Sensory Perception through an Electro-Tactile Stimulus Array on the Tongue

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Abstract—This paper details an investigation into sensory substitution by means of direct electrical stimulation of the tongue for the purpose of information input to the human brain. In particular, a device has been constructed and a series of trials have been performed in order to demonstrate the efficacy and performance of an electro-tactile array mounted onto the tongue surface for the purpose of sensory augmentation. Tests have shown that by using a low resolution array a computer-human feedback loop can be successfully implemented by humans in order to complete tasks such as object tracking, surface shape identification and shape recognition with no training or prior experience with the device. Comparisons of this technique have been made with visual alternatives and these show that the tongue based tactile array can match such methods in convenience and accuracy in performing simple tasks.

Keywords—communication; stimulation; sensory augmentation; tactile; electrodes

I. INTRODUCTION

Human-computer interaction (HCI) is mostly visual based. This is primarily due to the brain’s efficiency in recognizing and interpreting new patterns and information through the visual sensory modality, something that develops very early in life [9]. Even though alternative methods of interfacing exist such as sensory substitutes or augmentations, whereby a (potentially non-human) sense is interfaced to the brain through a substituting sensory modality, they are rarely implemented as those input sensory modalities require extensive training in order to be interpreted by the brain on a subconscious basis [12, 13], and even with training these methods often suffer poor information throughput [7].

Tactile interfaces are a common method of sensory substitute due to their typically non-invasive approach and relatively low cost. The brain also interprets the stimulation of tactile receptors with a 2D spacial awareness, meaning images can easily be portrayed and interpreted through that sensory modality [10]. Therefore, such methods seem a promising future alternative to visual instruments in machine interfaces. However, in order to become a truly viable replacement the method must be effective without the need for long term training, similar to how a typical visual interface can be almost instantly interpreted by the brain.

A wide range of trials involving visual substitution through tactile stimulation of the skin were developed in the pioneering work of Paul Bach-Y-Rita et al [1–5, 11], and in the late 90’s the work developed into an electro-tactile array on the tongue (labeled the "Tongue Display Unit", TDU). Thus far tongue mounted tactile arrays seem promising as the trials in [1-5] demonstrate a clear increase in performance in tasks such as shape identification compared with similar trials on areas such as the fingertips [1]. This increase can likely be partly explained by the tongue’s high tactile resolution and extra sensitivity/conductance [1, 8].

However, it’s also possible that the improvement in performance is related to the difference in how the brain perceives the stimulation depending on the location of the receptors. In this case the receptors on the tongue are part of the digestive system. Therefore, as the sense has a greater pre-existing influence over the survival and health of the individual, it seems possible that the brain is better equipped to recognize and process patterns observed through those senses. This hypothesis is reflected in the (noted but unmeasured) observation of a shorter training period required for those subjects undergoing shape recognition trials through the tongue versus those trialing fingertip methods in Bach-Y-Rita’s early comparative studies [1].

Intriguingly in [11] the authors reported on trials involving the use of electro-tactile stimulus of the tongue as an aid to computer-assisted surgery. In this case the procedure involved presenting positional information on surgical instruments to the surgeon such that the surgeon was not distracted in terms of extraneous visual stimuli. As the stimuli were outside the scope of visual substitution the results would suggest that augmentative substitutes are similarly effective when presented through the tongue.

Work similar to this could potentially be adapted in order to suit a wide range of potential applications within HCI and as well as providing an alternative to visual computer feedback for individuals there is also the possibility that augmentative methods could be well suited for the sensory impaired. For example, a blind person may benefit more from having an augmentative ultrasonic sense than by having a visual substitute, provided the information can be displayed in an intuitive way.

In the research reported here we have picked up on the work presented in [1-5] in order to investigate the learning potential of humans with regard to shape representations on the tongue using electro-tactile arrays. However, in line with [11]...
we have also investigated the use of such arrays for positional guidance of an individual. In our studies, speed of response has played a major role.

In the section which follows we describe the experimental set up and the different tests actually performed. Subsequently we present the results from those tests and then discuss the implications and possibilities that arise.

