IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 17 March 2023, accepted 18 April 2023, date of publication 19 May 2023, date of current version 31 May 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3278093

RESEARCH ARTICLE

Digital Smell: Toward Electrically Reproducing Artificial Smell Sensations

KASUN KARUNANAYAKA[1,2], (Member, IEEE),
ADRIAN DAVID CHEOK[1,3], (Senior Member, IEEE),
AND SOMAIYEH VEDADI[1,4], (Member, IEEE)
[1]Imagineering Institute, Iskandar Puteri 79200, Malaysia
[2]Mixed Reality Laboratory, University of Colombo School of Computing, Colombo 00700, Sri Lanka
[3]i-University, Tokyo 113-8656, Japan
[4]McMaster University, Hamilton, ON L8S 4L8, Canada

Corresponding author: Kasun Karunanayaka (ktk@ucsc.cmb.ac.lk)

This work was supported by the University of Colombo School of Computing through the Funding Scheme Research Allocation for Research and Development under Grant UCSC/RF/MXR/GN001.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the Imagineering Institute Institutional Review Board (IIIRB).

ABSTRACT Artificially reproducing smell sensations, without using chemical odorants, would change the future multisensory internet experiences. This article presents a computer-controlled smell reproduction technology proposed for stimulating human olfactory receptors, using weak electric pulses. We developed a concept prototype that can generate rectangular-shaped weak electrical pulses in different frequencies (0–30 kHz), duty cycles (0–100%), and currents (1–5 mA). This prototype is tested by stimulating the middle nasal concha region of 31 healthy human participants. During our studies, 8 participants reported chemical and fragrant smell sensations for the stimulation parameters 1 mA with 70 Hz. For 1 mA with 10 Hz, 8 participants reported sweet smell sensation, while 6 participants reported chemical smell sensations. The key novelties of this paper include: 1. describe the development of the first computer controlled digital device for stimulating the olfactory receptor neurons, 2. Testing this new technology on human subjects including the parameters that were not previously tested, 3. Recording the intensities for 22 types of sensations (smell-related and non-smell-related) that could be produced by the electrical stimulation. 4. investigate users' perception on the usefulness of this type of technology.

INDEX TERMS Virtual olfactory sensations, electrical stimulation, electric smell, multisensory internet, virtual experiences.

I. INTRODUCTION

Digitizing smell sense has become an essential need in multisensory communication and mixed reality research [1]. However, current technological developments for simulating smells solely rely on chemicals [2], [3], [4], [5], [6], [7], [8], [9]. These chemical-based technologies have limitations such as being expensive for long term use, require routine maintenance and refilling, and difficulty of controlling the distribution pattern of odor molecules through the air. Nevertheless, direct electrical stimulation of receptors has helped in the study of both hearing and sight, which is expected to lead to sensory prostheses.

The work discussed in this paper is a part of a large, long term, research project of the authors on developing digital taste and smell actuation technologies. We first presented a digital taste actuation technology using electrical stimulation in 2011 [10]. A communication protocol to transfer taste over the Internet was proposed in 2012 [11]. Another digital taste technology using thermal stimulation was published in the IEEE TVCG journal in 2018 [12]. The concept of producing smell sensations using electrical stimulation was proposed

The associate editor coordinating the review of this manuscript and approving it for publication was Charalambos Poullis.

by the authors in 2016 [13]. Image article of electrically stimulating human nasal conchae was published in the Medical Clinical Image Library in 2018 [14]. Further, a non-peer-reviewed book chapter [15] described an early prototype with some initial test results but did not provide the detailed research results as shown in this paper.

This paper is the next expansion of our research and first peer-reviewed paper with latest user evaluation results. The key novelty of this research is the development of the first computer controlled digital technology that can be used to electrically stimulate olfactory receptors in the nasal cavity. Here we describe the testing of this technology on human subjects. We recorded 22 olfactory epithelium induced sensations. Further, we investigated the odor sniffing ability before and after the electrical stimulation. Finally, we studied the users' perception towards this technology in future scenarios. Our next objective is to investigate and identify sets of stimulation parameters that can produce smell sensations. If this approach becomes successful, we will be able to digitally communicate and reproduce smells through the internet as we do with the audio and visual sensations. This would overcome the drawbacks of chemical-based systems and pave the way for numerous new lines of investigation in fields such as Human Computer Interaction (HCI), Augmented Reality (AR), Virtual Reality (VR), gaming, Internet shopping, and medicine.

This paper is organized as follows: Section II discusses the previous works in electrical stimulation of the olfactory epithelium. Section III provides an overview of the device. Technical and use evaluation results are presented in the section IV, while Section V critically assesses the advantages, limitations, future work, and potential applications of this technology.

II. RESEARCH BACKGROUND

Human nose is a part of the chemosensory system, which helps to discriminate a vast variety of odors and flavors. The ability to smell in humans is said to be weaker than other mammalians due to fewer smell genes in their body (for example, rodents have more than 1100 smell genes [16], while humans only have 350 functional genes [17]). On the other hand, humans have complex olfactory bulbs and orbitofrontal cortices, which provide them with more sensitive and dynamic abilities for the sense of smell [18]. However, much information about the sense of smell still appears ambiguous and contradictory. This may be due in part to the complexity of presenting olfactory stimuli as well as the fact that all the necessary mechanisms are still being discovered. For example, in 2014, Bushdid et al. suggested that humans can detect at least 1 trillion different odors [19]. However, this claim was rebutted by Meister [20], and argued that there were failures in the mathematical model used by [19].

The human olfactory system plays a key role in enhancing one's everyday life experiences via emotions and memory. Moreover, a memory of smell lasts longer and it is easy to recall than a memory acquired verbally [21]. Smell memories are thought to have proven qualities, such as resistance to interference, uniqueness, and independence from other modalities known as "Proustian characteristics" [22]. Interestingly, smell, as well as taste, has been found to be directly connected with mood, stress, retention, and memory functions [23].

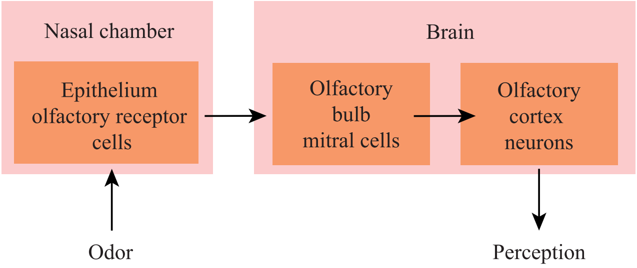


FIGURE 1. **Scheme of the human olfactory system.**

When the odor molecules enter the olfactory epithelium, they bind with olfactory receptors, which are expressed in olfactory sensory neurons in the nose [24]. Then, olfactory receptors trigger a series of signals within the cells that ultimately results in the opening and closing of ion channels. This increases the concentration of positive ions inside the olfactory cells. This depolarization causes the olfactory cells to release packets of chemical signals called neurotransmitters, which initiate a nerve impulse. Odor information is then relayed to many regions throughout the brain [25], which is then perceived as smell. This natural mechanism is shown in Fig.1.

In HCI, VR, and AR the sense of smell is used to deliver multisensory experiences and sometimes to alter other sensory inputs [5], [9], [26], [27], [28]. Multisensory technologies and their applications in terms of interaction, design, and challenges have been discussed recently in many places [29], [30], [31], [32], [33]. To avoid the limitations of the chemical-based smell delivery systems, finding alternative methods that can effectively reproduce olfactory sensations without chemicals is becoming a necessity.

Electrical stimulation can create depolarization in the nerve cells, which can then induce action potentials with sufficient depolarization magnitude [34]. Electrical stimulation on the tongue can produce taste sensations in a practice known as electrogustometry [35]. Perhaps, it can be argued that electrical stimulation of the olfactory receptors may reproduce smell sensations as well. Therefore, the research described in this paper is based on experimenting with sensations produced by electrical stimulation in the nasal cavity. Our approach of stimulation of the nasal cavity is shown in Fig.2.

There have been few studies on electrical stimulation of the olfactory mucosa. In 1973, a medical study used anodal and cathodal stimulation to stimulate the human olfactory neuroepithelium [36]. Anodic stimulation produced odor perceptions such as vanilla, almond, and bitter almond, whereas cathodic stimulation produced a burnt sensation. However,

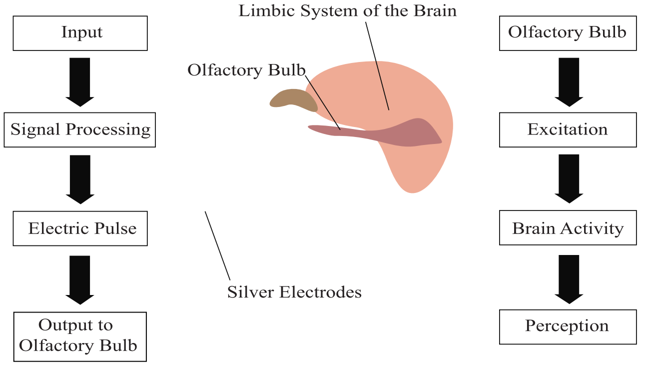


FIGURE 2. The concept of stimulating human nasal concha using weak electric pulses.

attempts made by Straschill et al. [37] and Ishimaru et al. [38] failed to reproduce similar results.

