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Yevgeny Beiderman
Michael Belkin
Ygal Rotenstreich
Zeev Zalevsky

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Yevgeny Beiderman,^a Michael Belkin,^b Ygal Rotenstreich,^b and Zeev Zalevsky^{c,*}

^aAgricultural Research Organization (ARO)—The Volcani Center, Agricultural Engineering Department, Beit-Degan 50250, Israel

^bTel-Aviv University, Sheba Medical Center, Tel-Hashomer 52621, Israel

^cBar-Ilan University, Faculty of Engineering, Ramat-Gan 52900, Israel

Abstract. We present the first experimental quantification of the tactile spatial responsivity of the cornea and we teach a subject to recognize spatial tactile shapes that are stimulated on their cornea. © 2015 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.JMI.2.1.016002](https://doi.org/10.1117/1.JMI.2.1.016002)]

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1 Introduction

The possibility of alleviating blindness is one of the most challenging tasks that researchers, particularly from the fields of neuroscience and nanotechnology, currently face. The recent technological advances in those fields led to the development of the concept of an artificial retina, in which a light-sensitive device is implanted in the eye in order to directly stimulate the retinal cells.^{1–4} However, such solutions, beside being very invasive, have significant limitations with respect to allowing high-resolution imaging over a long period of time.

The cornea is the most densely innervated body tissue.^{5,6} The nerves' density of the corneal epithelium is 300 to 600 times larger than that of skin. Most of these nerves are sensory producing touch, thermal, and chemical sensations, mostly manifested as pain. These nerves are mostly derived from the ophthalmic division of the trigeminal nerve and serve to protect the eye, preserve the integrity of the ocular surface by being the afferent arm of the blink reflex, and ensure the optical characteristics of the eye by being instrumental in the stimulation of tear production. The anatomy of the corneal nerves has been studied before.^{7–10} The cornea of the eye is innervated by the peripheral nerve endings of several types of sensory neurons classified based on their response to different modalities of stimulation such as mechanosensitive neurons and thermosensitive neurons. However, there is no data regarding the two-point discrimination threshold of the human cornea.

Following our former research,^{11,12} we proposed to mount a camera and, after proper encoding, to transmit the visual information to a special contact lens that will perform tactile stimulation of the cornea and, therefore, will allow “seeing” with the eyes, not via the retinal photoreceptors that are connected to the visual cortex but rather through the tactile sensors of the cornea. In this way, it is similar to Braille reading that is done not via the finger tips but rather via the tactile sensation of the cornea. This technology can potentially be a noninvasive sensory substitution, allowing blind people to perceive images. The purpose of this study is to show for the first time that the tactile sense of the cornea has spatial discrimination capability and

thus can be used to transmit spatial information. Corneal tactile stimulation can thus be potentially considered for use as a vision substitute for blind people by teaching them to associate the tactile feeling of the stimulation to real spatial shapes and images. All of the features we show in this paper are in preliminary human trials.

2 Experimental Preparation

In order to stimulate the eye, we have built an air pumped system consisting of nine air pipes arranged in one cluster of a 3×3 matrix. The signal spatial distribution over the eyeball was performed by fabricating a matrix attached to goggles which are worn on the face. The tubes were formed in a matrix with a pitch of 2.5 mm, while the air pipe's inner diameter was 0.5 mm as shown in Fig. 1(a). In order to distinguish between the different pipes, we marked them in a sequential way starting from the upper left corner in the arrangement of the 3×3 matrix [see the numbers marks in Fig. 1(a)].

Our air output stream was produced by an external electric pump motor, while the speed of the air in each channel was at a magnitude of approximately 0.5 m/s. The room temperature was 20°C. Air pressure was applied constantly in each tube according to a predefined pattern in the matrix. Later, the matrix structure was used to apply air pressure stimulation to the cornea while it was placed 3 mm away from the eyes of the subjects participating in our clinical trials.

In Fig. 1(b), we show the experimental stimulation device operated on one of the subjects participating in our clinical trials. The left-hand goggle's eye glass was replaced with the air tubes matrix. The air pipes are connected to an air pump motor. Mechanical valves were attached to each pipe and were opened or closed according to the predefined pattern on the matrix.

The matrix pattern is flat; however, the eye has a ball structure. There was a concern about the different air diffraction spot sizes on a cornea due to the different air paths from the channels to the cornea. However, a simple calculation shows that it is negligible. Let us consider a circle equation:

*Address all correspondence to: Zeev Zalevsky, E-mail: zalevsky@biu.ac.il

Fig. 1 (a) Air pipes arrangement with its numbering (including matrix pattern marking). (b) The experimental setup including the various components used in the setup.

$$x^2 + y^2 = R, \quad (1)$$

where x, y are the spatial coordinates, while R is the radius of the circle. The circle represents the surface of the eye. Let us find the air path difference between the on-axis point on the circle perimeter ($x_0 = 0, y_0 = 0$), against a point shifted by a horizontal pitch of 2.5 mm. Let us define dy to be the difference in the air path. Taking into account that the radius $R = 15$ mm (for the human eye) one finds, after substitution in Eq. (1), that dy is ~ 0.2 mm if the matrix is positioned about 3 mm from the cornea. This difference is negligible.