II. METHODS

A series of low resolution electro-tactile arrays were constructed along with a basic signal control box, with numerous LED outputs and button inputs. This device was then used to conduct a series of experiments involving tests and short games that would be used to evaluate the efficacy of the methods against visual alternatives. These tests were trialed on six volunteers who were all given one practice session with a pattern identification trial before being asked to take part in one of the measured experiments. The tests were designed with simplicity in mind such that they could be easily repeated using arrays on other parts of the body in future work in order to compare the efficacy of each method.

Electro-tactile stimulation of the tongue requires significantly less power than other areas of skin due to the tongue’s moist coating and the tactile receptors being found closer to the surface [1, 8]. Therefore, the stimulatory signal of the electro-tactile array was variable up to only 5V, with current levels up to roughly 500μA. The signal was a binary waveform consisting of 4ms bursts of three 0.5ms pulses separated by 10ms. This signal was then fed through transformers with outputs coupled with capacitors to ensure that a zero net charge was applied and to ensure full circuit isolation. This gave a sensation of light vibration on the tongue surface and kept the effects of receptor fatigue to a minimum.

Due to a number of constraints all prototyped arrays consisted of a three by two grid of six stimulation points, this was well suited to the experimental purposes. Nodes of different sizes were tested, where the larger the nodal diameter the further apart the nodes had to be in order to be clearly distinguished due to the larger resulting area of electro-stimulation. Throughout the tests users were able to calibrate the stimulation for each individual node, as expected many users required the nodes at the back of the tongue to use a higher voltage due to the variability in the receptor sensitivity along the surface of the tongue [11].

B. Capability Testing

Before each volunteer was given a recorded task, a simple pattern recognition test was performed in order to confirm that the user was able to distinguish between the different nodes, this also gave them an opportunity to calibrate the stimulation.
of the array. The computer was used to randomly select a node on the array and stimulate it for three seconds. This was repeated a total of six times and then the entire pattern was repeated once more. The user was then prompted to repeat the six stage pattern with any errors being recorded at the end. Volunteers were required to achieve six correct answers before continuing, and this was the case with all test subjects after three attempts or less.

C. Shape Recognition Testing

A test was proposed with the intention of exploring in more detail the relationship between image perception and the tactile stimulation of the tongue. This test was to expand on Bach-Y-Rita’s shape recognition experiments [1] by looking at identification of orientation and size of an image with respect to the refresh rate of nodal exchanges (or the presentation of an image versus individually stimulated points).

In this test simple three point triangles were placed with various orientations and sizes onto the tongue (see Figure 1), limited to eight choices due to the resolution of the array. Triangles were chosen randomly and this occurred a total of six times before the user was prompted to reproduce the pattern.

Each triangle was displayed for three seconds in total, during which time the three nodes were stimulated one after the other at a fixed rate. The fixed rate of individual nodal stimulation was chosen at the start of each test and represented the refresh rate. This was done in order to observe the fundamental differences in how those qualities were perceived through an image of a shape (high refresh rate) and a shape made of individually stimulated points (low refresh rate).

The test was repeated throughout using only triangles of varying orientation, excluding those four shapes of varying size, in order to compare the perception of orientation with perception of size. The results, taken as an average success rate across all tested individuals at each refresh rate, would then show how successfully both qualities were identified and whether the perception of the stimuli as an image would yield any immediate benefits or disadvantages over conventional tactile mapping.

D. Object Tracking Test

An experimental game was proposed in order to investigate the application of instruction based object tracking through the tongue array with respect to reaction speeds. The game took place within a virtual five by five grid; two objects were placed randomly within the grid by the computer. One object represented the computer and the other represented the player (see figure 2).

The objective for the player was to move within the grid using a joystick and to match the computers position. Throughout the game, at fixed predetermined intervals, the computer would randomly move up or down one space in each axis. The instant before each computer movement the total distance between both objects in both axes was counted by the computer. These measurements were then averaged at the end in order to give a general error score for that round (where each round consisted of fifty total computer movements).

Throughout the tests the time interval between computer movements was altered in order to observe the increase in player error as the reaction speed allowance decreased. This meant that the reaction speed of the player could be observed and compared to visual stimuli by repeating the experiments using a visual interface.

For the primary experiments using the tongue array the user was given a single practice session of 10 computer moves in order to grow accustomed to the method. There was a focus on eliminating the possibility of long term training and therefore users were only given one session with the system, lasting no longer than an hour in total in order to trial a wide sample of reaction time allowances.

