AirDisplay: Experimenting with Air Flow as a Communication Medium

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Abstract. This paper presents a psychophysical experiment using a multi-fan device to communicate information to the user via air intensity and direction. We describe the implementation of a prototype, the AirDisplay. We identify the most effective configuration at which users can discern different air patterns by manipulating the fans' speed, the distance between the fans, and the different air patterns. Experiment results support the use of air to communicate information.

Keywords: Non-contact haptic feedback · Air streams · Multi-fan device

1 Introduction

Despite the variety of senses that humans possess, the vast majority of user interfaces target the human vision and hearing senses. This work examines the suitability of air streams to be used alongside personal computers to communicate information. Our prototype, the AirDisplay, utilizes the intensity and direction properties of air to exploit the human's ability to feel mechanical pressure (mechanoreception).

The use of air to communicate nonintrusive ambient information has a number of potential applications. For example, changes in the state of data (e.g. stock prices) can be mapped to the air flow intensity. Air streams can be used to enhance realism and immersion in games (e.g. on collisions, increasing speeds or in battle scenes). Furthermore, air streams can be used for untethered silent notifications. A message can be conveyed via an inaudible air stream, making it less noticeable by shoulder surfers.

These applications depend on the use of multiple air streams which the user can perceive separately. Our experiment sought to verify if this was possible and to determine the appropriate number of air sources and configuration of the device.

One of the earliest recorded uses of air to communicate information was by the cinematographer Morton Heilig. Heilig introduced Sensorama in the late 1950s, an "Experience Theater" targeting all human senses and using air to simulate wind [6]. Ishii et al. sought to use air to convey messages in the ambientROOM project [8], but controlling the flow of air proved challenging as reported in a later experiment [7].

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Suzuki and Kobayashi created a projection-based stereo display that used an air jet interface. The setup used air nozzles, 3D glasses, and a paddle that is to be held by the user [13]. The air nozzles created pressure on the paddle to simulate touching a 3D object. Unlike AirDisplay, it required wearing glasses and holding a paddle. Its maximum height range was 30 cm, while AirDisplay has a height range of 40 cm.

Most of the existing work that used fans was focusing on virtual reality applications. Previous work used big fans to simulate wind conditions in VR environments [3, 10]. Cardin et al. [2] developed a head mounted display with 8 fans to add realism in a flight simulator. Our approach, on the other hand, involves less bulky equipment and smaller fans that can be mounted on monitors. Air was also recently used to provide pneumatic feedback in in-car interaction [14].

Sodhi et al. demonstrated AIREAL [12], a haptic device that delivered tactile sensations in air. AIREAL used air vortices, directed by actuated nozzles. It provided tactile feedback of up to 8.5 cm resolution at a distance of 1 m from the device. Gupta et al. described AirWave [4], a stand-alone device intended to be placed in close proximity to computers. It provided at-a-distance haptic feedback using vortex generators. AirWave's resolution is 10 cm at a 2.5 m distance.

AirDisplay differs from AirWave and AIREAL in that it focuses on air streams rather than vortices. The usage of air streams emitted by fans is less expensive, and simpler to setup, operate, and manufacture than AIREAL. Unlike AirWave, AirDisplay uses small, flexible fans that can be integrated into the production of monitors.

Other works investigated haptic feedback through air suction [5, 9, 11, 14]. Unlike air streams, air suction has a rather limited range, making it more suitable for touch screens, but not for at-a-distance haptic feedback.

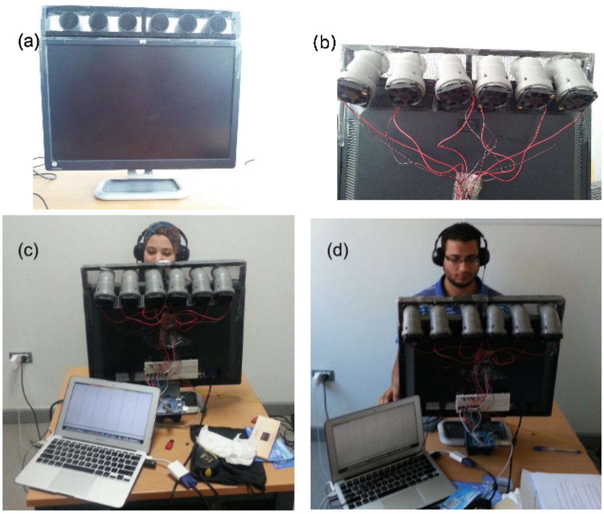

Fig. 1. (a) AirDisplay mounted on a monitor, (b) AirDisplay back view, (c) and (d) participants taking part in the experiment.

