Smelling Screen: Development and Evaluation of an Olfactory Display System for Presenting a Virtual Odor Source

Haruka Matsukura, *Student Member, IEEE*, Tatsuhiro Yoneda, and Hiroshi Ishida, *Member, IEEE*

Fig. 1. Using the proposed olfactory display system (smelling screen) as a digital signage of coffee.

Abstract—We propose a new olfactory display system that can generate an odor distribution on a two-dimensional display screen. The proposed system has four fans on the four corners of the screen. The airflows that are generated by these fans collide multiple times to create an airflow that is directed towards the user from a certain position on the screen. By introducing odor vapor into the airflows, the odor distribution is as if an odor source had been placed onto the screen. The generated odor distribution leads the user to perceive the odor as emanating from a specific region of the screen. The position of this virtual odor source can be shifted to an arbitrary position on the screen by adjusting the balance of the airflows from the four fans. Most users do not immediately notice the odor presentation mechanism of the proposed olfactory display system because the airflow and perceived odor come from the display screen rather than the fans. The airflow velocity can even be set below the threshold for airflow sensation, such that the odor alone is perceived by the user. We present experimental results that show the airflow field and odor distribution that are generated by the proposed system. We also report sensory test results to show how the generated odor distribution is perceived by the user and the issues that must be considered in odor presentation.

Index Terms—Virtual reality, multimedia, olfactory display, wind dislpay

1 Introduction

We perceive the environment around us through the information that is obtained from our sensory systems. Most of this information comes from our eyes and ears. Therefore, it is natural that most research efforts on virtual reality systems have been devoted to the development of visual and audio displays for the realistic presentation of three-dimensional images and surround sound [1]. The sense of touch also provides rich information. Haptic displays have been an active research topic for decades [1]. In contrast with vision, sound, and touch, the sense of smell is often underestimated, and comparatively less attention has been paid to olfactory display technologies.

• *Haruka Matsukura is with Tokyo University of Agriculture and Technology. She is also a Research Fellow of the Japan Society for the Promotion of Science. E-mail: haruka.matsu@gmail.com.*
• *Tatsuhiro Yoneda is with Tokyo University of Agriculture and Technology. E-mail: 50012643066@st.tuat.ac.jp.*
• *Hiroshi Ishida is with Tokyo University of Agriculture and Technology. E-mail: h_ishida@cc.tuat.ac.jp.*

Manuscript received 13 September 2012; accepted 10 January 2013; posted online 16 March 2013; mailed on 16 May 2013.
For information on obtaining reprints of this article, please send e-mail to: tvcg@computer.org.

Olfaction nevertheless plays a vital role in a variety of situations, although we do not always notice it. For example, the sensation of food flavor is a combination of the taste and smell of food [2]. If you hold your nose and drink grape juice, you are limited to the basic taste sensations, e.g., sweet and sour. However, when you open your nose, you immediately recognize the flavor of grape. People often vividly recall a past experience that is associated with a certain smell. The odor-evoked memories are known as the Proust phenomenon [3], which is attributable to the anatomical structure of the brain. The olfactory cortex in the brain has a direct link to the limbic system, which is critical for the experience of emotions and memories [4]. The sense of smell unconsciously affects a person's impression of the environment. Diffusing favorable scents in retail stores is effective towards improving customers' impression of the store environment [5]. Customers in scented stores tend to feel that they have spent less time shopping than they have actually spent.

Considering these unique characteristics of olfaction, various types of olfactory display systems have been proposed and developed in recent years. An olfactory display is a device that generates odor vapor. Presenting the generated odor to the user of a virtual reality system should create a more realistic experience. Nakaizumi et al. once noted that the experience of a virtual world without scents would be similar to being in a spacesuit that has no contact with the air in the virtual world [6]. Specific scenes of movies can be rendered impressive when relevant scents are released at those scenes [7]. The smells that are generated by olfactory displays can be used as special effects of computer games [8]. Olfactory displays can also be used for digital signage. Most advertisements on streets and in stores try to draw customers' attention using visual and audio cues. Digital signage that emits an aroma will render the advertisement impressive and distinctive. Some specialty stores, including bakeries and popcorn shops, already use the scents of their products to catch customers' attention [5].

To provide the user with a sense of smell, an olfactory display generates a vapor of odorous chemical substances and delivers it to the user's nose. A potential limitation of current olfactory display systems is that most of them simply eject odor vapor directly toward their users. Such systems are sufficient for presenting ambient scents in the virtual environment, but may not be sufficient for reproducing the situation, in which an odor is emanating from a specific object. For example, the grass scent in a meadow is distributed almost uniformly throughout the field since the odor source, i.e., the grass, is uniformly distributed. However, if there is a single rose flower in the meadow, the distribution of its sweet smell is localized around the flower. The intensity of the perceived rose scent changes with one's relative position to the rose, which leads to the perception of the odor source location. Suppose that the rose smell is presented to the user from an olfactory display device simultaneously with an image of a rose flower shown on a digital signage screen. The user may not perceive that the smell is coming from the image since the spatial distribution of the smell is centered not around the image of the flower, but around the olfactory display device. If the device is placed in the user's field of view, he/she immediately recognizes that the odor is coming from the device.

We propose a new olfactory display system. To impart to the user a sensation that an odor is emanating from a certain position on a screen, we generate a localized odor distribution around that position. This position serves as a virtual odor source, and can be set at an arbitrary two-dimensional location on the screen. The user can freely move his/her head in front of the screen to sniff at various locations, and can experience realistic changes in the odor intensity with respect to the sniffing location. The structure of the proposed olfactory display is simple but not unrealistically straightforward. Consequently, the users do not immediately notice the mechanism of the odor distribution. This feature enhances the reality of the users' experience. The proposed system can also be used as a wind display that generates an air current that blows to the user's face from a specific position on the screen.

The remainder of our paper is organized as follows. After presenting a summary of related research in Section 2, we describe the structure of the proposed olfactory display system in Section 3. In Section 4, we describe the results of the measurements that we conducted to confirm the odor distribution. Section 5 summarizes the results of the experiments we conducted to evaluate the user's perception of the odor distribution. Section 6 concludes this paper.

2 Related Research

The history of olfactory displays dates to Sensorama in 1962 [9]. Since then, various types of olfactory displays have been developed. The primary research focus has been on the development of mechanisms that allow switching between multiple odors and delivery of odor vapor with a controlled odor concentration. Considering the complexity and diversity of the olfactory receptor cells in mammalian noses [10], it is unlikely that an arbitrary smell can be generated simply by mixing a small set of primary odors. Therefore, in a typical olfactory display system, one ready-made mixture of odorous chemicals in liquid or solid form is prepared to generate each specific smell. The olfactory display reported in [7], for example, can hold up to eight bottles of different odorant mixtures. The device reported in [11] uses aroma chips, in which fragrances are encapsulated in a hydrogel. Heating an aroma chip with a Peltier device generates the odor vapor.