In 1997, another study conducted by Ishimaru et al. [38] recorded olfactory bulbar potentials using 2 mA and 0.5 Hz; nevertheless, no smell sensation was reported by the subject. The same research team later developed an alternative to psychophysical olfactometry using evoked olfactory bulbar potentials in electrical stimulation. However, no sensation of smell reported during these experiments as well [39]. In a different study, electrical stimulation-related evoked potentials were directly recorded from the olfactory tract, however, authors were unable to produce smell sensations [40].

The latest report by Weiss et al. [41] stimulated the olfactory neurons with electrical currents ranging from 0.05 mA to 0.8 mA with frequencies of 2 Hz, 10 Hz, 70 Hz, 90 Hz, 130 Hz and 180 Hz. Odor perceptions were not reported during the experiment; however, they were able to measure several non-olfactory sensations such as pinpricks, flashes of light, cooling, tingling, and electrical current. Further, significant difference in perceived intensity of smell during the electrical stimulation was reported.

In an experiment with epilepsy patients, Kumar et. al [42] reported that 11 out of 16 subjects perceived smell sensations. Two subjects experienced pleasant smells while the rest experienced unpleasant smells. The stimulation was done using 3mA, 6mA, and 9mA currents with 50Hz frequency for 5 seconds. The experiment took place on the ventral surface of the frontal lobe where subdural electrodes need to be implanted. Since this method is highly invasive it cannot be practically developed as a technology to reproduce smell sensations digitally.

The works mentioned above have delivered mixed results. Most importantly, electrical stimulation produced action potentials in the nerves during most of the experiments and in couple of cases smell sensations reported. In this study, we tested different range of stimulation parameters that other researchers did not use, such as current from 1 mA to 4 mA with frequencies 2 Hz, 10 Hz, 70 Hz, and 180 Hz. Furthermore, most of the previous works only discussed or measured limited number of sensations. We recorded results for 22 different sensations that electrical stimulation may produce that includes 10 smell-related and 12 non-smell-related sensations. We believe this is useful to measure because the sense of smell is connected with other systems in the brain such as gustatory system, and limbic system which deals with emotions, memories, and arousal. Thus, it is evident that electrical stimulation can produce complex sensations. Secondly, this kind of characterization has not been studied before, therefore, these results will be useful for future researchers in selecting ideal stimulation parameters.

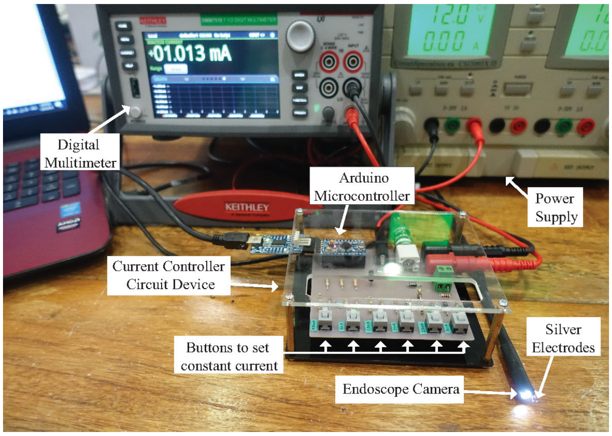


FIGURE 3. Electric smell prototype: This device produces constant current output ranging from 1–5 mA with variable frequencies. The pair of silver electrodes attached to endoscope camera was used to stimulate nasal cavity with weak electrical pulses.

Our approach is different from the works mentioned above from the medical field in many ways. Our main objective is to develop a controllable and repeatable digital technology to generate smell sensations without chemical odorants. We decided that this technology should be a device that can be plugged into computers and it should be able to be programmed and controlled through the computer. Also, this device needs to generate electric pulses of different frequencies, currents, pulse widths, and stimulation times. To provide more stimulation possibilities, we wanted this device to be capable of stimulating diverse sites at the ventral surface of the inferior, middle, and superior nasal concha. If electrical stimulation produces any kind of smell sensation using this proposed technology, we can represent that type of smell sensation as an electric signal, and then reproduce the same sensations on humans using electrical stimulation.

III. DEVICE DESCRIPTION

We developed a proof of concept prototype which is shown in Fig.3 with the purpose of stimulating the olfactory receptors. It consists of a current controller circuit, an Arduino microcontroller, two silver electrodes attached with an endoscopic camera, a DC power supply, and a software program. The silver electrodes are custom made with dimensions of 100 mm in length and 0.5 mm in width. It also contains a spherical tip of 0.8 mm diameter at one end. This sphere tip supposed to contact with inner wall of the nose during the stimulation.

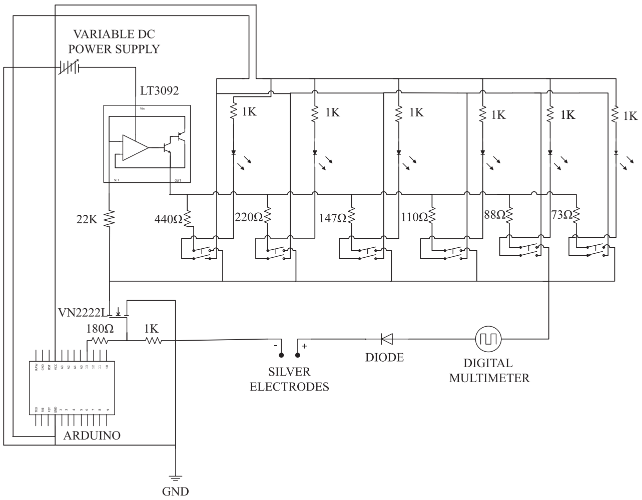


FIGURE 4. Schematic of the current controller circuit.

TABLE 1. Measured actual current output and error.

Intended Value(mA)	Observed Value (mA)	Error
0.5	0.49	2%
1	1.02	2%
1.5	1.49	0.7%
2	1.98	1%
2.5	2.49	0.4%
3	3.02	0.7%

The controller circuit mainly functioned as a current controller. It can generate constant current square wave pulses from 0.5 mA up to 10.5 mA with a 1 mA difference. The amount of current generated by the circuit can be configured using five push buttons shown in Fig.3. These buttons are configured to output 0.5 mA, 1 mA, 1.5 mA, 2 mA, 2.5 mA, 3 mA. By switching on one or more of them, it is possible to configure the output current from 0.5 mA to 10.5 mA. (e.g., By activating both the 0.5 mA and 3 mA buttons together, a total of 3.5 mA current will be produced). However, we found that 5 mA is the maximum harmless current for human subjects [43]. Therefore, we stimulated the subjects for a range between 1 mA to 4 mA. This was similar to the range of stimulation currents which were used in [39] but we used different frequencies and stimulation times. The maximum load resistance of this device is up to 4 kΩ. The power supply produces a variable voltage up to 30 V.

Microcontroller program controls the frequency of stimulation pulses and stimulation time. For the user experiments, we programmed the device for four frequencies: 2 Hz, 10 Hz, 70 Hz, and 180 Hz which are identical to the stimulation frequencies used in [41].[1] However, we have tested these frequencies using much higher current (1 mA–4mA) and these combination of current and frequency was never tested before on human subjects. We have recorded and analyzed the accuracy of the signal produced under different stimulation settings. Some sample measurements are showed in Fig.5. Regarding the amplitude, maximum of 2% error was recorded with compared to the intended current output and actual current output as reported in Table 1. This is probably due to component tolerances. Negative spikes at the falling edge was recorded probably due to stray inductance. From the equation $V = L\frac{di}{dt}$, a negative voltage was likely induced from stray currents, as there are considerable changes in current values during the transient phases.

For successful stimulation, electrodes need to read resistance from the skin. Therefore, a digital multimeter was connected to the controller circuit to monitor the output current during the stimulation. Using the endoscopic camera, researcher who operate the device was able to see whether the two electrodes are near the area of stimulation and readings from the multimeter provided the confirmation of whether the two electrodes are touching the surface of the skin. If the electrodes were not touching properly, the multimeter outputs 0 mA. This device can be controlled using any serial port client and the based on the keyboard inputs received through a USB connection Arduino microcontroller produces the intended output signal.