2 Design Issues

The human face has an abundance of Merkel's disks and Meissner's corpuscles, the two most sensitive Mechanoreceptors in the human skin [1]. Hence, we decided to position the AirDisplay around the monitor, to enable the output air to easily reach the user's face. We expect this to enable the user to differentiate between air streams. We decided to start with a single row of air sources mounted on the top of the monitor.

We decided that the device should communicate information to the user in two ways: whether the air source is on or off, and the intensity of the steady air stream coming from each source. By creating several distinct air streams at the same time, we could establish combinations of air streams that constitute a pattern. Each pattern would represent a meaningful piece of information to the user.

3 Evaluation

The goal of this experiment was to determine the most effective setup for the air sources. There are many parameters to be considered. Environment-specific parameters, like temperature and humidity, surely have an influence. However, in this study, we were interested to determine the most effective distance between adjacent air sources and the level of air intensity that would enable the user to distinguish different air patterns. An arrangement with essentially no space between fans enables us to increase the resolution of the display (number of air sources). However the user might find it difficult to discriminate between different air streams. Running a fan too slow might make its output unnoticeable, while running it too fast might disturb the user. We also wanted to investigate which air pattern can be most easily detected by users.

3.1 Apparatus

The hardware consisted of 6 fans aligned horizontally and placed inside a rectangular frame mounted on the top of the monitor.

Fan Selection. Directing air to the user's face raises concerns related to comfort, and to eye and skin irritation. The 259-1356-ND[1] fan has the moderate air flow, and minimal noise our project requires. It measures 50 mm L × 50 mm H × 10 mm and produces air flow up to 15.2 CFM (0.430 m^3/min) using 6100 rpm motor.

Physical Design. To ensure that there are no visual influences or distractions to the user, we had to conceal the fans. We installed each fan at one end of a curved plastic tube with diameter 45 mm, with the other end facing the user (see Fig. 1). The tubes add greater directionality to the air stream.

[1] KDE1205PFVX.11.MS.A.GN fan description manufactured by Sunon. http://www.digikey.com/product-detail/en/KDE1205PFVX.11.MS.A.GN/259-1356-ND/1021205.

Circuit. We used an Arduino Mega[2] to control the fans, since it has a high number of Pulse Width Modulation (PWM) pins. The Arduino chip cannot power the six fans to the maximum rpm, so an external power source was used. Transistors were used to control the current flowing to the fans with respect to the PWM signal.

Software. A custom desktop application was developed to control the fans and collect input from participants. In each trial, vertical buttons, each corresponding to the fan above, were displayed. The participant had to select the buttons corresponding to the fans from which she felt streams of air. When done with selection, the participant has to press the "done with selection" button. For each trial, the software records the time to complete the task, the actual fans in operation, and the participant selection.

Air Patterns. We picked 17 representative air patterns as unique trials to avoid having the participant do all the combinations. The patterns fall into 6 distinct groups: one fan at a time (P1), two adjacent fans (P2), left three and right three fans (P3), all fans (P4), alternating fans (P5) and no fans (Table 1).

Table 1. Air patterns

Fan1	Fan2	Fan3	Fan4	Fan5	Fan6
✓					
	✓				
		✓			
			✓		
				✓	
					✓
✓	✓				
	✓	✓			
		✓	✓		
			✓	✓	
				✓	✓
✓	✓	✓	✓	✓	✓
✓		✓		✓	
	✓		✓		✓
			✓	✓	✓
✓	✓	✓			

Air Flow. We picked a low speed (3050 rpm/6.8 CFM), a moderate speed (4575 rpm/11.5 CFM) and a relatively high speed (6100 rpm/15.2 CFM) to evaluate the user's ability to discern different air current intensities.