The simplest method to deliver an odor to the user's nose is to allow the odor vapor to diffuse into the environment [12]. However, the timing of odor delivery to the user's nose and concentration of the delivered odor cannot be precisely controlled. It is also difficult to effect rapid switching between different odors. In the olfactory display systems described in [7] and [8], an odor vapor in the headspace of a selected bottle is delivered to the user's nose through a tube attached to a headset. The odor can be switched from one to another using computer-controlled solenoid valves. The intensity of the odor that is presented to the user can also be changed through the solenoid valves to dilute the odor vapor with clean air.

The wearable olfactory display that is reported in [13] has a similar hardware setup, and consists of solenoid valves. Its reduced size allows the user to walk around in an immersive virtual or real environment while being presented with odors. An olfactory display system reported in [14] uses ink jet devices to attain more precise control of odor concentrations and rapid switching between odors. The system generates odor vapors by shooting tiny droplets of liquid-phase odor samples into an airstream. The most recent version of this system has a reduced size and is mobile [15]. The scent collar [16] is also a wearable device for odor presentation.

Presenting ambient scents with these olfactory displays is relatively straightforward. Delivering an odor vapor with a constant concentration to the user's nose simulates the situation, in which a scent with no specific source is present in the environment. However, it is difficult to simulate the situation in which a scent emanates from a specific location or an object. In principle, changing the concentration of the odor vapor presented to the user with the position of the user's nose renders the user aware of the odor distribution in the virtual environment [13][17]. However, it is challenging for current olfactory display technologies to reproduce rapid changes in odor intensity with slight movements of the nose.

The olfactory display system that we propose herein takes a different approach to this issue. We generate an odor distribution from a virtual odor source in real space. There are only a handful of olfactory displays that can generate a spatial odor distribution. The scent projector reported in [6] delivers an odor through air cannon. The device shoots odor-vapor-trapped vortex rings of air. Inducing two odor-containing vortex rings to collide and collapse in front of the user's nose generates a spot-like spatial distribution of the odor. However, the odor presentation by this device is essentially discrete in time. A virtual odor source that continuously releases odor vapor cannot be presented with this device. Scent of Space is an art installation that consists of a gigantic wind tunnel [18]. Users can walk in the system and sniff around. A smell is delivered to the user by generating a uniform airflow field in the system and introducing an odor vapor upstream relative to the user. A specific zone in the wind tunnel along the airflow can be selectively scented using this technique. However, the large size of the entire system limits its application.

An olfactory display device named a multi-sensorial field display (MSFD) [19] consists of two motorized fans. The airflows that are generated by the left and right fans collide midair and are deflected towards the user. By introducing odor vapor into the airflows that are generated by the fans, a spatial odor distribution is generated as if it were emanating from the airflow collision point. The position of this virtual odor source can be moved laterally by adjusting the balance of the fan speeds. Although the Treadport Adaptive Wind Tunnel (TPAWT) [20] is based on a similar hardware setup to MSFD, TPAWT has so far been used only for wind generation. The olfactory display system presented herein is a two-dimensional version of MSFD. The position of the virtual odor source can be set at an arbitrary two-dimensional position on a screen. Although the fundamental concept and preliminary results of the experiments have already been presented in [21] and [22], a refined system now enables us to present an odor distribution without inducing an airflow sensation. This paper presents the results of our extensive evaluation of the proposed system.

The proposed system can also be used as a wind display. In typical wind displays that have been developed to date, a number of fans or air blowers are placed such that they surround the user [23]. Activating a fan placed in that direction reproduces wind from an arbitrary direction. However, if the fans are placed in the user's field of view, the sense of reality is impaired. The user immediately notices that the wind is blowing from the fans. In the proposed system, the airflow that blows towards the user is generated from the airflow collision point on the screen. Therefore, the user feels as if the airflow is coming out from the screen. The origin of this airflow can again be shifted to an arbitrary position on the screen.

3 Smelling Screen

We term our proposed olfactory display system as a smelling screen. Fig. 1 shows how we use the proposed system. We generate an odor distribution around the image of a cup of coffee that is shown on the LCD screen. The user has sniffed at various locations, and has found that the smell is emanating from the image of the coffee. Fig. 2 illustrates the structure of the smelling screen. We attached a U-shaped cover with a pair of axial fans on its lower and upper ends on each side of a 24.1-inch wide LCD screen. The lower and upper fans in each cover face against each other. The openings of the left and right covers face towards the center of the screen. All the fans are connected to custom-made microcontroller boards for measurement and speed control. The tube for releasing odor vapor is attached to each fan.

As shown in Fig. 2, the airflows that are generated by the upper and lower fans in each cover collide with each other and merge into a single stream of airflow that comes out of the cover opening. The airflows that come out from the left and right covers again collide on the screen. As a result of this second collision, the airflow that leaves the screen from the airflow collision point is generated. By introducing odor vapor through tubing into the airflows that are generated by the fans, an odor distribution that spreads from the airflow collision point on the screen is generated. If the user sniffs at various locations on the screen, the perceived intensity of the odor becomes strongest near the airflow collision point, as if the odor source were placed there. This airflow collision point is perceived as an odor source. The location of this "virtual odor source" can be set at an arbitrary position on the screen by adjusting the speeds of the four fans. The vertical position of the virtual odor source can be adjusted by changing the balance of the airflows from the top and bottom fans. The balance of the airflows from the left and right fans determines the lateral position of the virtual odor source.

The fan speeds also determine the velocity of the airflow that comes from the airflow collision point towards the user's face. A speed of 1000 rpm is the minimum required to maintain the rotation of the fans that were used in the smelling screen reported in [21] and [22]. For this fan speed, the airflow speed that blows in the user's face becomes 0.5 m/s. The user perceives this airflow when he/she brings his/her nose close to the screen to sniff. We consequently replaced the fans with those of a wider speed range. The minimum speed of the new fans is 120 rpm. The speed of the airflow that blows in the user's face can be reduced to 0.1 m/s, which is sufficiently slow, thus the user does not feel the air movement [24]. With this airflow speed, the user is solely presented with the odor distribution.

As noted in the previous section, the proposed system can also be used as a wind display by simply stopping the odor release. With the maximum fan speeds (3900 rpm), the speed of the airflow that blows in the user's face reaches 0.8 m/s. A faster airflow speed can be achieved by replacing the fans with those that are more powerful.

In the experiments that we describe in the following sections, we tested two different airflow speed settings. In the first setting, termed high airflow, we adjusted the speed of the airflow that blows in the user's face to 0.5 m/s. In the second setting, termed low airflow, we reduced the speed to 0.1 m/s to render it unperceivable. We generated the odor vapor by bubbling air at a flow rate of 500 mL/min through a liquid perfume of peach dissolved in ethanol solvent (BLANKY F-12, AUG). We released the vapor into the airflows (generated by the fans) through tubing. We set the release rate of the odor vapor at each of the four fans to 125 mL/min. When the user brings his/her head too close to the screen, his/her face is directly exposed to the airflow and odor that comes out from the openings of the U-shaped covers. To avoid this problem, we placed two poles (one on the left and other on the right) 230 mm from the LCD screen. We stretched a string between the poles to show the limit distance. The subjects were instructed to sniff the screen from this distance. The maximum distance at which the peach smell could be perceived was 500 mm.

