were used to characterize participants reaching movements under the two feedback conditions; movement time: the time elapsed from the movement onset to termination, peak speed: the maximal hand speed during the movement, path length: the total displacement of the hand from the beginning to the end of the movement, and endpoint error: the distance between the hand's final position and the target. Surprisingly, there were no significant differences between movements performed with SSD feedback compared to those performed with visual feedback in term of movement time, peak speed and path length. Average endpoint error in both types of movements was smaller than 0.5 cm. It is likely that with further practice participants will be able to perform movements with an even smaller endpoint error using the EyeMusic SSD. The main limit on the study is the fact that it did not include any blind subjects. As previously explored, because the subjects were sighted it is possible that rather than using auditory information directly to control movement, they "translated" it into a visual image of the target location, and acted based on this image. However, the study is strengthened by the fact that there was no visual information given of the target directly before or during the testing block, so there was no possibility to perform any vision based calibration between trials, which could help to improve subsequent trials (Levy-Tzedek et. al., 2012) Furthermore, the use of sighted subjects is auxiliary, because it allows for the movements using an SSD to be compared to the movements of the same individuals using sight. This helps to better define this capability using the device. With blind subjects there would be no comparison point, because the subjects can only reach out blindly. Nonetheless, a future experiment with blind individuals would reveal the ability the ability of blind subjects to create a spatial representation, and act on it, without the possibility of mediation by visual imagery. Still these results are important since those obtained from the SSD block can be used in a future study as a comparison point for blind individuals using an SSD. Furthermore, if the blind can replicate the accuracy level reached in this study by the sighted subjects, then performing daily tasks with an SSD is feasible, and thus the prospects of the rehabilitative use of SSD's are broadened.

Novel SSD's what they offer to the world of rehabilitative techniques: Eye Music and The Vibe

Thus far, various experiments have demonstrated the ability of blind users to use SSD's on various levels. However, most auditory SSD's generate unpleasant sounds and also lack color information. For some this provides for a bland and somewhat irritating experience at times. Eyemusic was created to address these issues by using natural instruments to convey visual information in a pleasant manner, while also conveying color information. Different instruments represent different colors and the ceiling frequency was limited to 1568 Hz, because high frequency ranges have been linked with unpleasantness. A study was conducted to see if the device accomplished these goals. The study included twelve blind participants, and ten sighted blindfolded controls. Part of the study included a survey which asked the participants to compare the pleasantness of EyeMusic with the pleasantness of the vOICe, the leading algorithm for many auditory SSD's. This was done by generating two second soundscapes using the vOICEe SSD and EyeMusic in their default modes with a two second break between them. All but two participants scored the soundscapes generated by the EyeMusic as more pleasant on average. Of these two participants one scored the vOICe soundscapes as equally pleasant on average, and the other found the vOICe soundscapes to be slightly more pleasant on average. On a whole these results are promising suggesting that EyeMusic could be a step forward in terms of user experience. Notwithstanding, the increased pleasantness and potential for prolonged use come at the expense of image resolution. Therefore, EyeMusic could be useful for tasks that that require prolonged use or when color is valuable to the user, while other devices, such as the vOICe, that offer higher resolution could be used for tasks demanding finer detail. One device does not have to replace the other; rather, each with its specific characteristics can be utilized at different points to augment the rehabilitative process. In addition, since the sounds generated by the device are relatively pleasant this may encourage users to use the system as pleasant sounds are said to induce positive emotions (Abboud et. al., 2014) The Vibe is another SSD developed that offers extra versatility, an important feature when trying to tailor the device for a specific user. The mechanism of the device is described above briefly. This unique format allows for several innovations. The first is pre-filtering of the video stream. A useful example of this is the application of a threshold to the captured pictures. The threshold can make a great number of receptors silent, and consequently can make the resulting audio signal less complicated and more comfortable for the user. A second example of pre-filtering is the use of a filter that computes as input to the Vibe a time difference of successive captured frames. With this kind of filtering, instead of producing a continuous and complex audio stream, the Vibe will generate sounds only if there are changes in the video stream. This functioning can also be more comfortable and less tiresome for the user than the static solution that continuously produces a complex sound. One can imagine building filters that combine thresholds and time differences for an optimal user experience. Another adaption is sensor distribution which affects the pixels addressed by each sensor of each receptive field. Receptive fields can thus be large or small, identical or different, overlapping or non- overlapping. The distribution of the sensors on the 2D plane of captured pictures can affect the perceptive abilities

of the user. Thus, the sensor distribution can be modified for specific users and in specific situations when different effects are wanted. Finally, the Vibe also offers the possibility to enhance the binaural perception and differentiation by the listener of the sound by adding inter-aural disparity cues to the sound like inter aural time differences. This can be done by adding delays to the transfer functions of the receptors (Hanneton, et. al., 2010) The versatility of the Vibe, allows for extra capabilities, which enhance the user experience and customization, allowing it in these respects to serve as a better rehabilitative tool.