Interfan Distance. Overlap between air streams coming from adjacent fans could confuse the users about the source of air, making it impossible for them to discern the

[2] Arduino Mega 2560. http://www.arduino.cc/en/Main/arduinoBoardMega2560.

air pattern. Based on experiments with different interfan distances in addition to air intensities, we selected the following interfan distances: 1.0 cm, 2.5 cm and 5.0 cm.

3.2 Participants

Eight participants (15 – 34 years old) volunteered for the experiment. There were 4 males and 4 females. Participants were screened for skin conditions, and no issues were reported. Participants did not receive compensation for participation.

3.3 Procedure

The experiment was conducted in controlled environment. Room temperature was fixed at 22 °C to reduce the chance of sweating. The participants used the software to identify the tubes from which they felt a steady stream of air, thereby identifying the air pattern. Participants wore noise-cancelling earplugs to avoid identifying the working fans by the sound of the motors. All participants were positioned at approximately 40 cm away from the center of the AirDisplay (Fig. 1c and d).

3.4 Design

There were two experimentally manipulated conditions. First, we experimented with three interfan distances: 1.0 cm, 2.5 cm and 5.0 cm. Second, we investigated three air flow values: 6.8 CFM, 11.5 CFM and 15.2 CFM.

A randomized within participant repeated measures design was used. The 2 conditions were counterbalanced between the participants: 4 participants did the interfan distance condition first, followed by the air flow condition. The other group of 4 did the air flow condition first, followed by the interfan distance. The 17 air patterns were randomized among the users. Each participant performed 3 blocks, each consisting of 153 unique trials (17 patterns × 3 air flows × 3 interfan distances). Hence, each participant did 459 trials. The total number of trials in the experiment was 3672.

3.5 Results

We computed two dependent variables. First was the Success Rate, which is defined as the percentage of trials with a correct selection of a pattern. Second was the Response time, which is defined as the time from the moment the fans in a specific trial start until the user completes the identification of the pattern.

Success Rate. A repeated measures ANOVA was carried out on the data using SPSS. Significant main effects were found for air flow ($F(2, 14) = 113$, $p < .0001$) and interfan distance ($F(2, 14) = 6.3$, $p < .05$). This shows the identification of the air pattern depends on the air flow intensity and the distance in-between the fans. There was no interaction effect between distance and air flow.

Post hoc analysis was carried out to compare success rates for all air flow values. There was a significant difference in the success rate for 15.2 CFM ($M = 6.6$, $SD = 1.3$)

compared to 11.5 CFM (M = 4.4, SD = .7); t(7) = 6.6, p < .0001. There was also a significant difference in the success rate for 15.2 CFM (M = 6.6, SD = 1.3) compared to 6.8 CFM (M = 2.3, SD = .7); t(7) = 13.4, p < .0001. The third pair also showed a significant difference for 11.5 CFM (M = 4.4, SD = .7) compared to 6.8 CFM (M = 2.3, SD = .7); t(7) = 11.5, p < .0001. Thus, 15.2 CFM had the highest success rate followed by 11.5 CFM, and finally 6.8 CFM.

We also used post hoc analysis to compare success rate for the different interfan distances. Two pairs showed significant differences; 5.0 cm (M = 5.3, SD = 1.4) compared to 1.0 cm (M = 3.5, SD = .6); t(7) = 3.3, p < .05, and 2.5 cm (M = 4.5, SD = 1.1) compared to 1.0 cm (M = 3.5, SD = .6); t(7) = 3.1, p < .05.

Table 2 illustrates the average success trials count for all participants with averages for each air flow intensity. The most effective configuration was at fastest (15.2 CFM) air flow since participants scored higher in that air flow value than the other two.

Table 2. Mean success rates (out of 17)

	6.8 CFM	11.5 CFM	15.2 CFM
1.0 cm	1.7	3.6	5.5
2.5 cm	2.3	4.5	6.8
5.0 cm	2.9	5.3	7.7
Avg.	2.3	4.5	6.7

To measure the effectiveness of each air pattern, we summed the success rate for each pattern across participants for each interfan distance and air flow (Table 3) Results show that using one fan at a time (P1) at the highest speed used (15.2 CFM) has the highest success ratio, followed by the moderate speed (11.5 CFM). The next best pattern was using two adjacent fans (P2) at the highest speed (15.2 CFM) followed by the moderate speed (11.5 CFM).