IV. USER EVALUATIONS

To investigate the effects of the device we tested it with human subjects in two ways: a. stimulated the nasal mucosa of subjects and recorded induced sensations, and b. studied whether electrical stimulation modify the odor sniffing ability. 31 subjects (11 females, mean age 24.5 ± 5.01) participated in these experiments. Most of the participants were undergraduate students, age between 20 to 23 years old, and a few non-student adults. The subjects were all below the age of 50 years. This selection was made because studies have revealed that ageing most often leads to decline of olfaction [44]. Each subject first filled out a questionnaire relating to his/her health status and allergies. Participants were physically screened by answering some general well-being questions. They also confirmed whether they have intact olfaction, nasal congestion, non-use of chronic medication of any kind, no current head injury, and no history of mental ailment. Nevertheless, to assure participant had a clear and unharmed nasal passage, every experiment preceded by nasal endoscopic examination.

The study design was submitted to the institutional review board (IRB). Approval was gotten after some modifications bordering on safety of participants were made. Before beginning the experiment, the procedure was explained in details and participants filled and signed a consent form before participating in the experiment which was conducted according to the ethics guidelines approved by the IRB. Nevertheless, a participant was free to quit the experiment if he/she felt the procedure was uncomfortable.

---

[1] Authors of the particular paper said "The stimulation parameters we tested using this design were a continuous sine wave delivered at 5 frequencies: 2, 10, 70, 90, 130, and 180 Hz, and a burst mode (5 cycles, 100-μs pulse width) delivered at 90 or 180 Hz, all applied at currents ranging from 50 up to 800 μA, at typically 10 μA intervals. A typical experiment lasted about 1 h."

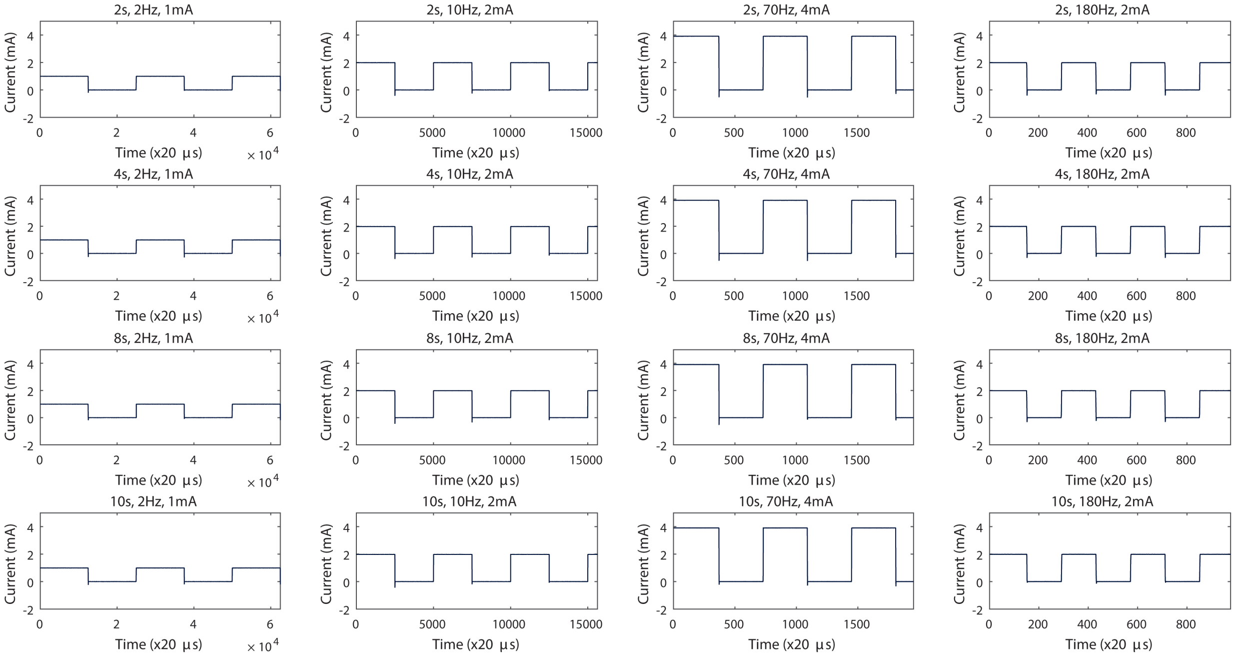


FIGURE 5. Different stimulation patterns recorded from the device which used to stimulate human subjects. Maximum of 2% error and negative spikes at the falling edge was observed probably due to component tolerance and stray inductance.

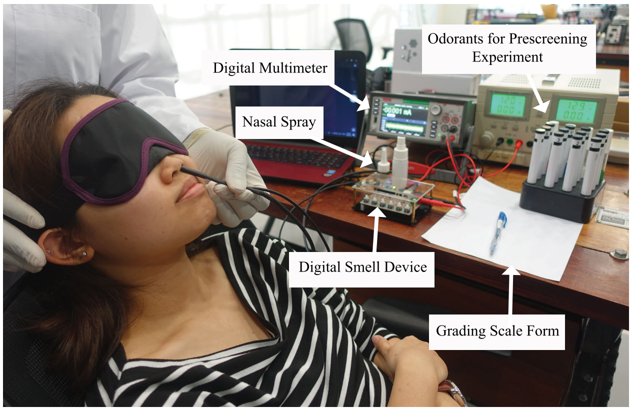


FIGURE 6. Stimulating the nasal cavity of a participant using the electric smell device.

A. PRE-SCREENING EXPERIMENT: SNIFFING OF KNOWN ODORANTS

Here we aimed at determining the smelling competence of the participants and to study the effect of electrical stimulation on the nasal cavity by sniffing known odorants. In this regard, 5 known odorants (orange, cinnamon, banana, pineapple, and peppermint) were randomly presented to the participants. In order to conceal the colour of the odorants, they were presented in a non-translucent container and numbered 1 to 5. Participants by closing either the left or right nose, sniffed each odorant one at a time, identify the type of odorant, and rate its intensity using a grading scale. Water was used to reset the olfactory receptors to their original state, therefore, after each trial, participants were asked to sniff water before sniffing another odorant. The process was repeated for all 5 odorants. This was done to determine the competence of the subject to identify different smells, and to rule out anosmia prior to the main experiment. The participants repeated this procedure after the main electric stimulation to compare the intensity of the odorants.

B. ELECTRICAL STIMULATION OF THE NASAL MUCOSA

In this study our aim was to electrically stimulate the nasal mucosa to induce smell or other sensations. Hence, we targeted different areas at the uppermost layer of the inferior, middle and superior conchae, as well as the dorsal septum. Nevertheless, our stimulations were majorly at the middle turbinate where olfactory local field potentials are easily acquired [45]. Eight different current and frequency combinations (1mA/2Hz, 1mA/10Hz, 1mA/70Hz, 1mA/180Hz, 2mA/10Hz, 2mA/70Hz, 2mA/180Hz, and 4mA/70Hz) were used as the stimulation parameters in this experiment. Order of using the stimulation parameters was randomized across the participants.

In a closed and comfortable room, participants were made to seat on an adjustable chair. We applied Azelatine[2] nasal spray in both sides of the nose to abate sneezing. To reduce distractions, the participant's eyes was covered with an eye mask. With endoscope camera guidance, the stimulating silver electrodes was gently inserted into the nasal cavity and gradually brought into contact with the targeted areas, as shown in Fig.6. This was followed by electrical stimulations done concurrently with nasal breathing as though normal sniffing [46], [47].

---

[2] Azelastine Nasal Spray, https://www.drugs.com/cdi/azelastine-spray.html

We measured the induced sensations using a measurement index that can record intensities of 22 different sensations. The sensations were divided into two categories: The first category consisted of the 10 basic smells (fragrant, fruity, citrus, chemical, sweet, minty, Toasted/nutty, decay, and pungent) as characterize by [48]. The second category consisted of induced non-olfactory sensations, which include cooling, heating, electric, pinprick, tingling, numbness, metallic, burning, pleasant, pain, lingering, and pressure.

Each participant went through eight trials. Duration of electrical stimulation was fixed at 10 s, with an inter-stimulus interval of 60 s. Although, all stimulation parameters commenced with an initial current of 1 mA but was gradually and repeatedly increased until 4 mA. During the interval between trials, participants filled a response form where they indicated the type of sensation perceived during and after every trial. Using a grading scale ranging from 0 (none) to 10 (strongest), they graded the intensity of the smell, before and after electric stimulation. The participants completed the response form for the eight trials, after which an analysis for each of the participants responses were made, and the parameters compared. The experiment lasted for about 45 minutes for each participant.

