Effects of Wind Source Configuration of Wind Displays on Property of Wind Direction Perception

Width of Wind Velocity Distribution and Accuracy of Wind Source Alignment

Takuya Nakano, Yuya Yoshioka and Yasuyuki Yanagida
Dept. Graduate of Science and Technology
Meijo University
Nagoya, Japan
e-mail: {{123430042, 113430024}@ccalumni., yanagida@}meijo-u.ac.jp

***Abstract*—We examined the property of wind direction perception at the frontal region of the head to find a guideline for optimal wind source arrangement. In previous experiments, localized winds produced by a single compact fan were used as stimuli. Such a localized wind is rather different from the natural uniform wind in a real environment. Because the subjects might be able to judge the wind direction based on the facial region hit by the wind, the performance of discriminating the direction of a localized wind may be different from that for a uniform wind. Thus, in this study, we examined the human ability to discriminate the wind direction using a uniform wind that covered the entire face and compared the result with that for a localized wind. We measured the Just Noticeable Difference (JND) in wind direction perception and found that there was a significant difference between the JND for a uniform wind and that for a localized wind.**

Keywords-Wind sensation; Sensory property; JND

I. INTRODUCTION

Recently, in the technical field of Virtual Reality (VR), systems that reproduce virtual environments using "wind sensation" have been developed. Wind sensation refers to a combination of sensations related to feeling the wind, which is considered to be a kind of haptic sensation [1]. By presenting non-contact stimulation to a user through a wind sensation, we expect the system to provide the user with a greater sensation of presence. Therefore, numerous systems incorporating wind displays have already been developed. For example, there are attractions in amusement parks that present a wind or fragrance with images and sound, e.g., "Soaring" [2] at Disney World. Movie theaters incorporating winds and scents, called "4DX," are now in operation [3]. In addition, to provide the sensation of existing in a target environment, several studies using wind sensations have been conducted. For example, Suzuki *et al*. developed a system that provides air-jet-driven force feedback through a ladle-like handheld tool, which achieved an interaction with force feedback in an untethered manner [4]. Minakuchi proposed the use of wind gusts to help users notice and understand information such as determining the location of an information source based on the wind direction, where the importance of the information is represented by the air volume [5]. Sawada *et al*. developed BYU-BYU-View, which is an input/output interface that uses wind. When a user exhales toward a special screen, a wind emerges from another user's screen. Thus, the user can utilize an application or communicate with a partner [6]. Furthermore, systems such as Windcube [7] and Immersive 3D Wind Display [8] have realized wind presentations from different directions by arranging multiple wind sources around a user. They showed by questionnaires that the simultaneous presentation of a movie and wind using these systems enhanced the sensation of immersion compared with the presentation of a movie alone.

However, in such studies, only a small number of wind sources have been used. Thus, it is unclear whether a precise wind direction can be reproduced using these systems. If the wind sources are arranged too sparsely, it is difficult to precisely reproduce the wind direction in the virtual environment. In contrast, if the wind sources are arranged too densely, users would not be able to discriminate the wind produced by neighboring wind sources, which is regarded as over-engineering. By taking the human ability to discriminate the wind direction into account when designing a wind source configuration, such over-engineering can be prevented, and a natural wind can be reproduced.

We examined the properties of wind direction perception to find a guideline for optimizing the wind source configuration when designing a system that reproduces an environment using wind sensation. In our previous studies[9][10], however, the results might have been affected by errors in the fan alignment (mounting angle) and the variance of the wind velocity distribution generated by each fan, because multiple fixed fans were used in the experimental setup. Furthermore, the localized wind generated by a simple fan was quite different from natural wind. In this study, we found a new guideline for wind source configuration by measuring the property of wind direction perception, using a uniform wind blowing on the entire face to prevent error due to the wind source.

The rest of this paper is structured as follows. Section 2 describes related and previous work. Section 3 presents the results of an experiment and discusses the apparatus and method. Finally, Section 4 concludes this paper.