Table 3. Pattern success in percentage

Air flow (CFM)		6.8	11.5	15.2	6.8	11.5	15.2	6.8	11.5	15.2
Distance (cm)		1.0	2.5	5.0	1.0	2.5	5.0	1.0	2.5	5.0
Pattern	**P1**	8	27	25	50	48	54	60	69	65
	P2	13	5	13	20	23	28	38	40	43
	P3	6	19	6	13	6	38	25	31	13
	P4	13	0	0	0	0	13	0	0	0
	P5	0	0	0	6	6	6	13	19	0

Response Time. A repeated measures ANOVA was carried out on the data using SPSS. Prior to the analysis, all measurements greater than 2.5 standard deviation were excluded. Significant main effect was found for air flow (F(2,14) = 8.6, p < .05). Thus, the user response time taken to identify the emitted air pattern depends on the air flow intensity. However, the change of the interfan distance did not have an impact on the response time. Post hoc analysis was carried out to compare response time means for the different air flow values. There was a significant difference in the response time for the highest speed, 15.2 CFM, (M = 8.8, SD = 2.2) compared to the moderate speed, 11.5 CFM, (M = 10.6, SD = 2.9); $t(7) = 2.6$, $p < .05$. There was also a significant difference in the response time for the moderate speed, 11.5 CFM, (M = 10.6, SD = 2.9) compared to the low speed, 6.8 CFM, (M = 7.8, SD = 1.6); $t(7) = 3.3$, $p < .05$. Table 4 illustrates the average response time for all participants.

Table 4. Mean response time (sec)

	6.8 CFM	11.5 CFM	15.2 CFM
1.0 cm	7.3	5.4	7.9
2.5 cm	7.4	8.5	9.1
5.0 cm	8.7	11.2	9.5
Avg.	7.8	8.4	8.8

3.6 Discussion

Results show that the higher the air intensity and the farther the fans the better the success rate. Hence, there is a trade-off between the resolution of an AirDisplay and the pattern detection accuracy. Lower air flow values, such as 6.8 CFM and 11.5 CFM, greatly reduce the ability of the user to detect the air stream pattern correctly.

The pattern analysis shows that the participants were able to identify a single air stream source (P1) fairly accurately (approximately 70 % at 15.2 CFM and 2.5 cm). This creates an opportunity for associating information with a single fan at a time. The results for two adjacent fans (P2) were less encouraging as the best score was 43 % at 15.2 CFM and 5.0 cm. The same applies to P3 (three right and three left fans) and P5 (alternating fans) as the participants were not able to identify the majority of the patterns. This suggests that the air streams were overlapping. The worst case was all fans (P4) only two users could detect the pattern, at all, and each did so only once. We attribute this also to the air flow overlap in the output.

The increase in air flow caused an increase in the average response time. This suggests that increasing the amount of air pumped out by the fan confuses the participants, who then take more time to identify the pattern.

4 Conclusion and Future Work

In this work, we demonstrated that air could be used to deliver information. The distance between fans and air flow affect the ability to identify the air stream pattern. The most promising configuration, for an outlet tube of 45 mm diameter, is 15.2 CFM air flow and 2.5 cm interfan distance, at 40 cm distance from the user. Using this configuration, we achieved 70 % success ratio for single fan patterns. Further experimentation should utilize the identified configuration.

The AirDisplay's hardware can be extended to detect the user's face and direct air streams towards it. Another step would be using a multi row and column set of air sources that would surround the user monitor. Thus, we would be able to simulate air streams coming from 4 directions: top, bottom, left and right. This will also enable us to investigate the recognition of more complex (e.g. alternating) patterns, and determine the optimal fan placement.

Further research might also investigate pattern recognition and response time on different body parts, such as back of hands or arms. We also plan to try smaller tubes to direct airflow, and experiment with air nozzles to target a smaller area on the user face. Heating and cooling elements will change the temperature of air in future experiments. In addition to the applications suggested at the beginning of this paper, we plan to invest in learning the user preference of desired functionality of air-stream based systems through evaluations and surveys.

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