1) FINDINGS

Out of the eight stimulation parameters used, 1 mA and 10 Hz, and 1 mA and 70 Hz gave the most important results for smell related responses. Fig.7 shows the resulted sensations based on the categorization by Castro et al. [48], reported by the participants in percentages. Chemical and fragrant smells was reported in 27% of the participants. Other smell sensations reported with 1mA and 70Hz includes fruity 20%, sweet 20%, toasted and nutty 17%, minty 10%, and woody 13%. Other stimulation parameters, 1 mA and 10 Hz, 17% reported fragrant smell, 27% sweet, 10% chemical, and 10% woody. During the 4 mA and 70 Hz stimulation 82% reported pain (the mean intensity value received for pain was 2.95 ± 0.85), while 64% reported pressure.

Fig.8 represents the mean intensities reported for each type of smell at different stimulation parameters. Intensity values were based on the 10-point grading scale (0 = none and 10 = strongest). For most of the sensations, intensity values were reported between 1 and 3. Participants reported that they felt pain (Fig.10) and tingling (Fig.9) sensations for the combinations, 1 mA 180 Hz and 4 mA and 70 Hz. Hence, we think combinations of high frequencies and high currents could be associated with pain sensation. We also observed at the same time that most participant reported pain when the stimulating electrodes were outside the olfactory cleft and touching the respiratory mucosa. Visual flashes were reported by two participants at stimulation of 4mA and 70Hz. Similarly, a previous study [41] also reported visual flashes using 0.45mA and 10Hz. Hence, we still do not understand the underlying factors contributing to most of the non-olfactory sensations.

TABLE 2. Mean intensities for sniffing known odorants before and after electrical stimulation'.

Odorants	Mean before	Mean after
Banana	6.8	6.3
Cinnamon	5.7	5.2
Orange	6.1	5.8
Peppermint	6.9	6.5
Pineapple	5.8	5.8

C. THE RESPONSE PRODUCED AFTER SNIFFING OF KNOWN ODORANTS

To study the effect of electrical stimulation on the nasal mucosa, we compared the intensities of several odorants before and after stimulation. We tested the ability of each participant to identify different kinds of odorants. The five known odorants presented to the participants were, banana, cinnamon, orange, peppermint, and pineapple. Table 2 shows the result of odorant intensity before and after electrical stimulation of the nasal concha. As shown in the table, the intensity before and after stimulation was almost similar for all odorants, nevertheless, most participants verbally reported they felt the odorants smelled different after the electrical stimulation. In this study, shapiro-wilk test was employed to assess the distribution of data because the sample of respondents was less than 100. The results show that data in this study were normally distributed. Hence, a paired sample t-test was conducted to compare the intensity of the odorants perceived by the participants before and after applying electrical stimulation conditions. There was a significant difference in the scores for cinnamon before electrical stimulations ($M = 5.73$, $SD = 1.946$) and cinnamon after electrical stimulations ($M = 5.17$, $SD = 1.895$) conditions; $t(30) = 2.288$, $p = 0.016$. However, there was no significant difference found in orange before ($M = 6.13$, $SD = 1.727$) and after ($M = 5.77$, $SD = 2.061$); $t(30) = 1.514$, $p = 0.141$, banana before ($M = 6.77$, $SD = 1.892$) and after ($M = 6.29$, $SD = 2.179$); $t(30) = 1.360$, $p = 0.184$, pineapple before ($M = 5.84$, $SD = 1.934$) and after ($M = 5.81$, $SD = 2.151$); $t(30) = 0.103$, $p = 0.919$, and peppermint before ($M = 6.90$, $SD = 2.441$) and after ($M = 6.55$, $SD = 2.234$); $t(30) = 1.283$, $p = 0.209$. $P < 0.05$ for cinnamon and $P > 0.05$ for orange, banana, pineapple, and peppermint odorants. Due to the mixed results received we could not conclude any strong opinion on this experiment, however, it would be safer to say that, electrical stimulation of the olfactory mucosa possibly influenced the perceived intensity of cinnamon odorants.

D. USER PERCEPTIONS ABOUT FUTURE DIGITAL SMELL DEVICE

Further, we conducted a survey to investigated the user perceptions about expected benefits, personal privacy, and

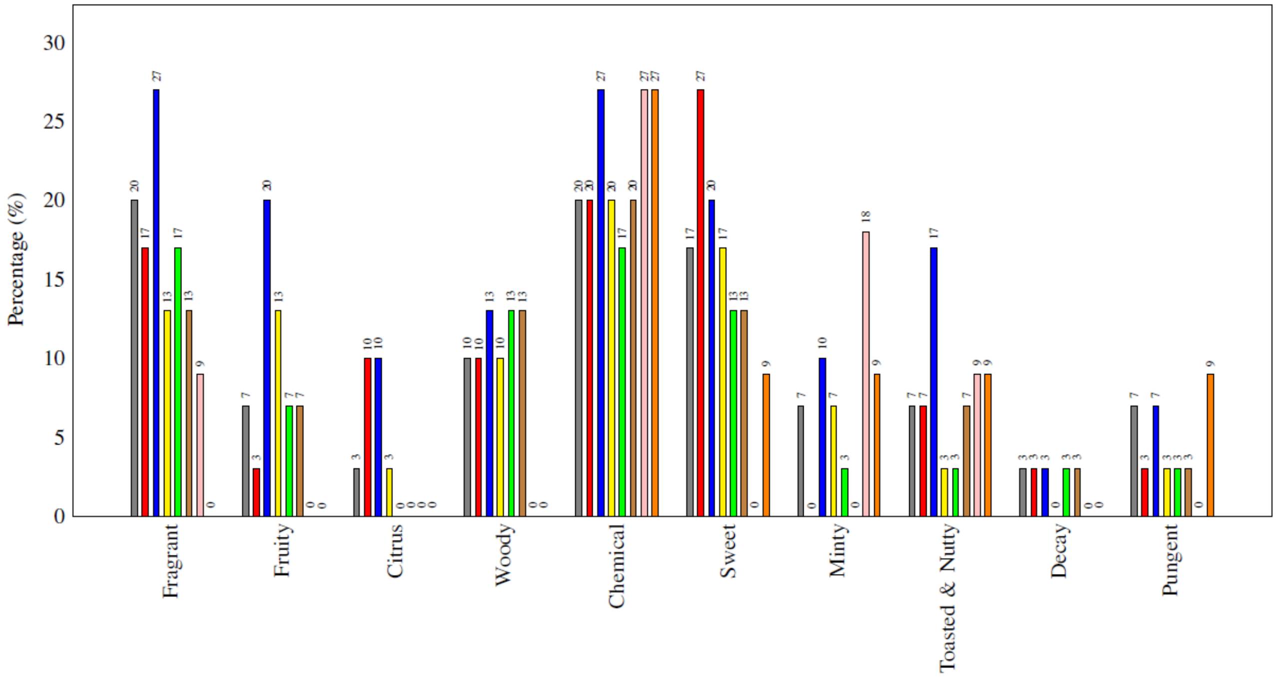


FIGURE 7. Percentage of the participants who reported 10 basic smells for different electrical stimulation patterns.

