A Study of Air-Based Interaction: Input and Haptic Feedback

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Abstract

Air is one of medium that has several properties that has a lot of potential to be used for developing various novel interaction devices for Human Computer Interactions (HCI). It has a wide range of use and application that is not limited for standard interfaces but also specialized interfaces such as for game interfaces and medical interfaces.

Although there have been several research on utilizing air for developing interaction devices. There are no research that utilize air to provide multiple interaction in one integrated interface. Therefore we are particularly interested in developing novel devices that capable to provide multiple interaction options in a single integrated interface, e.g., can work both as input interface as well as output interfaces.

We designed and developed several novel air-based prototypes using two air properties which are air-flow and air-pressure. In general, our work is categorized into three applications that can best leverage the use of air properties and show the significant impact of air-based device for human computer interaction (i) multimodal interactions (visual and tactile), (ii) fMRI-compatible interfaces (input and tactile), and (iii) game interfaces (input and tactile).

Through our work we are able to achieve novel interaction devices. We have verified the benefits of air. We have also confirmed that air can be utilized to provide effective input and output which can dramatically enhance user engagement and expand new research and industrial opportunities.

In summary, this dissertation contributes to the field of interaction technologies by expanding possibilities and interaction bandwidth of air-based interaction devices. The conclusion drawn and designs proposed will benefit future research studies not only in the field interaction technologies but also in the field of brain science and game interaction. Our work will also have important implications for providing valuable user interfaces for better education, data visualization, medical/rehabilitation, and entertainment (game, virtual reality).

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

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DEDICATION

to my dear mother, Jasmaniar

Chapter 1

INTRODUCTION

1.1 Research Background

Interaction technologies play an important role in Human-Computer Interaction (HCI) and have important connection with other fields such as education [34], medical care (e.g., rehabilitation) [16], video games [12], and data visualization [38]. Engaging technologies can improve human well-being and quality of life [8, 69]. Conventional interaction devices such as keyboard, mouse, and touch interfaces have limited options in providing engaging interaction to users. Thus, a large body of HCI work focuses on engaging technologies, such as tangible interfaces [29, 59], non-contact tactile interfaces [19, 26], and multi-modal interfaces [31, 55].

1.2 Research Issues and Objectives

Air is one good medium to provide engaging user interfaces. Some studies recently have explored the use of air for user interfaces [36, 53, 54]. Although air have been utilized as a medium to develop various devices and robots, most past works mainly focus on providing output interaction [13, 19, 63, 78]. To our knowledge little work has explored the use of air to provide input, multiple-channel output, or both input and output simultaneously through a single medium. Specifically, most of existing devices utilized compressed air and convert its energy into mechanical motion through pneumatic actuators. This method severely limits how air can be utilized to provide interaction between human and computer, especially for input. This is because there was little exploration of the capabilities of air properties and limited resources that could facilitate the development of air-based interaction devices.

This work aims to leverage the use of air for novel interaction. We are the first to comprehensively explore and study the use of air for both input and output interaction.

To increase the interaction bandwidth and choices of air-based interaction devices, this dissertation leverage the use of air properties to demonstrate the use of air as interaction technologies in three scenarios: a) Multimodal interaction, b) fMRI interaction, and c) game interaction.

The outcomes of this dissertation are:

