Analyzing, Comparing and contrasting Tactile-to-Vision Sensory, *Tongue Display*, *Abdominal skin, and* Visual-to-Auditory Devices: A Holistic Reference for People Who Need to Find a Suitable Device

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ABSTRACT
In addressing the issue of visual impairments, sensory substitution techniques are employed to develop varies devices, aiming to compensate and regain the blind population some degrees of visual functions. Based on the sufficient research over the decades on neuroplasticity, specifically the compensatory plasticity, the mere ideas about these devices were turned into reality. The blinds are exposed to varies types of devices to compensate for their lost vision. This is a holistic view that guides their choices are absent. The current literary review has analyzed sensory substitution devices (SSDs) that utilize 2 sensory modalities (auditory and tactile), where 3 types of devices are discussed in total (tongue display unit, devices for abdominal skin, and visual-to-auditory devices). A comparison and contrast of these devices are presented. Overall, due to the lack of empirical evidence and data of the users' experiences of these devices, the current comparison is very limited and is mostly deductive. Therefore, future studies should be providing more user data and experiences to fill this gap for such comparison and, in turn, provide the blinds effective guidelines to make suitable choices in terms of their situations.

Keywords: *sensory, substitution, device, compare, review*

1. INTRODUCTION

There are more than 2.2 million people in the world wide who suffer from visual impairment of varies degrees, and this existing population generates a significant financial burden to the global economy [1]. Therefore, a viable solution to address the issue is in need targeting this wide range of blind population. Studies in the field of neuroscience may shed some light for the possible solutions.

Neuroplasticity as a broad concept describes human brain's capacity to "change its activity in response to intrinsic or extrinsic stimuli by reorganizing its structure, functions, or connections" [2]. Among the extraordinary possibilities brought by this function we possess, neuroplasticity provides the sensory disabled population opportunities to minimize and compensate for the lost function. Human brain, specifically the central nervous system (CNS), has the capability to compensate for sensory losses [3]. This ability is referred to as "compensatory plasticity", meaning that human beings can cope "with the loss of vision by developing supernormal skills when using one of the remaining senses" [4]. For example, comparing to the sighted controls, studies found improved olfactory performance, tactile acuity, and speech/tone discrimination among the blind individuals. These changes accompany, or are caused by, biological changes in the brain, such as increased olfactory bulb volume or cerebral blood flow.

Based on this nature, researchers have developed sensory substitution devices (SSDs) to help regain partially the lost sense through the stimulation toward remaining senses. For instance, the blind can regain some functions of vision through systems of auditory-to-vision substitution, where visual images are translated into auditory information which the subject could hear [5]. For sighted individuals, visual images are transformed by the visual system into biological signals and "sent along the optic nerves in the form of patterns of nerve action potentials" [3]. Sensory substitution techniques are replacing the signals from one sense (the lost one) by the other ones. After training, the brain is able to "interpret the nerve impulses as a visual image, after decoding the patterns of afferent impulses" [3]. Such substitution can theoretically be utilizing any of the remaining senses, yet there are several that appear to function better than the others. For example, tongue and abdominal skin are explored as tactile substitutions [6,7], and, apparently, ears will be employed to transmit auditory information [8].

While researchers have developed numerous viable sensory substitution devices, many blinds may not be completely suitable for some of the devices due to personal factors. For instance, blinds who still have "residual peripheral vision" cannot localize sound as precisely as thoroughly blind subjects [4], suggesting that tactile-to-vision substitutions are more suitable than auditory-to-vision strategies. Research has been focusing on a single or a few types of SSDs at a time, but a holistic overview is absent, which can be hopefully addressed by the current paper.

2. METHOD

The current study is a literary review, where relevant research and studies are collected, analyzed and referred (in the discussion). A total of 10 studies are selected for the analysis of all types of devices. These studies are retrieved through google scholar, jstor, science direct, and research gates. Keywords used to retrieve these studies include: sensory, substitution, devices, blind, auditory, tactile, neuro-plasticity, visual, tongue, abdominal, skin, voice. These studies are selected because they address one or more of our targeted types of sensory substitution devices, provide empirical evidence (data and experiences) of users on these devices, and have accessibilities for the researchers.