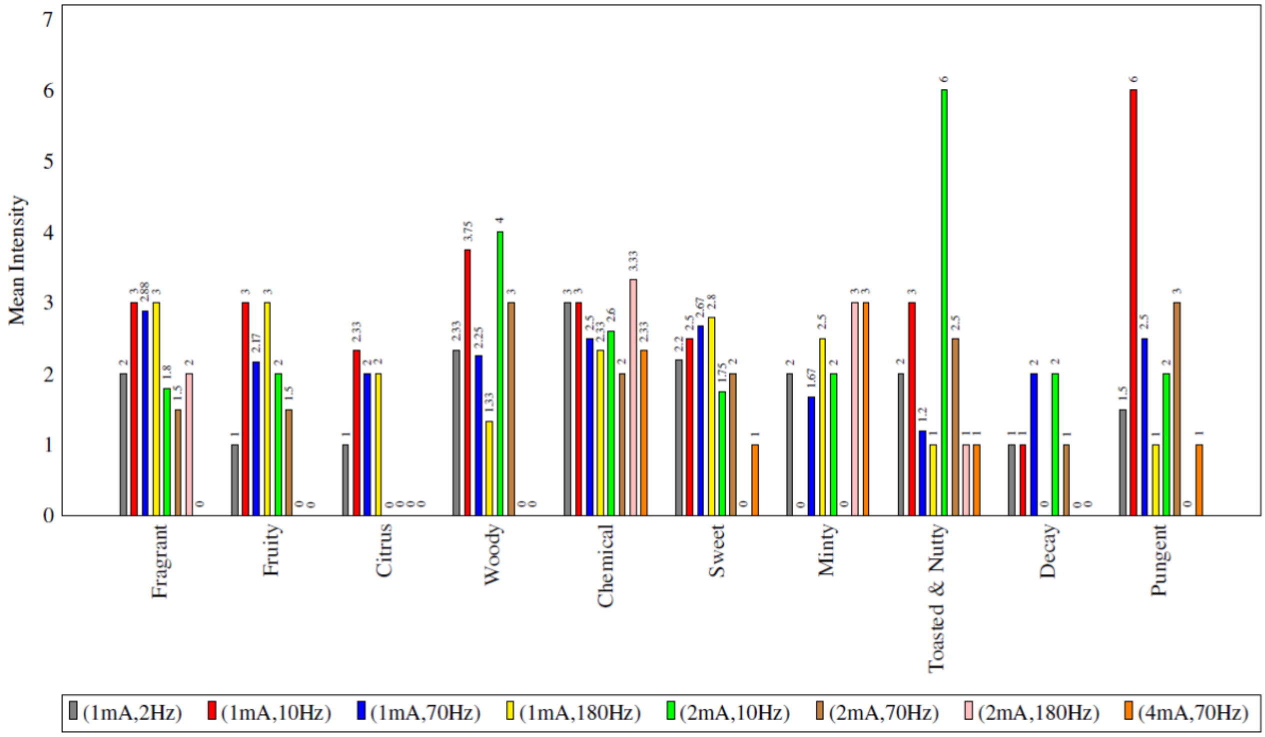


FIGURE 8. Mean intensity of 10 basic smells for different electrical stimulation patterns. Sum of the perceived intensity of the smell (range: from 0-no smell to 10-highest imaginable intensity)/Total number of participants who felt that smell for that stimulation parameters.

adoption intention of this device. We defined those factors as follows;

Expected benefits: Previous works have suggested the role of utilitarian factors as an antecedent to technology adoption [49], [50]. In addition to that, we have used hedonic factors as in [51] and [50].

Personal privacy: Here, we concerned that possibility of hacking could affect personal privacy. According

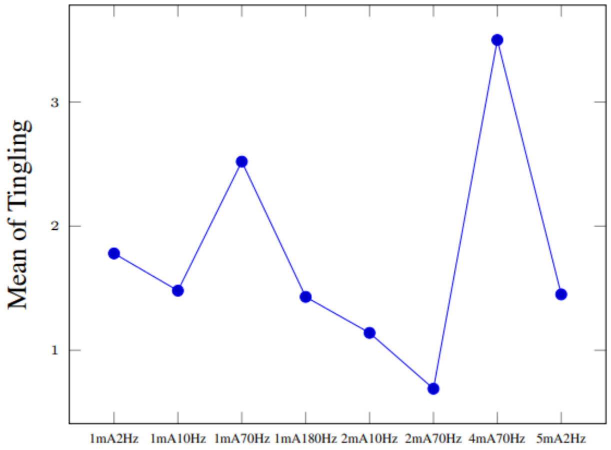


FIGURE 9. Mean intensity of the tingling induced by different electrical stimulation patterns. Calculated using a range 0 - 10 (where 10 is the most).

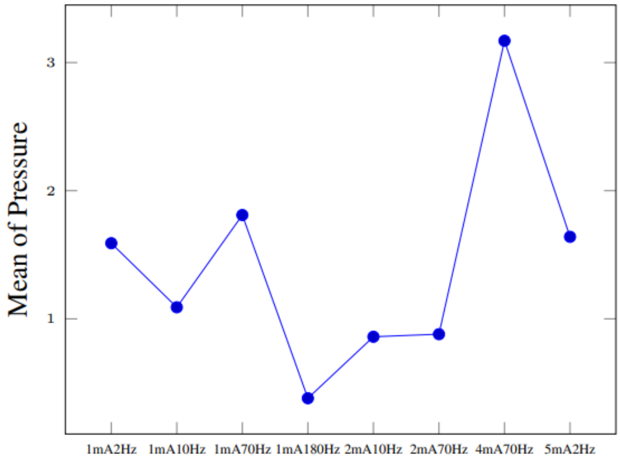


FIGURE 10. Mean intensity of the pressure induced by different electrical stimulation patterns. Calculated using a range 0 - 10 (where 10 is the most).

to [52] and [50] concerns of the users on privacy threats prevents the development of trust in the technology.

Adoption intention: Here we tested the expected easiness to use the technology as well as adoption intentions regarding the using and purchasing [53]. Further, works by [54] and [55] have shown that adoption intentions can be affected based on the adoption intention of their peers.

1) RESEARCH PROCESS AND DATA ANALYSIS

The combination of survey and open-ended questions were used in this study. Our sample consisted of 91 participants (35 females, Age range 20 or above). All 91 participants were familiar with using Internet and email. 20 Participants knew about this research before. Out of these 20 participants, 15 participated to the 'Electrical Stimulation of the Nasal Mucosa' experiment that discussed earlier.

Participants received a link to the survey through email. They were supposed to watch a 3 min and 6 s long project video before answering the questionnaire. This video provided a quick overview of the research including the concept of electrical stimulation, objectives, procedures for the stimulation, results, and future directions.

The questionnaire we used to collect the data was developed based on the works of [50] and [53]. This questionnaire had two sections, first section contained 14 questions with 5-point Likert scales (1 strongly disagree to 5 strongly agree). The second section of the questionnaire contained with 6 open-ended questions.

We measured the internal consistency reliability of the survey based on Cronbach's alpha. The value of 0.89 obtained showed that the questionnaire is a reliable measure. The 'Cronbach's alpha if items deleted' values for all items were between 0.83 and 0.89; which are similar to the Cronbach alpha of the whole scale (0.89), indicating that item deletion will not improve the internal consistency of the questionnaire in any significant way. Therefore, we used all the items in this questionnaire.

2) FINDINGS

Fig.11 shows the percentage of participants who answered these questions with either 4 (agree) or 5 (strongly agree) on the 5-point Likert scale.

Expected benefits: Related to the expected benefits, 69.2%, 75.8%, and 79.2% of participants rated that Digital Smell Device could be entertaining, fun, and enjoyable. These findings are in line with open-ended results, for example, participants like this device because it is "fun, easy to use and could open new possibilities". This shows the participant expected hedonic benefits from this device. Further, 56.1% and 38.5% of the participants rated this device could increase productivity and efficiency of their life. Some answers received through the qualitative questions were "Because it can ease human life in many situations such as Internet shopping and ordering foods", "It opens a new medium of communication", and "I can communicate olfactory information.", "Sometimes I want to try some new shampoo or body lotion but wonder about the smell. This device if possible it could give the example like going into the store and smell those substances before deciding on brands.", "I can imagine that there is huge potential in such technology for any application involving memory. I could imagine it being very useful in augmented and virtual reality contexts - definitely to increase the experience, impact on immersion, etc.", "Could help in medical industry for patients who are suffering with smell distortion", and "More realistic information can be shared".

Personal privacy: Related to the personal privacy, 59.4% and 55% of participants rated that their personal privacy could be in danger if, for example, hackers gain access to the device. Again, this finding is in line with our qualitative data like "Someone can misuse and hack the device if it's not protected.", and "As this device is electrically controlled, it will be easy for some people to hack into this device and use it for their own benefits."

Adoption intention: Regarding the adoption intention, 52.8% and 72.6% participants expected that future digital

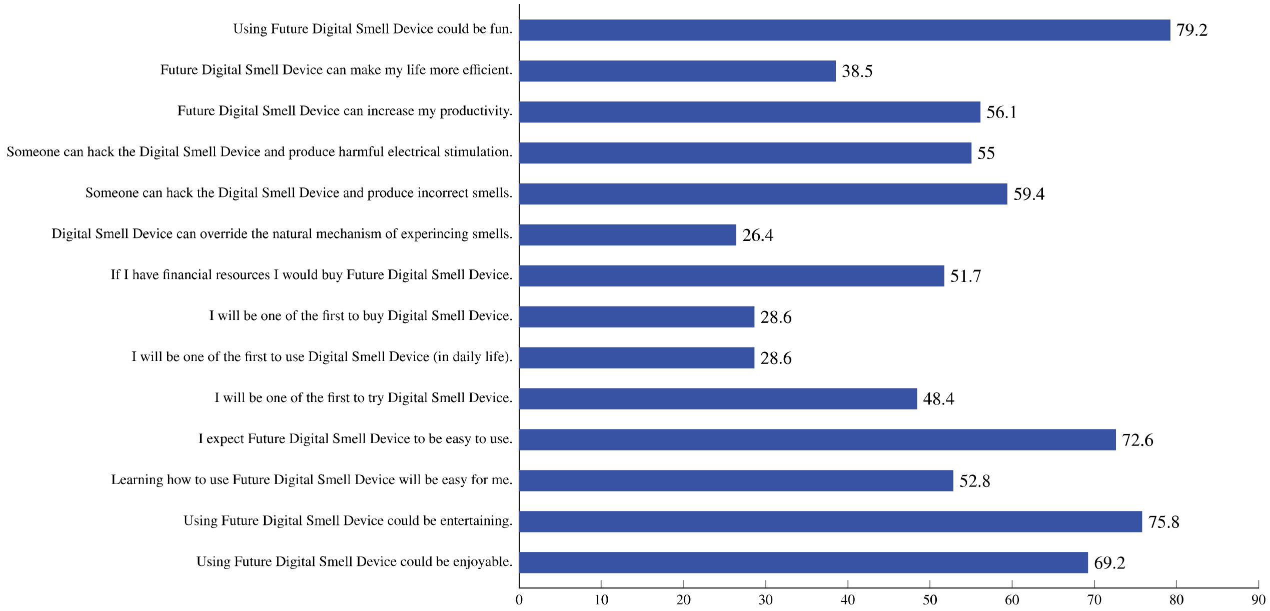


FIGURE 11. **Percentage of participants who rated either 4 (agree) or 5 (strongly agree) on the 5-point Likert scale.**