II. Related Work

Several studies that reproduce an environment using wind sensation have been conducted. A historic example is the famous Sensorama simulator [11] by Heilig. Sensorama was a game in which a player felt like they were riding a motorcycle. Sensorama provided not only visual and auditory stimuli but also tactile and olfactory stimuli, including a wind sensation provided by a wind blowing from the front.

More recently, Moon *et al*. showed that the sensation of presence can be improved by providing wind in addition to showing a movie of a snowstorm [7]. Kosaka *et al*. [8] arranged 25 fans on a dome-shaped frame at intervals of 45°: eight fans on each of three levels (ear-height, 45° higher and 45° lower) and one at the top of the dome. They showed a movie of a person swinging with and without presenting the wind. As a result, the presentation of wind achieved a higher sensation of reality than that without wind. Cardin *et al*. mounted eight fans on a head mounted display at intervals of 45° and presented wind with a movie of a flight simulator [12]. Lehmann *et al*. conducted an experiment to evaluate the sensation of reality for three conditions: presenting only a movie of snow flurries, the movie with wind from a ventilator mounted on a traverse system, and the movie with wind from two fans mounted on a worn helmet. The results showed that 75% of the subjects reported that the ventilator provided the greatest increase in realism [13]. Matsukura *et al*. developed a system that gave a user the sensation that an odor was emanating from a certain position on the screen, by producing winds generated by fans at four corners of the screen and allowing them to collide in front to form a wind in a direction orthogonal to the original direction [14]. They first made vertical winds produced by four fans located at the corners of the screen collide two by two to form two horizontal winds (leftward and rightward) along the screen. They then made these two horizontal winds collide to produce a wind heading toward the user sitting in front of the screen. Hirota *et al*. developed a system that could provide variable wind direction. They presented wind from two fans set in different directions and let them collide obliquely. By controlling the velocity of the wind from each fan, they succeeded in presenting an intermediate wind between two directions [15].

Some researchers have studied the property of wind sensation perception. Kubota *et al*. reported that the wind perception threshold of the face was about 0.2 m/s, depending on the temperature or fluctuation of the flow velocity [16]. Kojima *et al*. investigated which part of the head was sensitive to wind stimulation, in the context of their wearable wind display for local skin stimulation [17]. Their results showed that the regions around the ears were the most sensitive. Hashimoto *et al*. examined the perception of wind at the fingertips [18]. They measured the absolute threshold using the limit method and the difference threshold using the constant method. They also measured the difference threshold of the directional perception. However, they did not conduct tests at the face.

Among these studies, we have focused on the human properties related to perceiving the wind direction. We examined the property of wind direction perception at the frontal region of the head. As a result, values for the Just Noticeable Difference (JND) in wind direction perception were obtained, but a significant inter-subject difference was observed. In this study, we found the possibility that subjects might discriminate the wind direction based on the area of the face touched by the wind [9]. Next, we conducted an experiment to examine the effect of the stimulation area of the face by measuring JNDs using multiple conditions for the stimulation area. We found a significant difference between JND values of wind discrimination for different conditions [10].

In these studies, a single fan was used to provide the wind, following many existing systems with wind presentation. However, natural wind is not a local phenomenon but a uniform sensation encompassing the entire face. Because the point that the wind hits affects wind direction discrimination, we supposed that the human performance of discriminating the wind direction might be different, depending on whether a localized or uniform wind was presented. Another problem in our previous study was that we used multiple fixed fans to present wind from various directions. This might have caused variations in the wind velocity and a slight alignment error for each fan. The slight alignment error might have affected the results because of the potential to discriminate the wind direction by the area hit by the wind. For example, when the wind hit the center of the face, it also hit the left side of the face if we misaligned the position of the fan located on the right side of the subject. Because we arranged the fans one by one by hand, there was a possibility that slight misalignments accrued.

Thus, in this study, we measured the JND values of wind direction perception at the frontal region of the head for both localized and uniform winds. In addition, we compared the JND obtained by using multiple fixed fans to that obtained by moving a fan, to assess the effect of the fan alignment error.