3. ANALYSIS TACTILE-TO-VISION SENSORY SUBSTITUTION DEVICES

Tactile sensory substitution is developed based on the fact that blinds have a better tactile spatial acuity as they rely more on the sense of touch, like reading Braille [5]. It was found also found, behind the performance enhancement, the biological evidence that occipital lobe is activated and stimulated among the Braille users [6]. Therefore, conveying visual information in ways that possess more potential has been the major goal of the researchers and designers. Two types of tactile devices have been developed and tested to be viable, which are described below.

3.1 Tongue Display Unit

Sensory substitution through tongue as a genre of tactile sensory substitution is developed based on the stronger sensitivity and perceptual ability which mediates complex spatial information comparing to that of, for instance, the fingertip losses [3]. Tongue Display Unit (TDU), like other tactile sensory substitution techniques, is a non-invasive device to replace the impaired or lost vision. A regular TDU consists of a rectangular or square electrode array that makes consistent contact with the tongue and exerts small electric pulses as stimulations. Another component is a camera usually attached to a pair of glasses for the convenience of wearing, like that of the Brain Port device [9]. What connects the camera with the electrode array is an information processor or a computer that converts the visual information, captured by the camera, of the environment into electric pulses which can be delivered through the electrode array to the tongue. This substitution, like other techniques, activates the occipital lobe that possesses the function of processing visual and spatial information. Ptito et al. (2005) conducted an experiment to investigate the changes in the cerebral blood flow (CBF) in the occipital lobe of the congenitally subjects and sighted controls after their experiences of training to use the TDU. Their task was to accurately determine the presented letter on the screen of a computer which is connected with the TDU device. After a week of consecutive training with 1 hour per day, increases in the CBF in the occipital lobe were only seen in the trained blind, suggesting that the TDU was indeed bringing visual experiences biologically for the blind. Furthermore, the blind subjects increase faster in their correctness and reaction time for the task comparing to the sighted controls, reaching averagely a correctness of around 90% and a response time of less than 10 seconds. However, users will definitely need more time to adapt to the device as a real-life situation is always far more complex than merely identifying letters on a computer screen. In a prospect study, Hertle et al. (2016) tested experienced Brain Port system's users' visual acuity and obstacle detection abilities. As a result, these users who has years of practices are able to identify a log MAR letter, suggesting a high-level of visual acuity. In addition, they have significantly less collisions on the obstacles, and they are able to walk in a preferred speed with the device.

3.2 Abdominal skin

Abdominal skin is another ideal location for visual-tactile substitution, which can be proved for several reasons. First of all, the abdomen is comparably flat and large so it has enough space for sensory substitution devices to operate on it. Furthermore, the abdomen is hardly used for sensing things, especially for navigation, so if it is used by sensory substitution device, the normal physiology phenomena and function will not be affected [7]. If the subject can sense changing vibration is a particularly important point to test the effectiveness of sensory substitution devices. The device called TSIGHT allows the subject to sense the vibration frequency changes on the abdominal area from little by little between 10 and 100%, which can help researchers check if there is something wrong with the dynamics of the actuators (Cancar & Diaz, 2013).

In common, the whole process of the operation of a sensory substitution device is collecting visual data and then using the information obtained from the visual data to get the final tactile signal. The visual data is collected by webcams and the tactile signal is collected by vibrating motors. Its working principle is that when an object gets closer, the frequency of vibration of the motors would increase at an extremely fast speed. Through such vibration, the subject can avoid hitting obstacles in advance [7]. VISL chips and electro-tactile array are also necessary parts of the devices. Most of the hardware implementation should go through the VISL chips and implementations can be faster in it. Electro-tactile has the same function to make the data processing be more efficient.

3.3 Visual-to-Auditory devices

Visual-to-auditory sensory substitution devices (SSDs) provide improved access to the visual environment for the visually impaired by converting images into auditory information. This device is initially created to compensate for blindness. SSDs convert images to sound based on visuospatial properties, with the right cerebral hemisphere potentially having a role in processing such visuospatial data. Research using the vOICe has addressed the question of how well people can learn to ‘see’ through the soundscapes. Auvray et al. (2007) demonstrated that novice, blindfolded participants were able to localize, recognize and discriminate between objects after an extensive 3-h device-led training session. Pollok et al. (2005) found similar competency in users trained over a 3-week period; Proulx and colleagues demonstrated that participants could learn to use the device by active use at home, and formal training was not required. [13]