smell device will be easy to use. Some comments received through the open-ended questions were "Through this device we can see various different experiences in our day to day life and I think it will minimize and easy the work.", "make the life style easy", "It appears that it might be easy to handle and wear". Further, 48.4% of them want to be one of the first to try but only 28.6% wanted to use this device in daily life, and 26.4% of the participants believed that this device can override the natural mechanism of experiencing smells. However, 28.6% rated that they will be the first one to buy this device. Further 51.7% said if they have financial resources they would like to buy it. probably, the rest of the participants who rated the device is easy to use or would like try are fallen into the category of 'influenced by peers' as discussed in [54], [55], and [53], which means when the people started to use Digital Smell Device the more people will purchase and use in their daily life.

V. DISCUSSION

The aim of this research was to electrically stimulate the human olfactory epithelium and to measure and characterize the corresponding sensations. Hence, our stimulations were majorly at the middle concha where olfactory local field potentials are easily acquired [45], while few were at the superior and inferior conchae, based on the results from epithelial biopsies on spread of olfactory mucosa [58], [59]. Stimulations with 1 mA and 70 Hz and 1 mA and 10 Hz combinations generated smell sensations such as chemical, fragrant, and sweet smells. Furthermore, some participants reported higher intensity levels for certain smells as shown in Fig.8. This indicate evidences that there could be an electrical path to generate smell sensations in human.

Comparison between related works and our research as shown in Table 3 revealed our study till date as the only non-invasive study that was successful on producing smells sensations using electrical stimulation, after the study reported by Uziel [36].

One of the key limitations we have experienced during our experiments was the reluctance of the participants to allow for the insertion of the electrode and camera because of the size of the camera and their concern for hygiene of the electrodes. By using a smaller endoscopic camera we may be able improve the usability of the device. Another challenge we faced during the experiments was the pain that subjects felt during the electrical stimulation. Anodic stimulation [41] can reduce the pain that subjects feel and therefore, in future we would like to use it as one of the testing methods. Another improvement we targeted to do is to provide electrical stimulation on the areas of the nasal cavity where it has minimum or no olfactory receptors (such as lower turbinate) and compare resulting sensations with the sensations produced by electrical stimulation of the areas which are known for the olfactory receptors. Using this method we will be able get a rough estimation on the incorrect user responses for smell sensations.

As the next step of this research, we started to collaborate with some medical experts to do more controlled experiments. This will include a fMRI experiment with stimulating olfactory receptors with natural odorants and electrical stimulation. Participants who already reported virtual smell sensations would participate in to this study. If both stimulation techniques activate approximately same areas of the brain, we will be able to argue that electrical stimulation can reproduce the similar sensation as chemical based smells do. However, this would be the topic for a future full paper.

Also, this method could be used as an alternative for sensory restoration [60] for people who lost their sense of smell due to some medical conditions. However, we acknowledge

TABLE 3. A comparison between the related works and 'Electric Smell Device'.

Title	Contributions	Stimulation Parameters
Stimulation of human olfactory neuroepithelium by long-term continuous electrical currents [36]	• Anodal stimulation produced odor perceptions, such as vanilla, almond, and bitter almond • Cathodal stimulation produced wide ranging burnt odor	Current:0.25–0.5 mA; and Stimulation duration:10 s
Effects of electrical stimulation of the human olfactory mucosa [37]	• Suppressed smell sensations of presented odorants	• Electrode put inside nasal cavity. Second electrode located on the right arm with frequency 60Hz; and Duration:1–10 s
Olfactory bulb potentials to electrical stimulation of the olfactory mucosa [56]	• Evoked potentials in secondary olfactory neurons.	• Voltage:1–20 V; Stimulation Length:0.2–0.5 ms; The electrodes were placed on the scalp near forehead
Olfactory evoked potential produced by electrical stimulation of the human olfactory mucosa [57]	• Showed olfactory bulbar potentials	• Current:2 mA; and Frequency:0.5 Hz
From nose to brain: Un-sensed electrical currents applied in the nose alter activity in deep brain structures [41]	• Some subject reported significant impact on the perceived intensity of smell when they sniffed during the electrical stimulation	• Current:0.05–0.8 mA; and Frequency:2, 10, 70, 90, 130, 180 Hz
Electrically stimulated olfactory evoked potential in olfactory disturbance [39]	• Olfactory evoked potentials were recorded	• Current:2 mA; and Duration:0.5 ms
Olfactory hallucinations elicited by electrical stimulation via subdural electrodes: effects of direct stimulation of olfactory bulb and tract [42]	• Nine subjects perceived unpleasant smells (like bitterness, smoke, or garbage, while two subjects perceived a pleasant smell (like strawberry or good food) and lastly, five subject did not smell anything.	• Invasive stimulation of frontal lobe with the Current: 3 mA, 6 mA, and 9 mA; Frequency: 50 Hz; and Duration: 5 s
Olfactory evoked potentials: experimental and clinical studies [40]	• Evoked potentials recorded directly from the olfactory tract	• Voltage:10–50 V rectangular pulse; Duration:0.1–0.2 ms; and Frequency:0.1–10 Hz
Electric Smell: Towards Artificially Reproducing Smell Sensations for Future VR and Multisensory Internet (this paper)	• 1 mA and 70 Hz, 27% reported chemical and fragrant smells while 20% reported fruity and sweet smells. • 1 mA and 10 Hz, 27% of participants perceived sweet smells while 20% reported chemical smell sensations. • Chemical smell was reported 17% or higher for all the different stimulations • Significant effects for tingling and pressure sensations obtained. • Participants reported slightly less perceived intensity of smell for sniffing after having stimulation	• Current:1–5 mA; Frequency:2, 10, 70, 180 Hz; Duration:10 s

the challenge in odor discrimination and generalization. To our knowledge, no research has been done to show if neurons have a consistent link to specific odors among individuals. Recent study by [61], has revealed that a specific pattern of neural activity cannot be tied to a class of odors. Furthermore, representation of a given odor will differ among different individuals across the different sections of the brain.

VI. CONCLUSION

Contributions made by this paper are as follows; first, we described the development of a computer controlled digital device that can stimulate the olfactory receptors using electric pulses. Second, we tested this device on human subjects (n=31) using parameters which were not previously tested (current: 1–5 mA, frequency: 2–180 Hz). Third, we presented the results reported for 22 different types of sensations during the electrical stimulation. One fourth of the participants reported some kind of smell sensation, including sweet, chemical, and fragrant. Forth, we tested the odor sniffing ability before and after the electrical stimulation for five odorants and found possibly electrical stimulation influenced the smelling ability for the cinnamon smell. Finally, through a survey, we found that this kind of device would be fun, enjoyable, and useful in future.

Today, Internet communication is mainly based on audio and visual. If the electrical stimulation of olfactory receptors can produce more complex smell sensations (e.g smell of a particular flower, meal, perfume, etc), it will revolutionize the field of communication. Similar to the users receiving visual/auditory data using a head mounted display (HMD)or using a headphone, and it will be possible to communicate and regenerate smell experiences digitally by small wearable gadgets. Digitizing touch and taste senses [10], [62], [63], [64] have already been achieved experimentally at the research level and could become an everyday standard in the near future. With the digitization of smell, we will be able to experience five basic senses digitally and it will create more applications and opportunities in fields such as human computer interaction, gaming, medicine, and internet shopping.

ACKNOWLEDGMENT

The authors would like to greatly appreciate valuable contributions made by their former team members of this project Surina Hariri, Sharon Kalu Joseph Ufere, Hanis Camelia, and Nur Ain Mustafa. Without their hard work this project would not have been feasible. They further acknowledge the generous support from the University of Colombo School of Computing under the funding scheme, Research Allocation for Research and Development under Grant UCSC/RF/MXR/GN001. This financial assistance greatly contributed to the success of their research endeavor by covering various research-related expenses.

REFERENCES

[1] P. Kortum, *HCI Beyond the GUI: Design for Haptic, Speech, Olfactory, and Other Nontraditional Interfaces*. Burlington, MA, USA: Morgan Kaufmann, 2008.