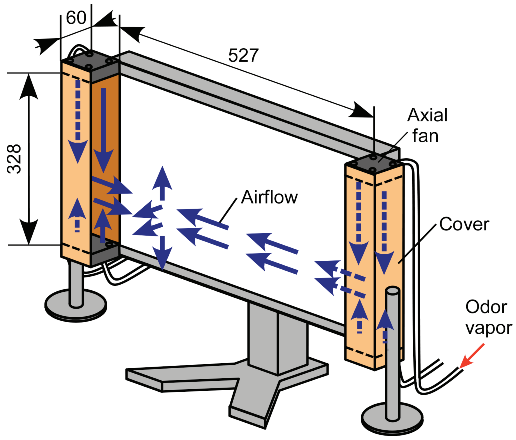


Fig. 2. Schematic diagram of the smelling screen (units are in millimeters).

For the proper operation of the smelling screen system, the speed of the ambient airflow must not exceed the airflow speed that blows in the user's face. All experiments described herein were conducted in a closed room with no air-conditioning. The speed of the ambient airflow in this environment was at most 0.03 m/s, and we observed no effects of this ambient airflow on the odor distribution. The speed of the ambient airflow in most office and home environments rarely exceeds 0.1 m/s except in the vicinity of air-conditioning systems. We successfully demonstrated the system with the high-airflow setting at the entrance hall of a building in our university during the open campus day.

4 Airflow and Odor Distribution Measurements

4.1 Measurement Method

We performed experiments to confirm the airflow generation and odor distributions. We defined 63 measurement points on a vertical plane 230 mm from the LCD screen. We used a hot-wire anemometer to measure the airflow speed. To obtain a single airflow distribution map, we measured the average of the airflow speed for 2 min at each of the 63 measurement points.

We measured the odor distribution with metal oxide gas sensors (TGS2620, Figaro Engineering). The sensor response is defined as the ratio of the resistance value of the gas sensor in clean air to that when the sensor is under exposure to a gaseous chemical compound. The value of the sensor response is unity when the sensor is exposed to clean air, and increases with odor concentration. We aligned nine gas sensors in a single measurement run. We initiated recording of the sensor responses 1 min after the start of odor release, and we calculated the time average of each sensor response over 2 min. We repeated the measurement run seven times at different heights to collect sensor response data at the 63 measurement points. We thereby obtained a single odor distribution map.

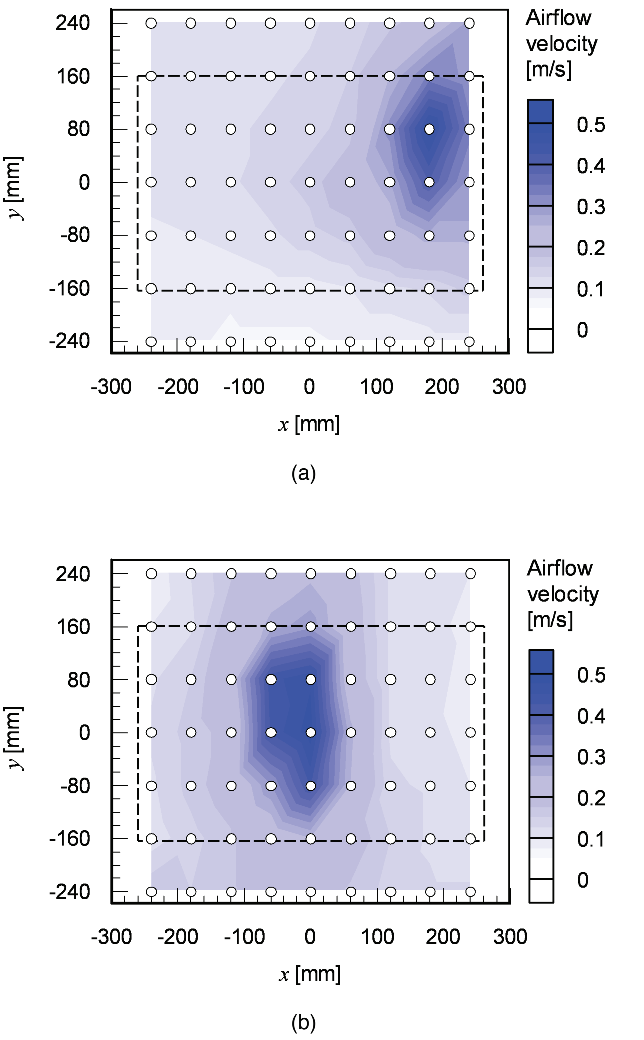


Fig. 3. Distribution of airflow velocity 230 mm from the display screen. We set the airflow collision point (or the location of the virtual odor source) at the (a) upper right corner and (b) center of the display screen. Dashed rectangles indicate the size and location of the screen, and open circles represent the positions where we measured the airflow velocity with a hot-wire anemometer.

4.2 Generated Airflow and Odor Distributions

Fig. 3 shows the results of the airflow distribution measurements for the high-airflow setting. The dashed rectangles in the figure indicate the size and location of the LCD screen. We set the origin of the coordinate system at the center of the screen. We set the airflow speed presented to the user to 0.5 m/s. We set the balance of the fan speeds such that the position of the final airflow collision point (or the location of the virtual odor source) came to the upper right corner (Fig. 3a) and to the center (Fig. 3b). The airflow that leaves the airflow collision point towards the user is clearly recognizable in Fig. 3. Adjusting the fan speeds can shift the position of the velocity peak.

Fig. 4 shows the obtained odor distribution for the same high-airflow setting. By adjusting the balance of the fan speeds, we set the position of the virtual odor source at the upper right corner (Fig. 4a), center (Fig. 4b), and lower left corner (Fig. 4c). The locations of the odor concentration peaks coincide well with the locations of the airflow velocity peaks. As shown in Fig. 2, the airflows that collide at the virtual odor source location on the screen are deflected not only towards the user but also in the upper and lower directions. Consequently, the observed odor and airflow distributions all have shapes that are slightly elongated in the vertical direction. Nonetheless, Fig. 4 clearly indicates that the odor distribution was