4. DISCUSSION

Though human tongue demonstrates a stronger perceptual sensitivity than some of the other areas of human skin [10], direct data or evidence that compares the upper limit of such sensitivity is absent. With a higher level of sensitivity, it is expected that tongue will react faster to the electro pulses delivered by the electrode array and presumably have a higher accuracy in identifying objects. However, considering the mechanism of the tactile SSDs, TDU is actually limited by its number of electrodes attached to the array, as tongue has a relatively small surface area to receive the signals comparing to that of, for example, the abdominal skin. There is no definite evidence to suggest a higher capability of the abdominal skin devices than the tongue, as it was not found in the recent papers. The current empirical evidence suggest that the TDU is capable of identifying letters even words with a response time of within 10 seconds after merely a total of 7-hour training [11], which in some degree suggests a higher accuracy. However, even for the experienced users who have been using TDU for a few years, collisions still exist when identifying the surrounding obstacles [12], which, presumably, the TDU may not support the perception of the environment at a large scale. It can be seen that TDU will perhaps be demonstrating its best function at tasks that requires accuracy and reactivity for tasks such as reading. However, the device will have to be taken off for other tasks that require the tongue or the mouth, like eating, drinking, and speaking.

In contrast, the device developed for the abdominal skin, as it vibrates to indicate the looming objects [7], may provide a stronger experience during navigation, which, in turn, could perform better by making less collisions. It is very hard to determine the extent to which abdominal skins are capable of activate and utilize the occipital lobe to gain “visions”, because this part of human body was hardly used for any perceptual purposes. In an innovation for the deaf, as presented in a TED talk by David Eagleman, abdominal and dorsal skin are utilized by the device for perceiving words, the deaf participant was able to perceive words quite accurately by perceiving the electric vibration. Note that both the SSD for the blind and the SSD for the deaf in this case utilize the abdominal skin and exert the information in the same type of vibration, and the capability of this area of skin is quite high for the deaf, suggesting the same for the blind, but the evidence is still lacking. However, an obvious advantage of the SSD on the abdominal skin is the little interference with other sensory organs. Comparing to the TDU and visual-to-auditory devices, which occupies the tongue and the ear that also possess other important functions which are interfered by the devices, the abdominal skin does not block any of the remaining senses. [13] The blinds can, therefore, gain a consistent visual access toward the environment. Such device will fulfill best of its function in environments that require the detection of looming objects or obstacles, like walking in the crowd.

Visual-to-auditory SSDs, obviously require the user to have a proper auditory system, are generally cheaper, and formal training of the usage of the device is unnecessary as demonstrated by Proulx et al. (2008). As it brings convenience in its accessibility and usage, only a little training time (a 3-hour training session) is required for being able to properly use the device (identifying objects for orientation), which is relatively short comparing with the other two tactile devices [16]. In addition, the device captures a high resolution of the image as 4000 pixels, which potentially demonstrates a high accuracy in object identification. However, the image-to-sound conversion has a 1 second interval, which is not consecutive comparing with that of eyes [14]. This may limit the activities the blind are capable of doing. For example, activities that require a response time of less than 1 second will not be appropriate for the blind. However, as also mentioned earlier, the visual-to-auditory SSDs occupy ears, which is also a crucial aspect of the human sensory system. [13] That is to say, devices like the vOICe sacrifices one's auditory system in order to regain one's visual functions, which can be dangerous as well in some cases, like crossing a road with looming vehicles, where one who wears such device may miss the whistle from the vehicle and lead to traffic accidents.

5. Conclusion

The current literary review aimed to summarize, compare and contrast the existing types of sensory substitution devices to provide holistic views over the choices the blinds and relevant institutions have toward device selections. A total of 3 types of device that utilize two sensory modalities——tactile and auditory——are introduced and analyzed. A discussion of their advantages and disadvantages based on their characteristics and empirical data of the user experiences are presented. It was found that the TDU features with a higher precision but at a smaller scale, which still incurs collisions during navigation, whereas the SSD on the abdominal skin provides a stronger response toward the obstacles and one's surrounding objects, but there is a limited notion toward its accuracy and precision; the vision-to-auditory devices are relatively more accessible due to its cheaper price, and it requires relatively less training time to use, yet a functional auditory system is required for the use. Both the TDU and auditory devices interfere with other sensory functions (hearing, speaking, eating, etc.), which can be a limitation for the designers to resolve.