[2] R. Tortell, D. P. Luigi, A. Dozois, S. Bouchard, J. F. Morie, and D. Ilan, "The effects of scent and game play experience on memory of a virtual environment," *Virtual Reality*, vol. 11, no. 1, pp. 61–68, Mar. 2007.

[3] J. F. Morie, D.-P. Luigi, C. Lathan, M. Pettersen, and J. M. Vice, "Scent delivery device and method of simulating scent in a virtual environment," U.S. Patent 7 484 716, Feb. 3, 2009.

[4] A. Bodnar, R. Corbett, and D. Nekrasovski, "AROMA: Ambient awareness through olfaction in a messaging application," in *Proc. 6th Int. Conf. Multimodal Interface*, Oct. 2004, pp. 183–190.

[5] Y. Choi, A. D. Cheok, X. Roman, T. A. Nguyen, K. Sugimoto, and V. Halupka, "Sound perfume: Designing a wearable sound and fragrance media for face-to-face interpersonal interaction," in *Proc. 8th Int. Conf. Adv. Comput. Entertainment Technol.*, Nov. 2011, pp. 1–12.

[6] D. McGookin and D. Escobar, "Hajukone: Developing an open source olfactory device," in *Proc. CHI Conf. Extended Abstr. Hum. Factors Comput. Syst.*, May 2016, pp. 1721–1728.

[7] S. A. Seah, D. M. Plasencia, P. D. Bennett, A. Karnik, V. S. Otrocol, J. Knibbe, A. Cockburn, and S. Subramanian, "SensaBubble: A chrono-sensory mid-air display of sight and smell," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, Apr. 2014, pp. 2863–2872.

[8] (Mar. 2018). *Scent Air*. [Online]. Available: http://www.scentair.com/why-scentair/scents/

[9] (Mar. 2018). *Scentee*. [Online]. Available: https://scentee.com/

[10] N. Ranasinghe, K. Karunanayaka, A. Cheok, O. Fernando, H. Nii, and P. Gopalakrishnakone, "Digital taste and smell communication," in *Proc. 6th Int. ICST Conf. Body Area Netw.*, 2011, pp. 78–84.

[11] N. Ranasinghe, A. D. Cheok, and R. Nakatsu, "Taste/IP: The sensation of taste for digital communication," in *Proc. 14th ACM Int. Conf. Multimodal Interact.*, Oct. 2012, pp. 409–416.

[12] K. Karunanayaka, N. Johari, S. Hariri, H. Camelia, K. S. Bielawski, and A. D. Cheok, "New thermal taste actuation technology for future multisensory virtual reality and internet," *IEEE Trans. Vis. Comput. Graph.*, vol. 24, no. 4, pp. 1496–1505, Apr. 2018.

[13] S. Hariri, N. A. Mustafa, K. Karunanayaka, and A. D. Cheok, "Electrical stimulation of olfactory receptors for digitizing smell," in *Proc. Workshop Multimodal Virtual Augmented Reality*, Nov. 2016, pp. 1–12.

[14] K. Kasun, U. S. Kalu, C. Hanis, and C. A. David, "Electric stimulation of human nasal conchae towards reproduction of olfactory sensations," *Clin. Med. Image Library*, vol. 4, no. 5, pp. 118–119, Oct. 2018.

[15] A. D. Cheok and K. Karunanayaka, "Digital smell interface," in *Virtual Taste and Smell Technologies for Multisensory Internet and Virtual Reality*. Cham, Switzerland: Springer, 2018, pp. 93–117.

[16] J. M. Young, "Different evolutionary processes shaped the mouse and human olfactory receptor gene families," *Hum. Mol. Genet.*, vol. 11, no. 5, pp. 535–546, Mar. 2002.

[17] G. M. Shepherd, "The human sense of smell: Are we better than we think?" *PLoS Biol.*, vol. 2, no. 5, p. e146, May 2004.

[18] J. P. McGann, "Poor human olfaction is a 19th-century myth," *Science*, vol. 356, no. 6338, May 2017, Art. no. eaam7263.

[19] C. Bushdid, M. O. Magnasco, L. B. Vosshall, and A. Keller, "Humans can discriminate more than 1 trillion olfactory stimuli," *Science*, vol. 343, no. 6177, pp. 1370–1372, Mar. 2014.

[20] M. Meister, "Can humans really discriminate 1 trillion odors?" 2014, *arXiv:1411.0165*.

[21] J. M. Annett, "Olfactory memory: A case study in cognitive psychology," *J. Psychol.*, vol. 130, no. 3, pp. 309–319, May 1996.

[22] V. Danthiir, R. D. Roberts, G. Pallier, and L. Stankov, "What the nose knows: Olfaction and cognitive abilities," *Intelligence*, vol. 29, no. 4, pp. 337–361, Jul. 2001.

[23] C. Youngblut, R. E. Johnston, S. H. Nash, R. A. Wienclaw, and C. A. Will, "Review of virtual environment interface technology," Inst. Defence Analyses Alexandria, Alexandria, VI, USA, Tech. Rep. IDA PAPER P-3186, 1996. [Online]. Available: https://apps.dtic.mil/sti/pdfs/ADA314134.pdf

[24] J. C. Leffingwell, "Olfaction–update, no. 5," *Leffingwell Rep.*, vol. 2, no. 1, pp. 1–34, 2002.

[25] L. Buck and R. Axel, "A novel multigene family may encode odorant receptors: A molecular basis for odor recognition," *Cell*, vol. 65, no. 1, pp. 175–187, Apr. 1991.

[26] T. Narumi, S. Nishizaka, T. Kajinami, T. Tanikawa, and M. Hirose, "Augmented reality flavors: Gustatory display based on edible marker and cross-modal interaction," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.*, May 2011, pp. 93–102.

[27] T. Yamada, S. Yokoyama, T. Tanikawa, K. Hirota, and M. Hirose, "Wearable olfactory display: Using odor in outdoor environment," in *Proc. IEEE Virtual Reality Conf. (VR)*, Apr. 2006, pp. 199–206.

[28] K. Karunanayaka, H. Saadiah, H. Shahroom, and A. David Cheok, "Methods to develop a low cost laboratory olfactometer for multisensory, psychology, and neuroscience experiments," in *Proc. 43rd Annu. Conf. IEEE Ind. Electron. Soc.*, Oct. 2017, pp. 2882–2887.

[29] M. Obrist, C. Velasco, C. T. Vi, N. Ranasinghe, A. Israr, A. D. Cheok, C. Spence, and P. Gopalakrishnakone, "Touch, taste, & smell user interfaces: The future of multisensory HCI," in *Proc. CHI Conf. Extended Abstr. Hum. Factors Comput. Syst.*, May 2016, pp. 3285–3292.

[30] C. T. Vi, D. Ablart, D. Arthur, and M. Obrist, "Gustatory interface: The challenges of 'how' to stimulate the sense of taste," in *Proc. 2nd ACM SIGCHI Int. Workshop Multisensory Approaches Hum.-Food Interact.*, Nov. 2017, pp. 29–33.

[31] W. Hürst, D. Iwai, and P. Balakrishnan, "International workshop on multimodal virtual and augmented reality (workshop summary)," in *Proc. 18th ACM Int. Conf. Multimodal Interact.*, Oct. 2016, pp. 596–597.

[32] A. Nijholt, C. Velasco, K. Karunanayaka, and G. Huisman, "1st international workshop on multi-sensorial approaches to human-food interaction (workshop summary)," in *Proc. 18th ACM Int. Conf. Multimodal Interact.*, Oct. 2016, pp. 601–603.

[33] M. Murer, I. Aslan, and M. Tscheligi, "LOLL IO: Exploring taste as playful modality," in *Proc. 7th Int. Conf. Tangible, Embedded Embodied Interact.*, Feb. 2013, pp. 299–302.

[34] R. Vogel. (Dec. 2016). *Understanding Anodal and Cathodal Stimulation*. [Online]. Available: http://neurologiclabs.com/understanding-anodal-and-cathodal-stimulation/

[35] E. K. Ellegård, D. Goldsmith, K. D. Hay, and R. P. Morton, "Studies on the relationship between electrogustometry and sour taste perception," *Auris Nasus Larynx*, vol. 34, no. 4, pp. 477–480, Dec. 2007.

[36] A. Uziel, "Stimulation of human olfactory neuro-epithelium by long-term continuous electrical currents," *J. Physiologie*, vol. 66, no. 4, pp. 409–422, 1973.

[37] M. Straschill, H. Stahl, and K. Gorkisch, "Effects of electrical stimulation of the human olfactory mucosa," *Stereotactic Funct. Neurosurg.*, vol. 46, nos. 5–6, pp. 286–289, 1983.