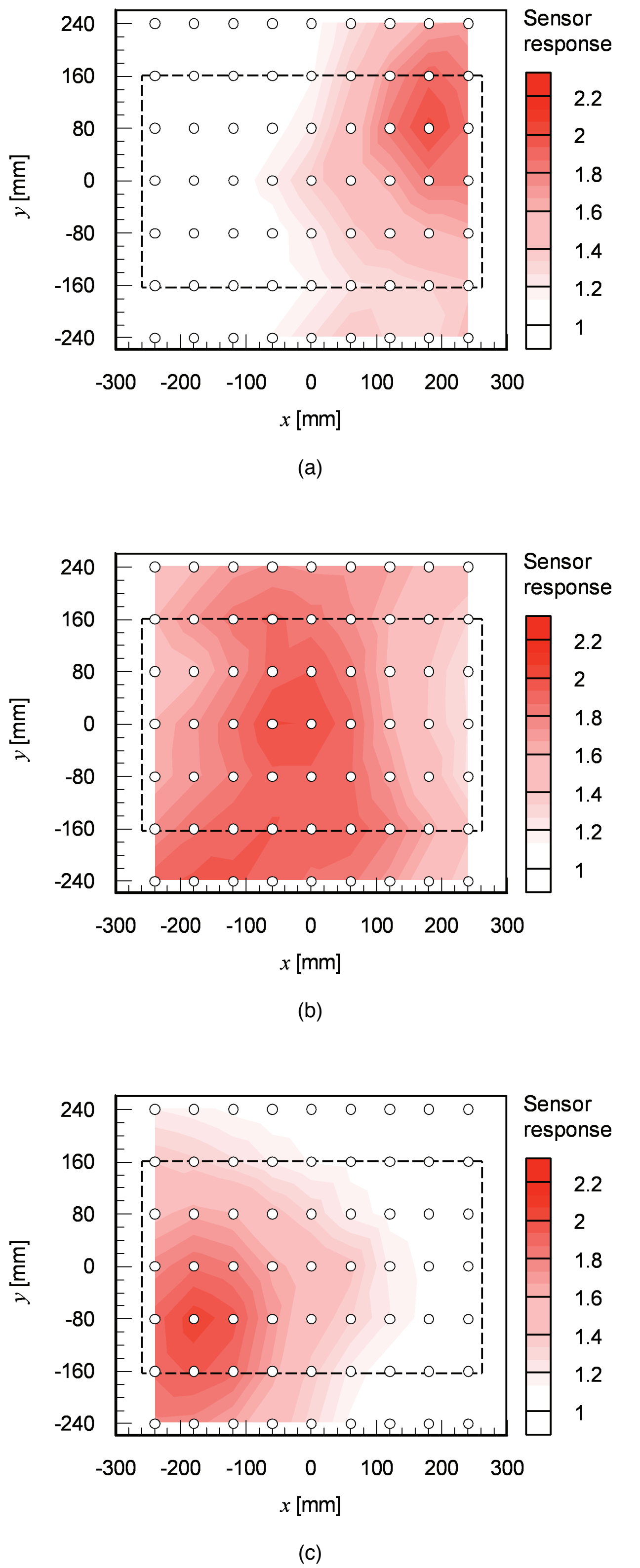


Fig. 4. Odor distribution 230 mm from the display screen. We set the location of the virtual odor source to the (a) upper right corner, (b) center, and (c) lower left corner. Dashed rectangles indicate the size and location of the screen, and open circles represent the positions at which we measured the gas sensor responses.

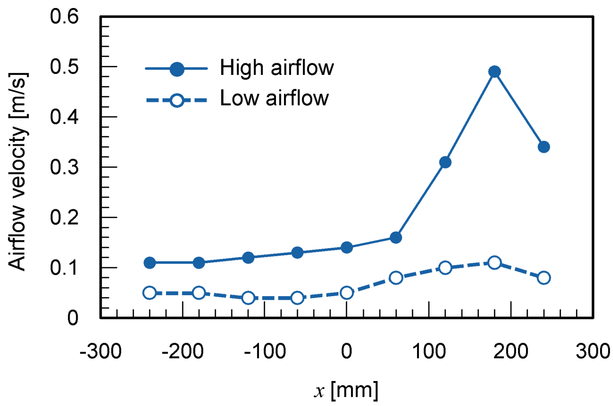


Fig. 5. Horizontal profile of airflow velocity at a height of y = 80 mm. We set the airflow collision point (or the location of the virtual odor source) at the upper right corner of the display screen.

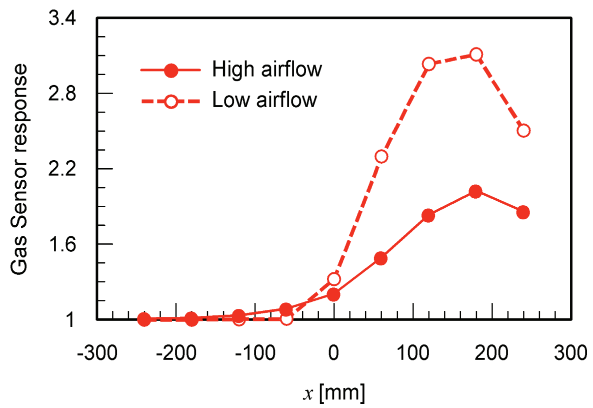
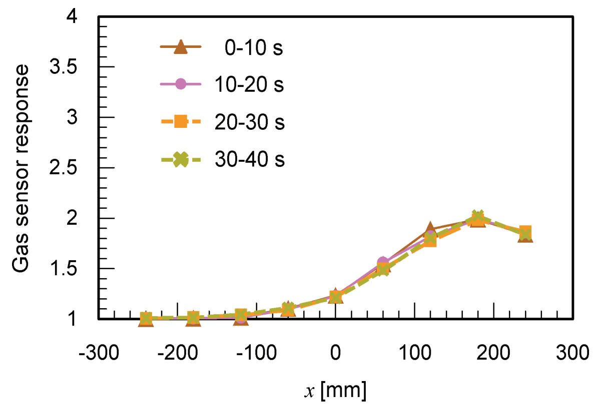


Fig. 6. Horizontal profile of odor concentration at a height of y = 80 mm. We set the position of the virtual odor source to the upper right corner of the display screen.

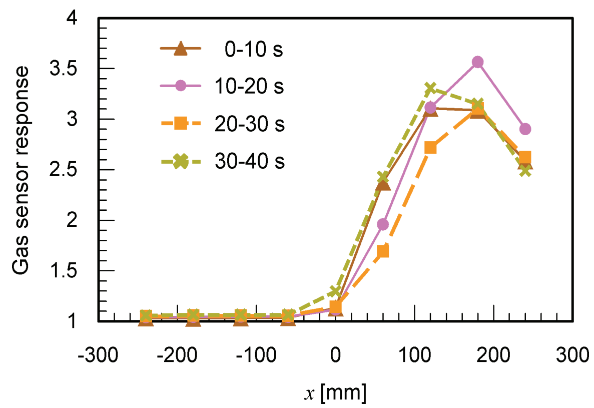
successfully generated as if the odor had been emanating from the position of the virtual odor source.

Fig. 5 compares the profiles of the airflow velocity around the virtual odor source location for the high- and low-airflow settings. We set the virtual odor source at the upper right corner of the screen, and we measured the horizontal profiles of the airflow velocity at y = 80 mm. We confirmed the generation of the airflow velocity peaks at the intended location for both speed settings. When we introduced the odor vapor into such localized airflows, the odor concentration profiles that are shown in Fig. 6 were generated as a result. The release rate of the odor vapor was same for both airflow settings. We obtained the higher odor concentration peak for the low-airflow setting since the released odor vapor is mixed with a lesser volume of air. When we sniffed at various locations along the screen, the peach smell was perceived as being around the virtual odor source location. The area of the perceivable odor was wider for the low-airflow setting than for the high-airflow setting.