III. Experiment

A. Apparatus

We used DC fans (SST-AP121 by SilverStone Technology Co. Ltd.; 120 mm^2) as wind sources, following the procedures used in our previous studies [9][10]. The maximum air flow was 1.0 m^3/min, and the operating noise was 22.4 dBA, measured 80 cm from the fan.

We selected this model of fan because it produces an airflow in a circular fashion using a fan filter and swirl-shaped fan grille and is well-suited to examine the properties of wind direction perception because it has better directivity than an ordinary fan. In Fig. 1, we show the airflow difference between this fan and an ordinary fan. The "ordinary" fan used for comparison was a DC fan (109R1212H102 by Sanyo Denki Co. Ltd.; 120 mm^2).

Figure 1. Air flow generated by fan (left: ordinary fan, right: SST-AP121)

The wind velocity distribution generated by SST-AP121 is listed in Table I. We measured wind velocities at intervals of 5 cm within the limits of a 20-cm square on a plane normal to the axis of the fan at a distance of 80 cm from the fan. The left, right, top, and bottom of the table correspond to the directions of wind movement. The unit is m/s. For a comparison with the ordinary fan, we show the wind distribution by 109R1212H102 in Table II. Both fans were driven at the rated voltage (12 V).

TABLE I. WIND DISTRIBUTION BY SELECTED FAN: SST-AP121 (UNIT: m/s)

	Far left	Left	Center	Right	Far right
Uppermost part	0.258	0.350	0.500	0.520	0.422
Upper part	0.576	0.862	1.102	1.062	0.692
Center	0.672	1.146	1.282	1.196	0.680
Lower part	0.416	1.176	1.282	1.066	0.582
Lowermost part	0.326	0.540	0.656	0.546	0.346

TABLE II. WIND DISTRIBUTION BY "ORDINARY" FAN: 109R1212H102 (UNIT: m/s)

	Far left	Left	Center	Right	Far right
Uppermost part	1.516	1.358	1.031	0.678	0.427
Upper part	1.798	1.658	1.308	0.923	0.700
Center	1.705	1.712	1.600	1.238	1.198
Lower part	1.306	1.413	1.381	1.376	1.372
Lowermost part	0.767	0.893	0.869	1.011	1.403

In Table II, the wind spreads to a wider area. In Table I, the wind is the strongest at the center, and the wind velocity becomes smaller in the outer regions. Looking at Fig. 1 and Table II, we can find that the ordinary fan produces wind in an oblique direction rather than straight ahead.

In previous studies [9] [10], we used a single fan as the wind source. In this study, however, we needed to present a uniform wind that could cover the entire face. According to Table II, a single "ordinary" fan was not sufficient to present a uniform wind because the ratio of the minimum to maximum wind velocity was only 0.201.

We designed wind source configurations to present a uniform wind. We found that the "selected" model of fan (SST-AP121) could produce a unimodal wind distribution, i.e., the wind velocity was larger at the center and smaller at the periphery. Therefore, by composing a 2 × 2 or 3 × 3 fan array, we expected to be able to present a uniform wind that could cover the entire face. The composed fan arrays as wind sources are shown in Fig. 2, and the measured wind velocity distributions produced by the fan arrays are listed in Tables III and IV, respectively.

Figure 2. Configurations of fans (left: 2 × 2, right: 3 × 3)

TABLE III. WIND DISTRIBUTION BY 2 × 2 FAN ARRAY (UNIT: m/s)

	Far left	Left	Center	Right	Far right
Uppermost part	0.914	1.358	1.116	0.954	0.920
Upper part	1.080	1.756	1.600	1.482	1.384
Center	1.364	1.862	1.798	1.752	1.452
Lower part	1.442	1.704	1.720	1.798	1.436
Lowermost part	0.920	1.180	1.342	1.792	1.370

TABLE IV. WIND DISTRIBUTION BY 3 × 3 FAN ARRAY (UNIT: m/s)

	Far left	Left	Center	Right	Far right
Uppermost part	1.658	1.796	1.650	1.662	1.598
Upper part	1.876	1.820	1.776	1.870	1.848
Center	1.754	1.834	1.930	1.868	1.788
Lower part	1.904	1.920	1.960	1.940	1.898
Lowermost part	1.704	1.942	1.964	1.892	1.754