[38] T. Ishimaru, T. Shimada, M. Sakumoto, T. Miwa, Y. Kimura, and M. Furukawa, "Olfactory evoked potential produced by electrical stimulation of the human olfactory mucosa," *Chem. Senses*, vol. 22, no. 1, pp. 77–81, 1997.

[39] T. Ishimaru, T. Miwa, T. Shimada, and M. Furukawa, "Electrically stimulated olfactory evoked potential in olfactory disturbance," *Ann. Otol., Rhinol. Laryngol.*, vol. 111, no. 6, pp. 518–522, Jun. 2002.

[40] M. Sato, N. Kodama, T. Sasaki, and M. Ohta, "Olfactory evoked potentials: Experimental and clinical studies," *J. Neurosurg.*, vol. 85, no. 6, pp. 1122–1126, Dec. 1996.

[41] T. Weiss, S. Shushan, A. Ravia, A. Hahamy, L. Secundo, A. Weissbrod, A. Ben-Yakov, Y. Holtzman, S. Cohen-Atsmoni, Y. Roth, and N. Sobel, "From nose to brain: Un-sensed electrical currents applied in the nose alter activity in deep brain structures," *Cerebral Cortex*, vol. 26, no. 11, pp. 4180–4191, Oct. 2016.

[42] G. Kumar, C. Juhász, S. Sood, and E. Asano, "Olfactory hallucinations elicited by electrical stimulation via subdural electrodes: Effects of direct stimulation of olfactory bulb and tract," *Epilepsy Behav.*, vol. 24, no. 2, pp. 264–268, Jun. 2012.

[43] P. G. Barash, *Clinical Anesthesia*. Philadelphia, PA, USA: Lippincott Williams & Wilkins, 2009.

[44] K. A. Seiberling and D. B. Conley, "Aging and olfactory and taste function," *Otolaryngologic Clinics North Amer.*, vol. 37, no. 6, pp. 1209–1228, Dec. 2004.

[45] H. Lapid and T. Hummel, "Recording odor-evoked response potentials at the human olfactory epithelium," *Chem. Senses*, vol. 38, no. 1, pp. 3–17, Jan. 2013.

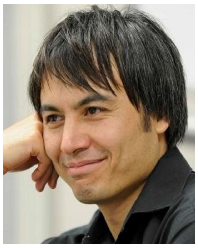
[46] D. Rojas-Líbano and L. M. Kay, "Interplay between sniffing and odorant sorptive properties in the rat," *J. Neurosci.*, vol. 32, no. 44, pp. 15577–15589, Oct. 2012.

[47] J. Mainland and N. Sobel, "The sniff is part of the olfactory percept," *Chem. Senses*, vol. 31, no. 2, pp. 181–196, Feb. 2006.

[48] J. B. Castro, A. Ramanathan, and C. S. Chennubhotla, "Categorical dimensions of human odor descriptor space revealed by non-negative matrix factorization," *PLoS ONE*, vol. 8, no. 9, Sep. 2013, Art. no. e73289.

[49] W. R. King and J. He, "A meta-analysis of the technology acceptance model," *Inf. Manage.*, vol. 43, no. 6, pp. 740–755, Sep. 2006.
[50] P. A. Rauschnabel, J. He, and Y. K. Ro, "Antecedents to the adoption of augmented reality smart glasses: A closer look at privacy risks," *J. Bus. Res.*, vol. 92, pp. 374–384, Nov. 2018.
[51] V. Venkatesh, J. Y. Thong, and X. Xu, "Consumer acceptance and use of information technology: Extending the unified theory of acceptance and use of technology," *MIS Quart.*, vol. 12, pp. 157–178, Jan. 2012.
[52] R. Connolly and F. Bannister, "Consumer trust in internet shopping in Ireland: Towards the development of a more effective trust measurement instrument," *J. Inf. Technol.*, vol. 22, no. 2, pp. 102–118, Jun. 2007.
[53] P. A. Rauschnabel and Y. K. Ro, "Augmented reality smart glasses: An investigation of technology acceptance drivers," *Int. J. Technol. Marketing*, vol. 11, no. 2, pp. 123–148, 2016.
[54] E. M. Rogers, *Diffusion of Innovations*. New York, NY, USA: Simon and Schuster, 2010.
[55] C. Pescher and M. Spann, "Relevance of actors in bridging positions for product-related information diffusion," *J. Bus. Res.*, vol. 67, no. 8, pp. 1630–1637, Aug. 2014.
[56] C. Yamamoto, "Olfactory bulb potentials to electrical stimulation of the olfactory mucosa," *Jpn. J. Physiol.*, vol. 11, no. 5, pp. 545–554, 1961.
[57] T. Ishimaru, M. Sakumoto, Y. Kimura, and M. Furukawa, "Olfactory evoked potentials produced by electrical stimulation of the olfactory mucosa," *Auris Nasus Larynx*, vol. 23, no. 1, pp. 98–104, 1996.
[58] N. E. Rawson and M. H. Ozdener, "Primary culture of the human olfactory neuroepithelium," in *Epithelial Cell Culture Protocols*. Totowa, NJ, USA: Humana Press, 2013, pp. 81–93.
[59] F. Féron, C. Perry, J. J. McGrath, and A. Mackay-Sim, "New techniques for biopsy and culture of human olfactory epithelial neurons," *Arch. Otolaryngol.–Head Neck Surg.*, vol. 124, no. 8, pp. 861–866, 1998.
[60] F. Fleiner, L. Lau, and O. Goktas, "Active olfactory training for the treatment of smelling disorders," *Ear, Nose, Throat J.*, vol. 91, no. 5, pp. 198–203, 215, May 2012. [Online]. Available: http://europepmc.org/abstract/MED/22614554
[61] E. S. Schaffer, D. D. Stettler, D. Kato, G. B. Choi, R. Axel, and L. F. Abbott, "Odor perception on the two sides of the brain: Consistency despite randomness," *Neuron*, vol. 98, no. 4, pp. 736–742.e3, May 2018.
[62] G. C. Burdea, *Force and Touch Feedback for Virtual Reality*. New York, NY, USA: Wiley, 1996.
[63] J. K. S. Teh, A. D. Cheok, R. L. Peiris, Y. Choi, V. Thuong, and S. Lai, "Huggy pajama: A mobile parent and child hugging communication system," in *Proc. 7th Int. Conf. Interact. design Children*, Jun. 2008, pp. 250–257.
[64] Y. Aruga and T. Koike, "Taste change of soup by the recreating of sourness and saltiness using the electrical stimulation," in *Proc. 6th Augmented Hum. Int. Conf.*, Mar. 2015, pp. 191–192.

KASUN KARUNANAYAKA (Member, IEEE) was a Research Fellow/Senior Research Fellow with the Imagineering Institute, Malaysia, from 2015 to 2019. He established the Mixed Reality Laboratory, University of Colombo. He is currently a Senior Lecturer with the University of Colombo School of Computing (UCSC), Sri Lanka. He is the Co-Founder of the UCSC Spatial Experience and Human Computer Interaction (USE-HCI) Laboratory and the Unmanned Aerial Vehicles Research (UAVR) Laboratory, UCSC. He conduct research related to mixed reality, multisensory user interfaces, and artificial intelligence. He coauthored more than 70 scientific publications. Several honors were bestowed upon him, including the ACM SIGCHI Honorary Mentioned Award, in 2015, the IEEE VR Honorable Mentioned Award, in 2018, the ACE Second Best Paper Award, in 2017, and the ACE Best Creative Showcase Demo Award, in 2011.



ADRIAN DAVID CHEOK (Senior Member, IEEE) was formerly a Chair Professor with the City, University of London, a Full Professor with the Graduate School of Media Design, Keio University, an Associate Professor with the National University of Singapore, and an Engineer with Mitsubishi Electric Research Labs, Japan. He is currently a Professor with i-University, Tokyo, and the Director of the Imagineering Institute, Iskandar Puteri, Malaysia. He is also the Founder and the Director of the Mixed Reality Laboratory, Singapore. He has been working on research covering mixed reality, human–computer interfaces, wearable computers and ubiquitous computing, fuzzy systems, embedded systems, and power electronics.

SOMAIYEH VEDADI (Member, IEEE) received the bachelor's and master's degrees in educational technology, in 2006 and 2008, respectively, and the Ph.D. degree from the Department of Educational Sciences, Mathematics and Creative Multimedia, Universiti Teknologi Malaysia (UTM). In her Ph.D. thesis, she has explored the effects of multi-sensory augmented reality on students' motivation in English language learning. She was a Lecturer with the Islamic Azad University of Share Rey, Tehran, Iran, from 2009 to 2011. She is currently a Visiting Researcher with McMaster University, Hamilton, ON, Canada. Her research interests include augmented reality technologies for kids, human–computer interaction, research methodology, and e-learning.