We also noticed that the odor distribution that was generated with the low-speed setting was less stable than that generated with the high-speed setting. Fig. 7 shows the shifts in the odor concentration profiles with respect to time. We calculated the time-averaged sensor responses for every 10 s (results are shown in the figure). The odor concentration profile that was generated with the high-airflow setting was stable, as shown in Fig. 7a. In contrast, slight fluctuations in the fan speeds and turbulence of the air around the screen rendered the odor concentration profile that was generated with the low-airflow setting unstable. The peak location shifted by 60 mm over time. Such



(a)

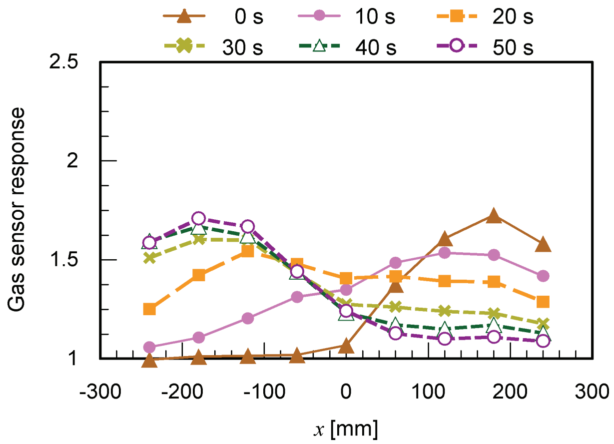


(b)

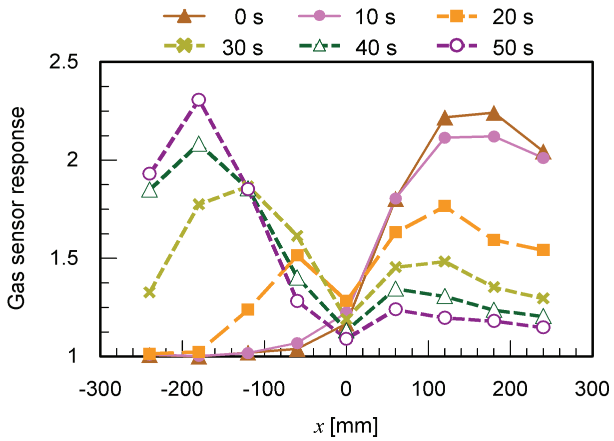
Fig. 7. Shifts of the odor distribution with respect to time. We set the position of the virtual odor source to the upper right corner of the display screen with the (a) high-airflow setting and (b) low-airflow setting. We aligned the gas sensors at a height of y = 80 mm. The averages of the sensor responses for every 10 s are plotted.

fluctuations are also observed for the odor distribution around a real odor source. The low-airflow setting is preferable if the user wants to experience real-life odor perception. If the user assigns higher priority to the stability of the odor distribution, as in digital signage applications, the high-airflow setting is preferable.

Fig. 8 shows the transition of the odor distribution for sudden changes in fan speeds. We changed the balance of the fan speeds to shift the virtual odor source location from the upper right corner to the upper left corner. Fig. 8 shows the horizontal profiles of the odor concentration at y = 80 mm. We again plotted the time-averaged sensor responses for every 10 s period. Since the speeds of the four fans were simultaneously changed, their balance was not maintained in the transition. Therefore, the odor concentration peak almost disappeared in the transition, and subsequently reestablished at a new location. The reestablishment of the odor concentration peak required 40 and 50 s for the high- and low-speed settings, respectively. This system may therefore be unsuitable for applications that require rapid transitions, e.g., to generate a virtual odor source at a different location for each scene in a movie. However, we do not think of this as a shortcoming. As described in the next section, approximately 1 min was required for the user to find the virtual odor source location. The position of the virtual odor source should be fixed at least for 1 min. Otherwise, the user may fail to notice the presence of the odor source. The response time of the gas sensors is a few seconds. The fan controller adjusted the



(a)



(b)

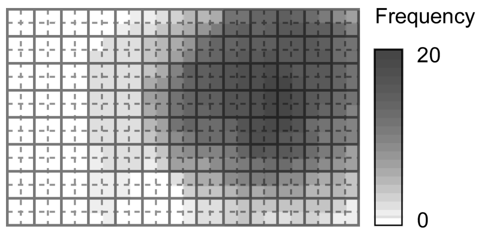
Fig. 8. Transition of the odor distribution when we changed the fan speeds to move the virtual odor source from the upper right corner to the upper left corner of the display screen. We generated the virtual odor source with the (a) high-airflow setting and (b) low-airflow setting.

speeds of the fans to the new set points within 10 s. Visualization of the airflow field using smoke confirmed that the slow transition of the odor distribution is owning to the time required to reestablish the stable airflow field at a new airflow collision point. When we started the odor release after the establishment of the stable airflow field, the user perceived the odor in several seconds.

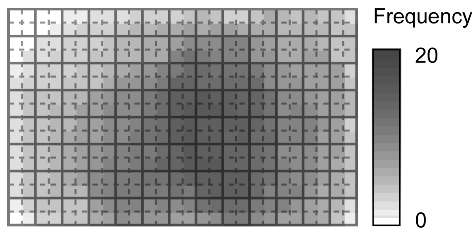
5 Perceptual Evaluation of Odor Distribution

5.1 Typical Procedure

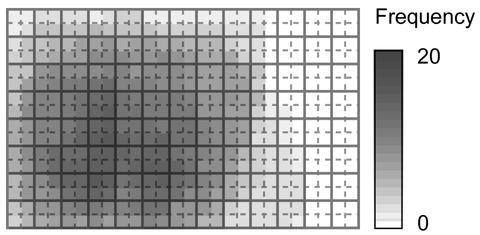
We conducted four sets of experiments to evaluate the perception of the generated odor distribution by the user. All the subjects were graduate or undergraduate students in our department. During the experiments, the subjects were asked to wear a noise-canceling headset to prevent them from obtaining any clue from the humming noise of the fans. We instructed each subject to maintain a constant distance (230 mm) between the screen and their nose. We indicated this distance to the subjects through the posts and string, as described in Section 3. When we noticed that the subjects were too far from or too close to the screen, we warned them to maintain the appropriate distance. In general, the subjects tended to sniff too close to the screen in an attempt to obtain better sniffing results. All the subjects clearly perceived the peach smell that was released from the smelling



(a)



(b)



(c)

Fig. 9. Overlapped odor distribution maps that were drawn by the subjects. We set the position of the virtual odor source to the (a) upper right corner, (b) center, and (c) lower left corner of the display screen.

screen system. They also clearly recognized the spatial changes in the intensity of the peach smell. Consequently, there were no significant individual differences in the results of the experiments.

The subjects were also instructed to slowly move their heads when sniffing around. When a person moves his or her head too quickly, the airflow that is caused by the motion of the head disturbs the odor distribution that is generated by the smelling screen. The odor distribution is reestablished in several seconds after the head motion is ceased. Before starting the experiments, we allowed each subject to experience the generated odor distribution by sniffing all over the screen. We set the fan speeds at least one minute before the start of each experiment to wait for the development of the airflow field that were generated by the system. The odor that is released from the system is dispersed in the room, and eventually spreads throughout the room. To avoid this, we initiated the odor release 20 s before the start of each experiment, and stopped it immediately after the experiment. When we tested the system in a room of 20 m^2, we could correctly localize the virtual odor source location after releasing the odor vapor continuously for 30 min.