From Tables III and IV, the minimum to maximum wind velocity ratios of the 2 × 2 and 3 × 3 fan arrays are 0.491 and 0.840, respectively. In other words, as the number of fans increased, the wind became more uniform. Based on this result, we decided that a 3 × 3 array was sufficient as a wind source unit to present a uniform wind within an area of 20 cm^2, which was a suitable size to cover the head. The unit size was 360 mm × 360 mm. When only the central fan in this unit was activated, it corresponded to the experimental condition of the previous studies [9] [10], in which a single fan was used as a wind source.

In previous studies [9] [10], we placed 13 fans in a range of –60° to +60° with respect to a subject at intervals of 10°. The wind from the front of the face was 0° and was presented from seven fans in a range of –30° to +30° at 1.3 m/s. The separation and limit of this stimulus were based on a prior study where we estimated the wind direction perception. The wind from the front of the subject (0°) was the standard stimulus, and winds from seven positions ranging from –30° to +30° were comparison stimuli. The JND of the wind direction perception was measured using the method of constant stimuli (Fig. 3). However, when using multiple fans, individual fan differences related to the mounting angle and wind distribution might cause a problem.

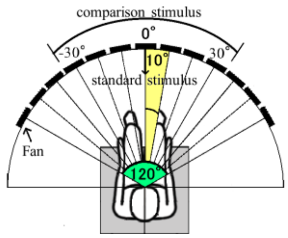

Figure 3. Experimental setup for measuring JND

To prevent individual fan differences from affecting the results, we used the single wind source unit shown in Fig. 2, instead of 13 separate fans. We attached this wind source unit to a moving platform that could be moved on an arc rail whose center was aligned at the center of the subject's head. With this experimental setup, we could eliminate the factor indicated in a previous study [9], where a slight misalignment of the fans could significantly affect the user's perception of the wind direction.

The distance between the wind source and the subject was 80 cm, and the wind velocity was 1.3 m/s. According to Tables I and IV, the newly configured wind source unit could provide wind with a faster velocity than that produced by a single fan, when it was operated at the rated voltage of the fan (12 V). Therefore, to make the wind velocity equal to that produced by a single fan, the wind source unit was operated at 8 V. The unit size was 360 mm × 360 mm, which corresponded to an angle of 25°.

We used a step motor unit (ASC66AK-N5 by Oriental Motor Co. Ltd.) to drive the platform carrying the wind source unit. The maximum rotation velocity was 360 rpm, and the maximum velocity of the platform was approximately 7.6°/s.

To prevent subjects from identifying the direction by the motor noise, we provided white noise using a portable audio player (Walkman NW-754 by SONY Co. Ltd.), along with noise-canceling earphones. Although we needed to prevent subjects from determining the fan location visually, to expose the maximum possible amount of skin area on the face to the wind, we did not use blinders. Subjects closed their eyes throughout the experiment. Fig. 4 shows an overview of the experimental setup.

Figure 4. Overview of experimental setup

To prevent any misalignment of the head position during the experiment, we used a chin support. We separated the small mount for the chin support from the table on which the rail was placed to prevent vibrations caused by the motor and gear from being transmitted to the subjects.

B. Method

We measured the JND using a constant stimulus method. Wind from 0° in front of a subject was the standard stimulus. Wind from any of seven positions within −30° to +30° at intervals of 10° was the comparison stimulus. The subject sat in front of the wind source and put their face on a chin support. The experiment started with their eyes closed.

First, the wind source presented the standard stimulus. Next, it was moved to any one of the positions from −30° to +30° and presented a comparison stimulus. The subject determined whether the comparison stimulus was to the left or right with respect to the standard stimulus. Next, the wind source returned to the first position (0°), and the standard stimulus was presented again, followed by the presentation of a comparison stimulus from any one of the positions from −30° to +30°. We repeated this procedure until each comparison stimulus (−30° to +30°) was presented 10 times, i.e., we presented 140 stimuli in total, including standard stimuli.