The stimuli received by the user through the array was instruction based, meaning the user had only an implicit idea of where within the grid they actually were. No visual feedback was allowed throughout the trials and users were blindfolded in order to ensure this. The instructions were presented as two bars across the tongue representing each axis and a stimulated point within those bars was an instruction to move either up or down along that axis. This allowed the user to quickly match the computers position in both axes simultaneously.

This test was performed on a total of three volunteers, who each repeated the tests afterwards using a visual display in order to compare the errors using both methods.

E. Surface Identification

This experiment aimed to look into the learning curve of a task using combined tongue and proprioceptive feedback to work out the shape of a simple 2D surface. The 2D surface was created by randomly allocating one value for each column in a five-by-five array.

This surface was then displayed to the user one column at a time using a bar type reading on the tongue (see figure 3). The user was able to navigate through the columns using a fixed dial acting as the proprioceptive feedback.

The user was then instructed to draw out the surface as quickly as possible. Incorrect attempts were passed back to the user by an invigilator until an accurate sketch was completed, at which point the timer was stopped.

In each case time taken and the tally of total sessions taken were recorded. This test was then repeated without the dial, using a fixed rate of navigation and the results were compared in order to observe differences in overall performance as well as to indicate the learning curves.

III. RESULTS

The basic nodal recognition tests were largely successful, where all volunteers were able to identify clearly the individual positions of the nodes. As predicted the success rate was affected by a function of nodal spacing and nodal diameter, where the larger the nodes the further apart they
must be spaced in order to be clearly defined.

B. Shape Recognition Results

The results of the shape recognition tests (Figure 4) showed an impressive accuracy across all test subjects at low refresh rates for both orientation and size identification. Values given indicate the average results in each case over the six users tested. Subjects employed a method of simply tracking the locations of each nodal activation and then consciously mapping the orientation of the resulting triangle.

As the refresh rate increased this method was experimented for both orientation and size, although tests including both variables saw a more dramatic decline in performance, most likely due to the larger group of triangles for selection.

However, as the refresh rate tended towards roughly 30FPS (frames per second) the results from tests excluding size variation saw a steep increase back to almost 100% accuracy.

At this point volunteers claimed they were able to 'naturally' feel the shape, no longer requiring a conscious mapping of stimulation. However, the results from orientation and size variation showed only a slight increase in performance, this is because although the shapes could be identified subconsciously the size information of the stimulation with respect to the input receptors was no longer clear to the volunteers.

C. Object Tracking Results

The object tracking tests were largely successful and users showed an impressive ability to track the computer. With no training for either method there was no consistent and observable variation in error with respect to the reaction speed allowance in both sets of object tracking results (Figure 5).

Figure 5. Surface identification results, taken throughout the training process. Results from trials utilizing the dial are displayed alongside the trials excluding the dial in order to compare the learning curves.

Although deviations are present within the results, a much larger collection of data would be necessary in order to observe clearly any differences in reaction speed within an accuracy of 100ms. However, it is clear that sensory feedback through the
tongue receptors can reach a speed closely rivaling that of sight and therefore no significant limitations are yet apparent.

D. Surface Identification Results

The results for the surface identification tests (Figure 6) showed a longer learning curve when using the dial. However, the results were consistently and increasingly improved using this method.

Both tasks within this test seemed to be affected significantly by training and therefore neither method was ideal due to the counter intuitive interface and methods. Although, even under these circumstances the training was completed within roughly twenty sessions and with each session taking no longer than thirty seconds the process was relatively fast.

IV. DISCUSSION

A. Volunteer Profiles

There were a total of six volunteers tested throughout these experiments, three male and three female all between the ages of 18 to 40. All were sighted except for one female who had been completely blind from an early age. All users participated in the shape recognition tests and some then attempted one of the other tests. Unless a user was taking part in a visual trial they were blindfolded at all times, with the exception of the blind volunteer and the surface mapping test (where users were required to sketch).

For all tests the five sighted patients gave similar results with no significant deviations. However, for the shape recognition tests the blind user showed a significantly lower accuracy. It is largely assumed that a blind patient may suffer in implementing a strategy for visual substitution as their visual cortex would be untrained and possibly utilized for another task completely and these results would partially support such a claim.