5.2 Odor Distribution as Perceived by Users

We conducted this set of experiments with 10 subjects (nine males and one female, 21–25 years old). None of them was a member of our own laboratory, and they all were unfamiliar with our research. We showed a 20-mm-square grid pattern on the entire display area of the LCD screen. We then generated the odor distribution with the low-airflow setting, and set the virtual odor source location at one of

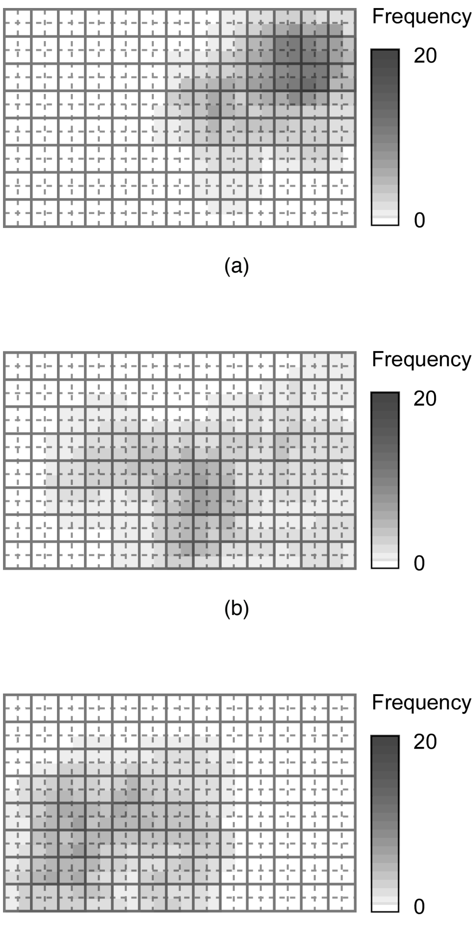


Fig. 10. Overlapped maps showing the area that encompassed the strong peach smell. We set the position of the virtual odor source to the (a) upper right corner, (b) center, and (c) lower left corner of the display screen.

the three locations, i.e., the upper right corner, center, and lower left corner of the screen. We instructed the subjects to sniff all over the screen and draw a map of the area where they perceived the peach smell. We also asked the subjects to draw a map of the area where the perceived peach smell was particularly strong. Each subject conducted two trials for each of the three virtual odor source locations in random order.

Figs. 9 and 10 summarize the results. Fig. 9 shows the overlapped odor distribution maps that were drawn by the subjects. The grayscale color of each cell in Fig. 9 represents the number of times that the cell was marked in the 20 trials across 10 subjects. Similarly, Fig. 10 shows the overlapped maps of the areas in which the perceived odor was particularly strong. The size of the entire grid pattern in each figure corresponds with the size of the LCD screen. The maps shown in Fig. 9 reflect the extent of the odor spread, and those shown in Fig. 10 are related to the location of the virtual odor source. As shown in these figures, the subjects correctly perceived the odor distribution that was generated by the proposed system, although the positional variations of the maps among the individual subjects were rather large. The airflows that were generated by the system were unperceivable. To construct a map only from the odor intensities that were perceived at various locations is not as straightforward as drawing a map of visible objects. When the virtual odor source was presented with the high-airflow setting, the individual variations of the perceived odor distribution became smaller [22].

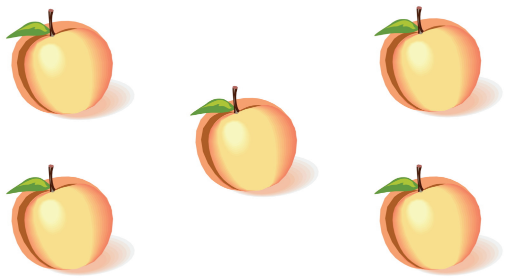


Fig. 11. Image shown on the screen in the experiments for which the subjects were asked to select an appropriate peach as an odor source.

5.3 Accuracy in Determination of Virtual Odor Source Location

In this set of experiments, we showed an image of five peaches with a diameter of 100 mm (Fig. 11) on the LCD screen. We set the virtual odor source position at one of the five peaches. We asked the subjects to sniff the peaches and select one of them as the odor source. Eight subjects (all male, 21–27 years old) tested the high-airflow setting. Four more subjects were added, and the total of twelve subjects (11 males and one female, 21–27 years old) tested the low-airflow setting. None of them was a member of our own laboratory. Each subject participated in five trials with different virtual odor source positions in random order.

We defined two performance indices to evaluate the results. SR1 shows the percentage of the trials in which the subjects selected the correct peach. SR2 shows the percentage of the trials in which the subjects selected either the correct peach or one of the adjacent peaches. For the scenario of the virtual odor source placed at the upper left corner, SR1 shows the percentage of the trials in which the subject selected the upper left peach as the odor source. SR2 shows the percentage of the trials in which the subject selected either the upper left peach, lower left peach, or peach at the center.

Tables 1 and 2 summarize the results of the experiments in the form of confusion matrices. SR1 was high for the high-airflow setting shown in Table 2. We attribute the reduced values of SR1 for the low-airflow setting to the larger fluctuations in the generated odor distribution. SR2 was high for both airflow settings. Despite the large variations in the perceived odor distribution, it was rare for the user to select a peach on the completely wrong side as the odor source.

5.4 Tolerance against Mismatch between Image and Odor Distribution

We conducted this set of experiments with eight students (all male, 22–25 years old) with the following procedure. (1) We showed an image of a peach on the upper right corner of the screen. We then generated the odor distribution, with its concentration peak at the location of the peach. (2) We allowed each subject to evaluate the fitness of the positions of the image of the peach to the position of the odor distribution. We then fine-tuned the position of the odor distribution to attain complete fitness. (3) We shifted the image of the peach to the left until the subject claimed that the position of the image was completely off of the odor distribution. (4) We asked the subject to evaluate the fitness of the image to the odor distribution at an interval of 30 mm between those two extreme positions. We asked the subject to score the result of the evaluation at each image location from 1 (complete mismatch) to 5 (complete fitness). The subjects participated in this set of experiments were all members of our own laboratory.

Table 1. Positions of the Peaches That Were Selected by the Subjects as an Odor Source. We Generated the Virtual Odor Source with the Low-Airflow Setting.

Position of virtual odor source	Position of peach selected by subject					Success rate	
	Upper left	Lower left	Center	Upper right	Lower right	SR1	SR2
Upper left	5	2	2	2	1	41.7	75
Lower left	0	5	5	1	1	41.7	83.3
Center	2	2	5	2	1	41.7	–
Upper right	0	0	5	6	1	50	100
Lower right	0	0	3	0	9	75	100

Table 2. Positions of the Peaches That Were Selected by the Subjects as an Odor Source. We Generated the Virtual Odor Source with the High-Airflow Setting.