Before starting the experiment, we tested whether a subject could hear the motor noise to prevent them from using sound to discriminate wind directions. If the subject could hear the motor noise, they were asked to turn up the volume of the white noise until they could no longer hear the motor.

The duration of each stimulus was 4.5 s, followed by an interval of 8 s, including the moving time for the wind source. The duration for a session was approximately 30 min. A subject was asked to attend two sessions: localized wind and uniform wind, in random order. We allowed a break of approximately 20 min between sessions to let the subject relax and cool the motor. Hence, the total duration of the experiment for one subject was approximately 80 min. Ten male subjects in their twenties volunteered for the experiment.

C. Results

Examples of plots showing the ratios of the times that subjects answered "right" for each comparison stimulus angle are shown in Figs. 5 and 6. Fig. 5 is an example of the results for a single fan, and Fig. 6 shows the results for the 3 × 3 fan array. We fitted a cumulative normal distribution curve and calculated JND values. The JNDs calculated for 10 subjects and a pilot study are listed in Table V.

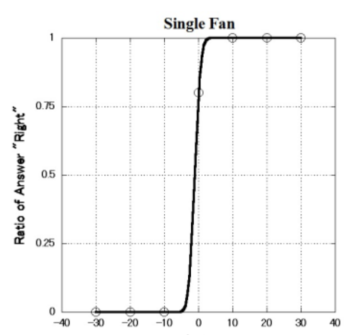

Figure 5. Ratio of times subject answered "right" (single fan)

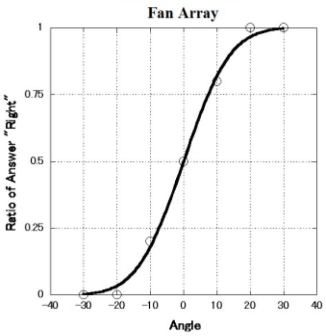

Figure 6. Ratio of times subject answered "right" (fan array)

TABLE V. JNDS OF ALL SUBJECTS (°)

Subject	Pilot study	Single	Unit
1	7.44	4.75	9.17
2	7.44	0.97	5.47
3	3.37	0.94	7.38
4	6.37	1.00	6.12
5	4.97	1.02	1.01
6	6.56	1.00	3.18
7	5.28	4.19	5.28
8	3.37	1.02	5.16
9	8.21	0.87	5.71
10	7.44	1.02	7.04

The average JND value for 10 subjects was 6.05° in the previous study, with values of 1.68° for a single fan and 5.55° for a fan array. The JND was larger for uniform wind. Eight subjects gave all correct answers except for 0° when using a single fan, whereas only one subject could give all correct answers when using a fan array. The standard deviations over the subjects were 1.73° for the previous study, 1.48° for a single fan, and 2.25° for a fan array.

Fig. 7 shows the average JND values, including the previous study [10]. "Pilot study (single)" refers to the results of the previous experiment with a single fan (but using different fans for different directions). "Single" shows the results when moving a single fan, and "3 × 3" shows the results with the fan array. The vertical axis is JND (in degrees). We conducted a t-test[19] to verify whether there was a significant difference between pairs of JND values. First, we conducted a t-test between the results of the previous study [10] and this study with a single fan.

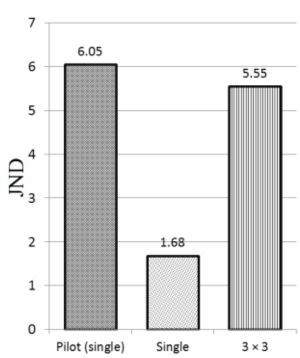

Figure 7. JND for each condition

Because the subjects in the past study and this study were not paired (they used two different groups of subjects), we conducted an unpaired t-test. The two-sided p-value was 0.00001, and there was a significant difference ($p < 0.001$). Because the subject groups of "single fan" and "fan array" were identical, we conducted a paired t-test. The two-sided p-value was 0.00026. Thus, there was a significant difference ($p < 0.001$).