1. An understanding of air properties for designing input interactions and haptic feedbacks.

2. Several new air-based interaction devices.

3. Practical guidelines for interaction device design for multi-modal, MRI, and game interactions.

1.3 Dissertation Overview

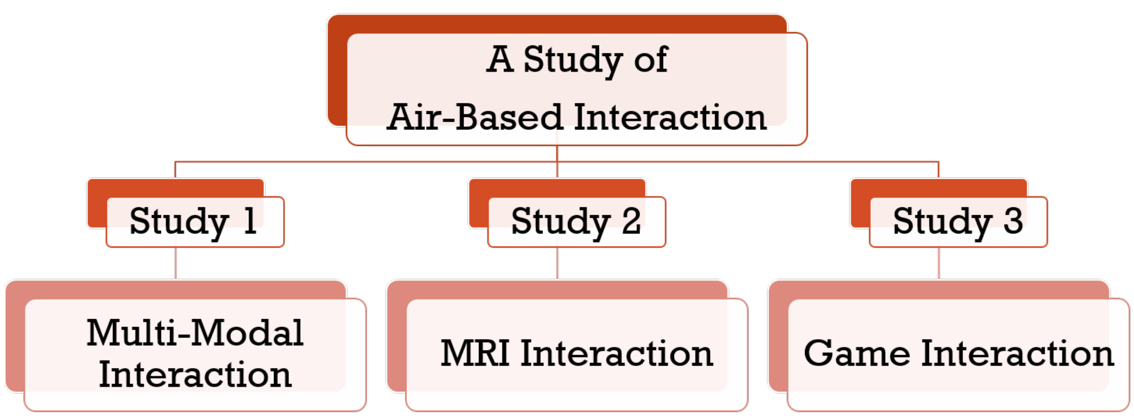


Figure 1.1: Dissertation overview.

1. In order to investigate the capability of air for multimodal interaction, we explored the suitability of air-properties to concurrently generate non-contact tactile sensations

with dynamic physical visualization. Additionally, we explored the ability of air flow force to create the sensation of patterns. The distinguishing feature of our prototype is that it can generate multi-point tactile stimuli and augment it with additional direct visual perception (i.e., physical visualization).

Moreover, to understand the effect of different visual feedback condition to user perception of non-contact tactile feedback, we conducted a systematic user study. The study also considers haptic perception on different haptic feedback patterns and various hand positions i.e., the significance of distance from the top of the device.

From this study we found out that air can be used to provide a significantly high detection rate by all participants in determining the position and/or the pattern generated. Moreover, the study results indicate that the direct visual perception of our prototype enhances the user's tactile perception level compared to other visual conditions.

2. Some parts of air-device were found to be invulnerable to electromagnetic interference EMI. Thus we proposed the use of air-based device for MRI environment which is a specialized application that is very sensitive with EMI. The strong magnetic field of functional magnetic resonance imaging (fMRI) and the supine position (lying with the face up) of participants in fMRI scanners severely limit how participants can interact during fMRI experiments.

   Despite its simple setup, air-based system is able to provide soft tactile feedback and record user responses/behaviors, which normally could not be achieved with an optical-fiber-based system. Additionally, the developed air-based prototypes comply with safety standard of fMRI-compatible devices. We also confirm that the prototypes can be used for continuous input device and also for giving soft tactile sensation concurrently. We also have provided several design consideration to develop air-based interaction device for use in fMRI environment. Furthermore, we proposed some applications of the prototypes.

3. Throughout the studies, we found that air-based devices are capable to provide multi-modal interactions and also able to be used to develop various novel interaction device for fMRI environment enabling new kind of brain experiments which are previously difficult to do without the air-devices.

   In this dissertation, one of our goal is to design and develop engaging interaction devices. Thus, we conducted a study to investigate whether air-based devices can engage users. We chose to investigate air-based device as a game interaction device since playing computer games is an enjoyable activity that is loved by many people. This study compared engagement and usability between a keyboard, a gamepad and air-based device.

   Our comparison with keyboard and gamepad found that air-based device outperformed other devices in immersion and fun, was well-accepted by participants, and can achieve equal performance after five trials of training. This suggests that air pressure can serve as a promising input for game interaction and can provide new forms of play.

Chapter 2

LITERATURE REVIEW

In this chapter, we discuss (i) interaction technologies for human computer interaction, (ii) air-based interaction technologies, and the current research gap.