Position of virtual odor source	Position of peach selected by subject					Success rate	
	Upper left	Lower left	Center	Upper right	Lower right	SR1	SR2
Upper left	8	0	0	0	0	100	100
Lower left	1	6	1	0	0	75	100
Center	0	1	7	0	0	87.5	–
Upper right	0	0	0	8	0	100	100
Lower right	0	0	0	0	8	100	100

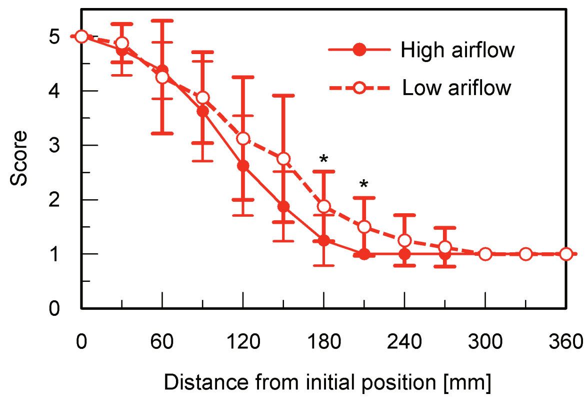


Fig. 12. Change in fitness between the image of the peach and the generated odor distribution. Asterisks indicate the significant difference between the fitness scores for the high- and low-airflow settings (paired t-test: $p < 0.05$).

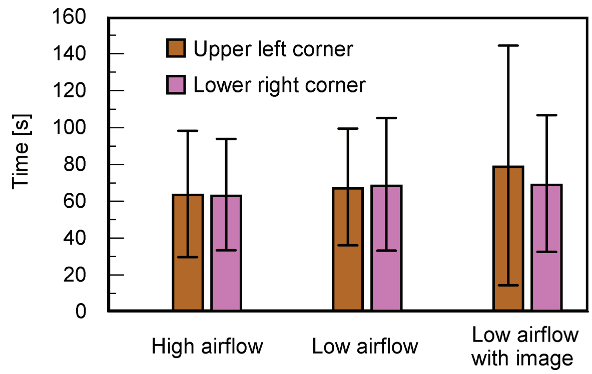


Fig. 13. Time required to deduce the virtual odor source location.

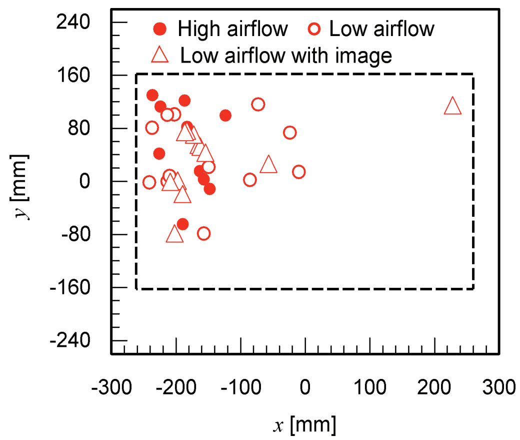
Fig. 12 shows the results of this set of experiments. There were significant differences in the scores with respect to airflow setting (high and low). We found the positional displacement between the image and odor distribution to be less noticeable in the low-airflow setting. We attribute this result to the wider odor distribution that was generated with the low-airflow setting. Fig. 12 also indicates that the displacement of 60 mm was almost unnoticeable for the subjects even for the high-airflow setting. Therefore, in general applications, there is no need for fine-tuning the position of the virtual odor source. We obtained similar results for the vertical displacement of the image. When the subjects participated in the experiments, they did not know the results of the odor distribution measurements described in Section 4. Therefore, we believe that the use of subjects from our own laboratory introduced no bias into the results.

5.5 Time to Search for Virtual Odor Source

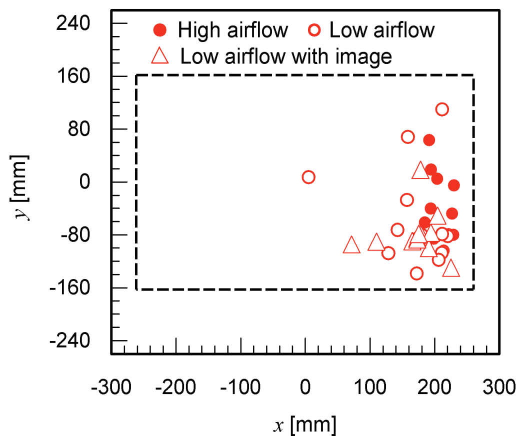
In the final set of experiments, we asked the subjects to find the location of the odor source. Twelve subjects (11 males and one female, 21–25 years old) participated in the experiments. Four of them were non-members of our own laboratory. The rest were the members of our laboratory, who participated in the experiments described in Section 5.4. We set the position of the virtual odor source at either the upper left corner or lower right corner. We did not inform the subjects of these choices of the virtual odor source location. Each subject conducted six trials that consisted of three scenarios for each of the two odor source locations. In the first scenario, we generated the odor distribution with the high-airflow setting, and the entire screen was filled with a white color. In the second scenario, we generated the odor distribution with the low-airflow setting. In the third scenario, we presented the odor distribution that was generated with the low-airflow setting to the user with an image of a peach at the location of the virtual odor source. We instructed the subjects to carefully sniff the screen and declare the odor source location by pointing it out using the mouse. We randomized the order of the six trials that were conducted by each subject.

Fig. 13 shows the time that was required to find the odor source location. For the 24.1-inch wide screen, the time that was required to find the odor source was approximately 1 min. We had originally expected that the time to find the source location would be shorter for the scenario of high rather than low airflow because the perceived airflow could be used as a clue to determine the odor source location. We also expected that the image of the peach would help the subjects to locate the odor source location. However, we found no difference in the results for these three scenarios. We did not inform the subjects of the fact that the position of the image of the peach and the area of strong airflow coincided with the position of the virtual odor source. Therefore, the subjects tried to sniff all over the screen in all three scenarios. The one-minute search time is simply the time required to scan the entire screen by slowly moving one's head. There was no significant difference in the search time between the subjects from our own laboratory and the others.

Fig. 14 shows the source locations that the subjects declared. In most trials, the subjects pointed at correct locations. The variations of the declared source locations are smaller for the scenario of high airflow because of the narrower and more stable odor distribution.



(a)



(b)

Fig. 14. Positions of the odor source, as declared by the subjects. We set the position of the virtual odor source at the (a) upper left corner and (b) lower right corner of the display screen.

The variations of the declared source locations also become smaller when an appropriate image is presented along with the odor distribution. Again, there was no significant difference in the results between the subjects from our own laboratory and the others.