D. Discussion

The results of this study using a single fan were different from those of the previous study [10]. The cause of this difference was considered to be either the alignment error of each fan or individual performance differences in the fans used to present winds from different directions in the previous study. Moreover, in the previous study, the fans were manually fixed on an arc-shaped frame, which might have affected the results. In this study, because we presented wind by moving a wind source unit on semicircular rail, there was little error from the mounting angle and individual fan differences. Thus, we obtained stable results. In the comparison of the results by a single fan and fan array, we found that it was more difficult for subjects to discriminate wind directions when a uniform wind was presented.

Although the JND of subject five for a uniform wind was smaller than that for the local wind, this consisted merely of the difference in the ratio of answering "right" for 0°. Except for 0°, the ratio of correct answers by this subject was 100% for both the local and uniform winds. For the other nine subjects, the JND values for the local wind were smaller. With the localized wind, subjects could discriminate wind directions based on the areas reached by the wind. With the uniform wind, it was difficult for subjects to discriminate the wind direction by the areas reached by the wind, because it blew on their entire face. Therefore, some subjects reported that they changed their strategy to discriminate the wind direction, i.e., focusing on the direction of airflow on the face.

The standard deviation for the fan array was larger than that for the single fan. This implies that subjects could discriminate wind directions using the areas touched by the winds for the local wind, whereas for the uniform wind, the methods used to discriminate wind directions differed among individuals. For the local wind, all of the subjects reported that they discriminated directions using the areas touched by the winds. For the uniform wind, three subjects discriminated directions by the side of the face where the wind flowed. Because the winds produced by the fan array had a larger range than those of the single fan, some subjects reported that they used their neck or arms as a reference for discrimination. In this way, individual differences are subject to occur when a uniform wind is used.

Moreover, differences in the level of concentration existed as individual differences common to the local and uniform winds. The subjects became sleepy in 15 out of 20 sessions (10 subjects, 2 conditions), because their eyes were closed throughout the session. A sensitive subject could detect the motion of the wind source unit by a slight variation in the illumination on his face. Two subjects noticed that the motor vibration was uncommonly transmitted. However, they noted that they could not discriminate the direction using this cue.

IV. CONCLUSION

In this study, we measured the JND of the wind direction perception of a local wind produced using a single fan commonly used for a wind display and a uniform wind produced by a fan array that was similar to natural wind. As a result, we found that the uniform wind provided larger JND values and made it more difficult to discriminate the wind direction compared to the local wind. By comparing the results with those of the previous study [10], we found that errors in the mounting angle and individual fan performance differences significantly affected wind direction perception. Thus, when designing a wind display, the following guidelines were obtained: (1) if one wants to present a uniform wind, the interval of the wind sources can be larger than when using a single fan, and (2) the fans should be arranged with extremely high precision if multiple fans are used to present winds in different directions.

The average ratios for the subjects answering "right" for 0° was 55% with a single fan and 41% with the wind source unit. It was thought that the center of the wind source was accurately aligned with the subject's face. However, because of the need for a strict fan configuration, the entire apparatus should also be arranged with extremely high precision.

In this study, the JND for a uniform wind was 5.55°, whereas the size of the wind source unit corresponded to approximately 25°. This means the size of the wind source unit was larger than the JND requirement. In this study, to present a natural wind, we used a 3 × 3 fan array as a wind source unit. Therefore, if we designed a wind display based on a fixed fan array, we would have to arrange fans with a sufficient density to cover all directions. However, we still believe that it is inappropriate to apply the JND value obtained in this study immediately, because there are numerous factors that affect the wind direction perception, e.g., the wind velocity, wind temperature, gender, and age. In this study, the subjects only concentrated on discriminating the wind direction. However, the existence of a movie or sound in an actual wind display might reduce the level of concentration on the wind. Thus, we might be able to make the wind sources sparser than indicated by the results of this study. In future work, we will further investigate the required precision when considering the property of wind perception to achieve acceptable wind displays for people regardless of age and gender. In addition, we are going to examine cross-modal effects with the other sensory modalities.

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