2.1 Interaction Technology

Research in Human-Computer Interaction (HCI) has been very successful and has fundamentally changed computing [47]. The term of interaction technology is that all of technologies that help bridge human and computer or computing machines to communicate and interact with each other. There are some type of interaction technologies that emphasize on software/application such as drawing program [6], text editing program [45], hypertext [50], and video games [74].

Interaction technology is not limited to software only but also some physical interaction device such as keyboard or mouse or gamepad. Technologies that have supported interaction between human and computer have evolved from direct manipulation [62] into natural interaction and gestural recognition [41].

A well designed and developed interaction technologies whether it is a software or a device, it can better improve the performance of the users in conducting their tasks. Therefore, a good interaction technology is a technology that can make the users enjoy and engaged while doing their tasks.

2.2 Air-based Interaction Technology

There are very wide variety of interaction technologies existing currently. This dissertation focuses on utilizing air-properties as a medium for designing and developing an engaging and useful interaction devices. Air as a medium have several properties such as air flow and air pressure that can be leveraged to provide interaction between human and computers.

Utilizing air pressure to develop interactive devices have been exemplified by several researchers, e.g., jamming interface [14], visual display with dynamic button [22], inflatable mouse [35], Pneui [76], robot interaction [60].

Suzuki et al. [63, 64] introduced their design of a tactile feedback device which utilizes air pressure to produce the feedback. Their main concern was to provide a tactile feedback device that places no restraints on the users, e.g. wires, rigid arms. Furthermore, their system controls the air jet according to the position of the air receiver, which is held by the users. Their system freed users from the restraints of wires, however the users needed to hold an air receiver stick to receive the tactile feedback. Hachisu et al. [20] utilize air suction instead of air an jet to provide tactile feedback. However, users still need to touch the suction surface to feel the feedback. Therefore it can not be considered to be a fully non-touch tactile device. Another devices that utilize air for tactile feedback has been developed by Gupta et al.[19] and Sodhi et al. [61]. Instead of using air jets, they use air vortex rings for tactile feedback and this device projects the air directly onto the users. Therefore users can feel tactile feedback without the need to touch or hold anything.

While there are already extensive amount of devices that utilized air properties to provide interaction between human and computer, current air-based interaction technologies only focus in generating feedback.

2.3 Summary of Research Gap

Our literature review revealed that there are considerable amount of researches have been done in utilizing air for interaction technologies. Despite this, current air-based interaction technologies are very limited in only providing single feedback (output) to user. There is a need to explore and investigate the capabilities of air for not only generating output or feedback but also to receive and record input interactions from users. Our review also revealed that air-based interaction technology have a huge potential for developing various novel interaction devices that enable unique interactions that were limited previously. This dissertation seeks to address these two research gaps and propose new interaction devices that further leverage the advantages of air properties.

Chapter 3

AIR-BASED MULTI-MODAL INTERACTIONS

3.1 Introduction

Physical visualization can provide more engaging user experience, however the main challenge for visualizing data using physical objects is representing changes in data dynamically. Although some works [15, 51, 52] tackled this limitation by using a matrix of actuated columns or acoustic levitation, touching a levitated object directly can disturb and occlude visual perception of the physical visualization. Thus, there is a need for tactile awareness without directly touching and disturbing the feedback with the user's hand. Some previous works provided non-contact tactile sensation by using air [19, 61, 63] and ultrasound [7, 27]. However, these devices are dedicated to generating non-contact tactile sensations only and

(a) (b) (c)

Figure 3.1: The AirVis prototype. (a) the user (hand) feels air-tactile sensation from the top of the device, (b) Multiple balls levitated to form a simple line, (c) Multiple balls form a simple pattern, with fan-motor noise around 58 decibels (dB).

they do not support this with direct visual feedback (i.e., physical visualization).

In order to present the suitability of air-properties for multi-modal interaction by concurrently generating non-contact tactile sensations with dynamic physical visualization, we developed a prototype named AirVis: an air-based physical visual and tactile display (Figure 3.1). We evaluated the design and technical challenge of developing an air-based multi-modal device. Furthermore, to understand efficiency and application of AirVis, we conducted a user study, we focused on investigating effect of multi-modal feedback (visual and touch) to user performance.