Long Term visual experiences in the blind induced by SSD's

Ward and Meijer (2010) investigated the phenomenology of two late onset blind users of the vOICe system. The users both report detailed visual phenomenology that developed within months of immersive use and has continued to evolve over a period of years. In addition, their long term use of the device seems to have produced an acquired synesthesia. Synesthetic experiences are percept in nature and are elicited by a stimulus and occur involuntarily. Furthermore, the experienced sensation co-exists with the induced one rather than replacing it. So, for a synaesthete a sound is seen, but it is also heard. This effect may be due to different mechanisms of plasticity that emerge after long term use of the device. One is unmasking of existing cross modal connections, and another is a slower reorganization perhaps associated with changes in synaptic connectivity. The two subjects in the study PF and CC both became blind at the ages of 21 and 33 respectively. PF currently has a small amount of light perception in the left eye, while CC has a low visual acuity that enables her to count fingers in front of her, and notice large objects in strong contrast. Both were asked a series of questions to understand their visual experience, how it developed, and the extent to which it comprises an acquired synesthesia. Initially, both were asked about perceiving edges, contrast and acuity. PF reports visual experience in terms of a non-detailed grey scale sketch. She says, "I cannot tell fine little tiny details. Rather my vision is based upon black and white and all the little gradients in between. The best way I try to describe this to people is : take a large black sheet of paper; now take a magical piece of white chalk and sketch me here on this stage in line drawing now make me three dimensional…". CC, like PF also claims not to get enough visual detail to identify a person's sex or age with the vOICe, but can sometimes differentiate sex based on clothing. She says, "I could tell whether they had a long coat on or shorts…" Both PF and CC report being able to perceive depth, but that the ability occurred gradually, and only after having flat visual experiences of edges and shading. PF described the acquiring of depth perception as a sort of eureka moment that occurred while she was washing dishes as she looked down at the sink and realized with astonishment, "Oh I can see down. I can see depth." In addition, both were asked about perceiving movement. The vOICe software normally converts one visual image per second into a soundscape and is not well suited for detecting fast moving objects. However, both PF and CC no longer report any subjective experience of jerkiness, nor is their experience a series of snapshots. PF describes it like using a flip book, "You don't see the different breaks between images." Likewise CC says at first it was like a very jerky movie, but now she experiences smooth movement. As far as acquired synesthesia, both PF and CC claim to be able to 'see sounds' when not using the vOICe. Their brains have internalized the vOICe rules for mapping between hearing and vision, and the rules are applied, both, when the device is worn, and when it is not. CC describes her synesthetic experience: "Monochrome artificially induced synesthesia, only in certain frequencies of sound. A small price to pay for very detailed vision, but the consultant's music next door sets me off as well (Bach Mass in B Minor)… It is not triggered by all sounds but by vOICe like sounds. It is almost as if you had a computer with two monitors running simultaneously different pictures… and sometimes you switched your attention between both." PF also gives visual descriptions, all monochrome, to a number of simple sounds. In addition, PF also believes her synesthetic experiences are stable, a hallmark feature of developmental synesthesia. On a whole, both the sound of human speech and the sound of most instrumental music do not elicit visual experiences. This study is enlightening, but also raises further questions. Would congenitally blind users acquire an altered sense of visual like space as a result of using the device, or is prior vision a prerequisite for these experiences that go beyond the scope of what the vOICe SSD delivers in most experiments? Furthermore, are the particular mappings used by the vOICe special in some way, or could any consistent mapping between vision and audition lead to these kinds of experiences? It is noteworthy that for both their phenomenology has developed over time. The length of time using the device may be the key to both of these questions, but further study on a larger sample size would be necessary.

Conclusion

The data from the studies supports the use of SSD devices in the rehabilitation for the blind. Most studies comparing the use of blind versus blindfolded volunteers showed increased potential for blind users using these devices. However, more data should still be collected. The present studies are limited by the relatively small sample size of volunteers, and the lack of real data following long term use. Additionally, the testing set up of the experiments cannot parallel the real world which is fast paced and demanding, so it would have to be determined if the clear benefits as demonstrated under testing conditions could be utilized in a real world setting, when the subject has little room for error. In the long term, sensory substitution devices

seem to be both a promising and innovative addition to the rehabilitation of blind people.

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