The first test was aimed to check subject's capability to distinguish between the predefined patterns of the transmitted signal and to quantify the time duration necessary to develop pattern discrimination capability. The predefined set of shapes was transmitted to the subjects' eyes. The set S_0 represents the predefined patterns in the coded way according to the marking made in Fig. 1(a):

$$S_0 \{ 1\ 2\ 3, \text{ (upper horizontal line)} \\ 2\ 5\ 8, \text{ (midvertical line)} \\ 7\ 8\ 9, \text{ (lower horizontal line)} \\ 1\ 5\ 9\ 3\ 5\ 7 \text{ (two diagonals-X shape)} \}. \quad (2)$$

The subject sight was completely blocked and the channel valves could not be seen or heard. Therefore, it was impossible to discover what the active channels are, except by doing the recognition via the tested tactile stimulation.

3 Experimental Results

A random pattern within the set S_0 was produced by applying air pressure through the tubes. The subject underwent two sessions for learning the patterns (each pattern once) before the test. Figure 2(a) shows the time course of the pattern recognition success probability. The two lines represent the two tests performed on the same subject. The last value represents the overall success rate. Note that all of our clinical trials that are described in this paper were performed under Helsinki approval # 1123-14-SMC.

We have extended our experimental quantification and tested on two different subjects, while the subjects underwent two rounds of learning of all the possible stimulation patterns (each pattern once) before the test. We collected the data results and presented them in a way which quantifies the temporal dependence of the success rate. For this, we plotted the success rate obtained per each temporal instance during the experiment as if that instance is the end of the experiment. Therefore, we just added all success results before that instance and divided it by the number of trials conducted up until then as shown in Fig. 2(b). The value at the end of the graph represents the overall success rate of the experiment. The summary of the statistics for the success probability per trial is shown in Fig. 2(c). The black bars refer to the standard deviation of the probability per given trail.

Fig. 2 (a) Time course of development of two-point discrimination success probability. The two lines represent the two tests performed on the same subject. The value at the end of the graph represents the overall success rate. (b) Time course of development of eye stimulation success probability. The last value represents the overall success rate. The experiments were performed on two subjects (magenta refers to subject #1 and the other two colors to subject #2 who was tested twice). (c) Summary of the statistics for the success probability per trial as the one shown in (b).

Fig. 3 Two-point discrimination resolution. The red bar (“1 versus 2”) represents the two-point discrimination probability. The blue bar (“Exact Match”) represents the probability of exact recognition of the transmitted signal within the set of S_1 (i.e., not only knowing if it is two points or one point, but also knowing the exact stimulation sequence). (a) Subject #1. (b) Subject #2.

The next set of experiments that we have performed involved quantifying the two-point discrimination capability of the cornea. The experiment was performed as follows: the subject was trained to distinguish between the two channels of stimulation (two points) transmitted separately and/or simultaneously. The subjects were trained before the test to recognize the signal. Usually it took about 1 to 2 min per training set. The main aim of the subject was to distinguish whenever the transmitted signal consisted of one or two channels simultaneously. The secondary aim was to exactly name channels were transmitted. The signal was transmitted randomly using a combination of the two predefined stimulation channels: the set S_1 consisted of {ch1, ch2, ch1 + ch2}. Three experiments per subject were produced with different distances between channels ch1 and ch2. The distances between the two stimuli channels were changed from 5 mm down to 3.5 mm and finally to 2.5 mm.

Two subjects were tested. Figure 3(a) refers to the statistics of subject #1, while Fig. 3(b) refers to the statistics of subject #2. The red bar (“1 versus 2”) represents the probability of recognition whether the transmitted signal consists of one or two channels (i.e., if we stimulate with one point the subject recognizes that it was one point and if we stimulate with two points the subject recognizes that it is two points’ stimulation without exactly naming the channels). The blue bar (“Exact Match”) represents the probability of exact recognition of the transmitted signal within the set of S_1 (i.e., not only knowing if it is two points or one point, but also knowing the exact stimulation combination). No significant change in the results was found with the change of distance for subject #1. The subject was able to make two-point discrimination at any Euclidian distance between the channels with the average rate of detection of approximately 81.8%. However, subject #2 showed a better performance at 3.5-mm distance (100%), while the average rate of detection was approximately 86.8%.