3.2 Related Work

This work focused on developing a device that can concurrently provide (1) physical visualization, and (2) non-contact tactile sensation, where the non-contact tactile sensation delivers a multi-point representation of the pattern of the physical visualization.

3.2.1 Physical Visualization

Ultrasound is able to provide either physical visualization [51, 52] or non-contact tactile feedback [7, 27]. However, the core limitation of ultrasound is that the same array of ultrasound can not concurrently provide both physical visualization and non-contact tactile feedback.

For concurrent visual feedback and tactile sensation, air is a promising method. In order to allow tactile sensation without occluding the physical visualization, a common approach is to provide the sensation in mid-air, separated from the visualization. For example, aerial tunes [3] levitate a light-weight ball in mid-air using a stream of air flow, thus enabling interaction with the levitated object. However, these devices are limited to only one object with a single point of tactile sensation, thus it cannot represent 3D data. Our work will fill this gap.

One challenge of using air to provide multipoint sensation is that air tends to spread around, thus we need to find ways to focus the air to provide a consistent tactile sensation. A single air source like that in Air Jet [63] or Aireal [61] would not apply in this case. Our solution is to represent each air source as one pixel, similar to the concept used in inForm [15] where a matrix of individual manipulable columns are used to represent different 3D information dynamically.

3.2.2 Non-Contact Tactile Sensation

Several works regarding non-touch tactile devices have been conducted. They can be classified into three classes based on their approaches: 1) ultrasound devices, 2) magnetic devices, and 3) air devices.

Ultrasound device

To the best of our knowledge, Iwamoto et al. [30] pioneered the work of non-touch methods for producing tactile feedback using ultrasound sound pressure. Later on, Hoshi et al. [26] improved the prototype by increasing the number of ultrasound transducers and by controlling the phase delay of the ultrasound transducers. Moreover, Hoshi et al. developed Touchable Holography [27], an aerial interaction system [24], and remote hand-writing system [25].

Carter et al. [7] expanded the ultrasound device to achieve multi-point feedback and developed UltraHaptics, a multi-point mid-air tactile feedback system for touch surfaces. Multi-point feedback is achieved by modulating multiple focal points at the same time. However, the pressure strength of the feedback diminished with the increasing number of focal points [73].

Ciglar [9] proposed the of ultrasound tactile feedback as a musical instrument. Alexander et al. [2] combined an ultrasound tactile device with a mobile TV and discussed its design constraints. Marshall et al. [42] developed Ultra-Tangibles and demonstrated an interactive table on which tangible objects can be freely moved.

Although the effective distance of ultrasound non-touch tactile devices is limited to 200-300 mm from the transducer surface, they have high spatial resolution compared to other non-touch tactile devices, e.g., air, magnetic. However, ultrasound non-touch tactile devices have the highest system complexity due to the high number of transducers used in their systems. Ultrasound tactile devices also need to focus the radiation pressure of several ultrasound transmitters to produce adequate radiation pressure.

Magnet device

Although their device is not completely non-touch, Lee et al. [39] and Weiss et al. [71] utilized magnets to produce mid-air tactile feedback. Weiss et al. [71] developed FingerFlux which utilizes magnetic force to generate tactile feedback. Attracting and repelling magnets arranged in a matrix, can create physical constraints on the table surface without using any physical devices. Though this requires no contact with the system, the feedback is limited to near the table surface, and users are required to wear or carry dedicated hardware due to the characteristics of the magnets which create the attract-repel forces.

Air device

Suzuki et al. [63, 64] introduced their design of a tactile feedback device which utilizes air pressure to produce the feedback. Their main concern was to provide a tactile feedback device that places no restraints on the users, e.g. wires, rigid arms. Furthermore, their system controls the air jet according to the position of the air receiver, which is held by the users. Their system freed users from the restraints of wires, however the users needed to hold an air receiver stick to receive the tactile feedback. Hachisu et al. [20] utilize air suction instead of air an jet to provide tactile feedback. However, users still need to touch the suction surface to feel the feedback. Therefore it can not be considered to be a fully non-touch tactile device.