Although the current study attempts to juxtapose SSDs, the absence of the corresponding evidence limited this study from providing a more thorough comparison in aspects such as required training time, interference toward other functions of senses, precision, scopes, and accuracy. Therefore, the current comparison, by no means, can be taken as a direct guideline for the choices of the SSDs, but rather a directional reference. Future studies should be aiming to fill these gaps to bring users more references for their own usage.

REFERENCES

[1] WHO. (2021). *Vision impairment and blindness*. World Health Organization. https://www.who.int/news-room/fact-sheets/detail/blindness-and-visual-impairment.

[2] Puderbaugh M, Emmady PD. (2021) Neuroplasticity. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing

[3] Bach-y-Rita, P. (1987). Brain plasticity as a basis of Sensory substitution. *Neurorehabilitation and Neural Repair, 1(2), 67–71*.

[4] Kupers, R., & Ptito, M. (2014). Compensatory plasticity and cross-modal reorganization following early visual deprivation. *Neuroscience & Biobehavioral Reviews, 41, 36–52.*

[5] Kupers, R., & Ptito, M. (2011). Insights from darkness. Enhancing Performance for Action and Perception - Multisensory Integration, *Neuroplasticity and Neuroprosthetics, Part II, 17–31*.

[6] Kaczmarek, K. A. (2011). The tongue display unit (TDU) for electrotactile spatiotemporal pattern presentation. *Scientia Iranica, 18(6)*, 1476–1485.

[7] Johnson, L. A., & Higgins, C. M. (2006). A navigation aid for the blind using tactile- visual sensory substitution. *2006 International Conference of the IEEE Engineering in Medicine and Biology Society*.

[8] Ward, J., & Meijer, P. (2010). Visual experiences in the blind induced by an auditory sensory substitution device. *Consciousness and Cognition, 19(1), 492–500.*

[9] Fletcher, D. C., & Arnoldussen, A. (2012, January 1). *Visual Perception for the Blind: The BrainPort Vision Device*. retinalphysician.com.

[10] Bach-y-Rita, P. (2006). Tactile Sensory Substitution Studies. *Annals of the New York Academy of Sciences, 1013(1), 83–91*.

[11] Ptito, M., Moesgaard, S., Gjedde, A., Kupers, R. (2005). Cross-modal plasticity revealed by electrotactile stimulation of the tongue in the congenitally blind. *Brain, 128(3), 606–614.*

[12] Hanna, N., Hertle, R. W., Culp, K., Doerr, M. B., True, M., Holmes, B., & Difranko, G. (2016). Analysis of sensory substitution ambulation using the brainport device in blind children versus controls. *Journal of American Association for Pediatric Ophthalmology and Strabismus, 20(4), e5*.

[13] Auvray, M., Hanneton, S., O'Regan, J.K., 2007. Learning to perceive with a visuo- auditory substitution system: localisation and object recognition with 'the vOICe'. *Perception 36 (3), 416–430*.

[14] Pollok, B., Schnitzler, I., Stoerig, P., Mierdorf, T., Schnitzler, A., 2005. Image-to-sound conversion: experience-induced plasticity in auditory cortex of blindfolded adults. *Exp. Brain Res. 167 (2), 287–291.*

[15] Proulx, M.J., Stoerig, P., Ludowig, E., Knoll, I., 2008. Seeing 'where' through the ears: effects of learning-by-doing and long-term sensory deprivation on localization based on image-to-sound substitution. *PloS One 3 (3), e1840.*

[16] Proulx, M. J., Brown, D. J., Lloyd-Esenkaya, T., Leveson, J. B., Todorov, O. S., Watson, S. H., & de Sousa, A. A. (2020). Visual-to-auditory sensory substitution alters language asymmetry in both sighted novices and experienced visually impaired users. *Applied Ergonomics, 85, 103072*.

[17] Massiceti, D., Hicks, S. L., & van Rheede, J. J. (2018). Stereosonic vision: Exploring visual-to-auditory sensory Substitution mappings in an immersive virtual reality navigation paradigm. *PLOS ONE, 13(7).*