6 Conclusions

In this paper, we presented a new olfactory display system that can generate an odor distribution along the screen. The airflows from the fans collide multiple times to create an airflow that leaves the screen towards the user. By introducing odor vapor into the airflows, the odor distribution is as if the odor were emanating from a certain position on the screen. The position of this virtual odor source can be set at an arbitrary position on the screen. The speed of the airflow that carries the odor vapor can be set lower than the human detection limit. This setting is preferable for virtual reality applications because it is unnatural to always perceive an odor with airflow. However, the odor distribution is less stable than that generated with a high-airflow setting. For digital signage or computer games, the high-airflow setting might be preferable because the individual variations in the perceived odor distribution can be minimized. The proposed system could also be used to develop a novel interactive multimedia system for exhibitions in museums. We used a liquid perfume of peach for the experiments. If we set a liquid coffee flavor in the system, it generates a smell of coffee. Using a multicomponent olfactory display described in [7] as an odor vapor generator for the proposed system will enable switching between multiple odors. The main drawback of the proposed system is that it cannot generate multiple virtual odor sources simultaneously. Moreover, we do not have a precise control over the release rate of the odor vapor, owing to the limited accuracy of the flow meter. The maximum distance at which the user can perceive the smell is 0.5 m, which might be insufficient for a digital signage with a large LCD screen. Our future research includes scaling our proposed display system up and down to adapt it to various screen sizes.

Acknowledgments

This research was conducted with the approval of the ethics committee in our university in regard to the execution of sensory tests on human subjects. This work was supported by Grant-in-Aid for Scientific Research (B), No. 22300073, and Grant-in-Aid for JSPS Fellows, No. 22-8255, from the Japan Society for the Promotion of Science. The authors would like to thank Enago (www.enago.jp) for the English language review.

References

[1] G. C. Burdea and P. Coiffet, *Virtual Reality Technology*, 2nd ed. Hoboken, N.J.: Wiley, 2003.

[2] M. Auvray and C. Spence, “The Multisensory Perception of Flavor,” *Conscious. Cogn.*, vol. 17, no. 3, pp. 1016–1031, Sep. 2008, doi:10.1016/j.concog.2007.06.005.

[3] S. Chu and J. J. Downes, “Odour-Evoked Autobiographical Memories: Psycological Investigations of Proustian Phenomena,” *Chem. Senses*, vol. 25, no. 1, pp. 111–116, Feb. 2000, doi:10.1093/chemse/25.1.111.

[4] R. S. Herz and T. Engen, “Odor Memory: Review and Analysis,” *Psychonomic Bull. Rev.*, vol. 3, no. 3, pp. 300–313, Sep. 1996, doi:10.3758/BF03210754.

[5] E. R. Spangenberg, A. E. Crowley, and P. W. Henderson, “Improving the Store Environment: Do Olfactory Cues Affect Evaluations and Behaviors?,” *J. Marketing*, vol. 60, no. 2, pp. 67–80, Apr. 1996, doi:10.2307/1251931.

[6] F. Nakaizumi, Y. Yanagida, H. Noma, and K. Hosaka, “Spotscents: A Novel Method of Natural Scent Delivery Using Multiple Scent Projectors,” *Proc. IEEE Virtual Reality*, pp. 213–218, 2006, doi:10.1109/VR.2006.122.

[7] T. Nakamoto and K. Yoshikawa, “Movie with Scents Generated by Olfactory Display Using Solenoid Valves,” *IEICE Trans. Fundamentals*, vol. E89–A, no. 11, pp. 3327–3332, Nov. 2006, doi:10.1093/ietfec/e89-a.11.3327.

[8] T. Nakamoto, S. Otaguro, M. Kinoshita, M. Nagahama, K. Ohinishi, and T. Ishida, “Cooking Up an Interactive Olfactory Game Display,” *IEEE Comput. Graph. Appl.*, vol. 28, no. 1, pp. 75–78, Jan. 2008, doi:10.1109/MCG.2008.3.

[9] M. L. Heilig, “Sensorama Simulator,” U.S. Patent 3 050 870, August 28, 1962.

[10] 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, doi:10.1016/0092-8674(91)90418-X.

[11] D. W. Kim, D. W. Lee, M. Miura, K. Nishimoto, Y. Kawakami, and S. Kunifuji, “Aroma-Chip Based Olfactory Display,” *Proc. 2nd Int. Conf. Knowledge, Information and Creativity Support Systems*, pp. 97–103, 2007.

[12] J. N. Kaye, “Symbolic Olfactory Display,” Master thesis, Media Lab., Mass. Inst. Tech., Cambridge, Mass., 2001.

[13] T. Yamada, S. Yokoyama, T. Tanikawa, K. Hirota, and M. Hirose, “Wearable Olfactory Display: Using Odor in Outdoor Environment,” *Proc. IEEE Virtual Reality*, pp. 205–212, 2006, doi:10.1109/VR.2006.147.

[14] J. Sato, K. Ohtsu, Y. Bannai, and K. Okada, “Effective Presentation Technique of Scent Using Small Ejection Quantities of Odor,” *Proc. IEEE Virtual Reality*, pp. 151–158, 2009, doi:10.1109/VR.2009.4811015.

[15] S. Sugimoto, R. Segawa, D. Noguchi, Y. Bannai, and K. Okada, "Presentation Technique of Scents Using Mobile Olfactory Displays for Digital Signage," *Proc. 13th IFIP TC 13 Int. Conf. Human-Computer Interaction*, vol. 3, pp. 323–337, 2011, doi:10.1007/978-3-642-23765-2_23.

[16] J. F. Morie, D. 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, February 3, 2009.

[17] H. Matsukura, A. Ohno, and H. Ishida, "Fluid Dynamic Considerations for Realistic Odor Presentation Using Olfactory Display," *Presence*, vol. 19, no. 6, pp. 513–526, Dec. 2010, doi:10.1162/pres_a_00019.

[18] U. Haque, "Scent of Space: An Interactive Smell System," *Proc. SIGGRAPH*, p. 35, 2004, doi:10.1145/1186223.1186267.

[19] H. Matsukura, T. Nihei, and H. Ishida, "Multi-Sensorial Field Display: Presenting Spatial Distribution of Airflow and Odor," *Proc. IEEE Virtual Relaity*, pp. 119–122, 2011, doi:10.1109/VR.2011.5759448.

[20] S. D. Kulkarni, M. A. Minor, M. W. Deaver, and E. R. Pardyjak, "Output Feedback Control of Wind Display in a Virtual Environment," *Proc. IEEE Int. Conf. Robotics and Automation*, pp. 832–839, 2007, doi:10.1109/ROBOT.2007.363089.

[21] H. Matsukura, T. Yoneda, and H. Ishida, "Smelling Screen: Technique to Present a Virtual Odor Source at an Arbitrary Position on a Screen," *Proc. IEEE Virtual Reality*, pp. 127–128, 2012, doi:10.1109/VR.2012.6180915.

[22] H. Matsukura, T. Yoneda, and H. Ishida, "Fragrant Multimedia Display System: Presenting Odor Distribution on Display Screen," *Proc. IEEE Sensors*, pp. 1029–1032, 2012.

[23] T. Moon and G. J. Kim, "Design and Evaluation of a Wind Display for Virtual Reality," *Proc. ACM Symp. Virtual Reality Software and Technology*, pp. 122–128, 2004, doi:10.1145/1077534.1077558.

[24] D. A. McIntyer, *Indoor Climate*, London: Applied Science, 1980.