In the last set of experiments, we tested the capability to perform two-point random pattern recognition with a distance of at least 5 mm between the two channels. To quantify this set of experiments, we would like to introduce an error metric which is as follows: If the transmitted signal channel is two and the recognized signal is six, then the metric distance of the error is 3.53 mm [Euclidean distance in our stimulation matrix of Fig. 1(a)]. In the case of transmitting two channels (i.e., two

points) simultaneously, the error distance is calculated as the minimum distance between the two combinations of the recognized and the transmitted channels. In a case where the transmitted signal was one channel and the recognized was two channels (or vice versa), the metric’s calculation is the sum of the errors’ metrics between the two recognized channels and the single transmitted channel separately.

The subject was trained before the test for 3 to 5 min. One can see in Fig. 4 the histogram of the error distances’ distribution. The stimulation pattern was constructed from any two points at a distance of at least 5 mm between them (and it included any possible patterns). For example, the pattern could be: (1,3), (2,9), (3,7), and so on. There are six instances of zero error distance (no errors). Half of the errors (two) are at a distance of 2.5 mm (the minimum distance in our trial). Two of the errors are at a longer distance of 3.53 mm.

4 Discussion

This work represents the implementation of the idea that the stimulation of the cornea with a 3×3 stimulus matrix can show a good capability of two-point discrimination. The recognition rate of the two-point discrimination is relatively high (81% to 86%). However, it is difficult to show an improvement over the canonical Braille method due to the spatial resolution limitation of our preliminary device.

Fig. 4 Histogram of stimulation patterns having at least 5-mm separation distance (two channels). We present the number of counts (i.e., experimental attempts) for each error distance between the recognized and transmitted stimulations.

In the present study, air at constant flow and at room temperature was used as a stimulus to evoke corneal sensation. Taking into account the sensitivity to pressure and temperature as well as the threshold of the distinct sensory neurons innervating the ocular surface, it is expected that the air at room temperature applied at a low flow will recruit both mechanosensitive neurons and cold thermosensitive neurons (usually activated by very low flow rates, lower than those needed to activate corneal mechanoreceptors). Therefore, we cannot conclude exclusively that only “tactile” activation is responsible for the responses quantified in the present work.

The current work suffers from the lack of the examined subjects. This setup demands a certain time learning experience and a good will to participate in the study from the subject. However, the two examined subjects showed relatively good results that are encouraging.

We expect to overcome the above-mentioned doubts during the next full-scale experimental work with the corneal electrical stimulation device also having higher spatial resolution. The electrical stimulation will also help us to solve the ambiguity of the multiple sensorial feedbacks we have probably experienced now.

5 Conclusions

As a conclusion, we can say that we were able, for the first time to the best of our knowledge, to demonstrate with preliminary human trials that the tactile sensing of the cornea has two-point discrimination capability which is better than 2.5 mm, and that this sensing capability can be used to identify basic spatial shapes and images. Those shapes and images were transmitted to the subjects’ cornea through a 3×3 pressure-based stimulation matrix.

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Yevgeny Beiderman received his first degree in mechanical engineering and his MSc degree in intermediate studies from Tel-Aviv University, Israel. He received his doctoral degree from the Faculty of Mathematics at Bar-Ilan University, Israel. His prime interest is in remote sensing, image processing, and biomedical optics. He published 18 papers and submitted 3 patents. He is now with the Engineering Department of the Agricultural Research Organization, Israel.

Michael Belkin is emeritus professor of ophthalmology in Tel-Aviv University and the director of the Ophthalmic Technologies Laboratory at the University’s Eye Research Institute at the Sheba Medical Center. He is also a senior consultant of the Singapore Eye Research Institute.

Ygal Rotenstreich is the director of the Electrophysiology Unit at the Tel-Hashomer Medical Center, Israel, and the director of the Retinal Research Laboratory at the Goldschleger Eye Research Institute, Tel-Aviv University, Israel. His research focuses on the development of novel treatments and diagnostic tools for incurable retinal and macular degeneration. He is a leading clinical trials, basic science and translational medicine studies aimed at a development of novel treatments and diagnostic tools for these blinding diseases.

Zeev Zalevsky received his BSc and direct PhD degrees in electrical engineering from Tel-Aviv University, in 1993 and 1996, respectively. He is currently a full professor in the Faculty of Engineering at Bar-Ilan University, Israel. His major fields of research are optical super-resolution, ophthalmology, biomedical optics, and nanophotonics. He has published more than 360 refereed journal papers, 200 conference proceeding papers, had more than 340 international presentations, 35 issued patents, 6 authored books, 3 books as an editor, and 27 book chapters. He received several prestigious national and international awards for his research and entrepreneurship-oriented activity.