Applying a more detailed statistical analysis on these results, that has been done in this paper, would seem to be without a strong basis. Perhaps the most interesting result was in fact the performance of the one blind subject, however one subject is merely a demonstration of concept. The results here should therefore be seen as merely a demonstration of efficacy and performance. Clearly one route for further research is merely to increase the volunteer sample size and range.

B. Shape Recognition Tests

The shape recognition tests were largely successful at showing how a simple and instantly viable method of sensory augmentation can be implemented with a high rate of success. The effects of refresh rate seem consistent with other bodily senses, where flicker fusion occurred beyond roughly thirty frames per second

This could even suggest that the images were processed using the visual cortex, although obviously far more evidence is necessary for such a claim to be substantiated. The indication that size information is scrapped via the image processing of tongue stimulation has large implications on future sensory augmentative methods, but little impact on implementations of visual sensory substitution, and perhaps more evidence that the data might actually be processed using the visual cortex.

Another observation worth noting was that each volunteer had a natural and overwhelming tendency to identify areas of the tongue surface in a fixed reference of orientation. For example, some subjects identified the back of the tongue as the top of an image and others flipped the image horizontally in relation to how the stimulation was actually applied on the tongue.

This was problematic as throughout these experiments the orientations of the shapes were identified with respect to one base frame of the tongue surface, where the top of a shape was at the tip of the tongue. Therefore, the base frame had to be adjusted accordingly in order to accommodate for the specific natural tendencies of each patient.

Attempts to correct or change the natural tendencies of patients, performed after all other tests, were unsuccessful even after extensive practice.

C. Object Tracking Tests

In machine interfacing it’s essential that the methods employed to interact with the brain are fast, if visual systems are to be considered a viable benchmark then the results from the object tracking experiments are promising. These results show a high success in reaction speed dependant tasks through tongue stimulation when compared with the visual method, even with no prior training.

D. Surface Identification Tests

The two main factors that contributed to the extended learning curves of implementations of the surface identification method were the added complexity of navigating through columns and the addition of proprioceptive feedback reliance.

Results showed that even with these added factors the learning rate was such that after a total of less than five minutes in both methods, subjects stopped benefitting from training. This may be extremely fast but it is also important to remember that a demand for higher accuracy using a higher resolution array would increase that period. The next step for this test is to repeat it with tactile arrays on other parts of the body. Results currently hint that the tongue would display a significantly shorter learning curve.

Further research here could also focus on highly accurate positioning on the tongue. That said, human tongues vary considerably in both shape and size and hence even an apparent standardization of results in this way may be prone to positional errors in terms of the sensory receptors of the tongue in relation to the overall tongue shape.
This research has demonstrated simple and successful methods of interfacing data through sensory augmentation of the tongue without the need for training. Although these methods were only implemented as simple proof-of-concept experiments it is easy to see how they could be similarly applied to much more vital tasks.

Results from the shape recognition tests were revealing. The curve in performance is a reminder that considerations must be made as to whether it is appropriate to display simple positions to the user or entire images. It was intriguing that by adding an element of size variation, the success of the experimentation was much lower. It seems a satisfying (but speculative) explanation that size identification is eliminated when the brain perceives images through the tongue.

However, more tests will be required in order to provide evidence to substantiate the idea of size identification invariability, which if true would be a significant limitation in the concept of tongue based sensory augmentation.

It is also an important consideration for machine interfacing if patients perceive the orientation of tongue stimulation differently, this would mean an option would need to be present to flip images both horizontally and vertically for individual patients.

It was interesting that all users learned very quickly what was required of them in the tests and learnt to respond appropriately. Yet when it came to shape orientation, whilst a natural configurational understanding appeared as part of the exercise, an inability to change this understanding in any way indicates the sensory route being accessed may well call on already organized neural processes.

The applications for this work within human-computer interaction are broad, with a strong possibility of implementing convenient and non-invasive alternatives to standard visual methods. However, it is also intended for this work to be explored within therapy for the sensory impaired as an alternative to sensory substitutive methods. Augmentative methods have the advantage in providing a wider range of sensory experiences that can be tailored specifically for the needs of the user, and if the problems of dedication and training can be eliminated then it could potentially become the favored approach.

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REFERENCES