Another devices that utilize air for tactile feedback has been developed by Gupta et al.[19] and Sodhi et al. [61]. Instead of using air jets, they use air vortex rings for tactile feedback and this device projects the air directly onto the users. Therefore users can feel tactile feedback without the need to touch or hold anything.

The air vortex device is considered to be low cost and low complexity. However, it can only project one single-point air vortex at a time and the doughnut-shaped shape perception is fixed. Air devices appear to be the most economical and least complex compared to ultrasound devices and magnetic devices.

Summary

In summary, there is a large number of studies that utilized ultrasound tactile devices for their systems but only a small number of studies that utilized air or magnetic devices. We found that there is no device like our prototype which has the following features, 1) low-cost[1], 2) multi-point non-touch tactile feedback, and 3) non-touch tactile feedback and visual feedback simultaneously.

3.3 AirVis - Air Based Visual and Tactile Display

AirVis is designed to levitate objects and generate air-tactile sensations concurrently using an individual air flow. Figure 3.2 shows that AirVis consists of arrays of transparent boxes/bodies which consist of an object inside and a fan-motor at the bottom. An array of fan-motors generate air-flow upward to push and levitate the objects. The generated air-flow exits through an opening at top of the box giving a soft sensation of touch to users hand/palm.

3.3.1 Hardware specification

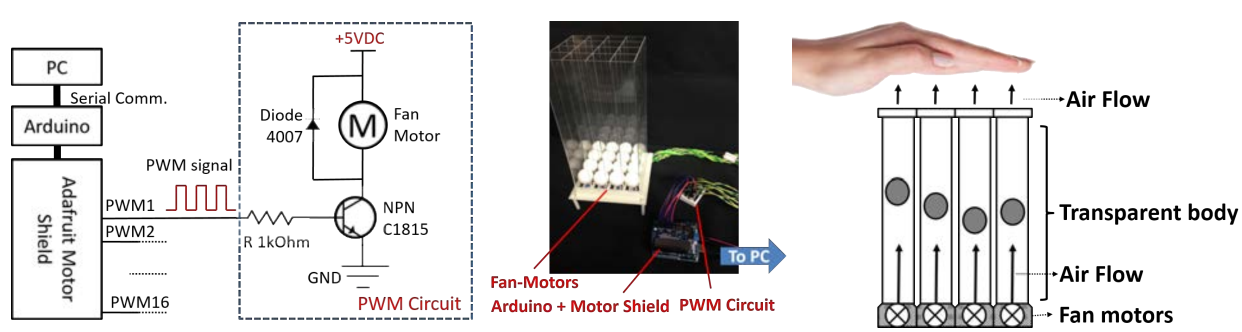
Figure 3.2a shows a diagram of circuitry for the AirVis. AirVis consists of sixteen 25×25 mm^2 fan-motors in a 4x4 array with a specification of $5v$, $0.21A$, and 2000 rpm each. All of the circuits and fan-motors are driven by a $5v$, $10A$ switching power supply. The complete prototype of AirVis is shown in Figure 3.2b.

[1]E.g., the cost of materials to build our prototype which consisted of an acrylic body, Styrofoam balls, fan-motors, Arduino, motor-shields, and power supplies was around 200-250 US Dollars (128-160 GBP).

The Arduino Uno microcontroller receives patterns and location information for each fan-motor from a PC via serial communication. Adafruit Motor shield then translate the information and sends the PWM signals to all the fan-motors through PWM circuits. The prototype allows the control of an individual ball or a group of balls forming a pattern using a keyboard or mouse.

Each PWM circuit consisted of an NPN transistor (C1815), a $1k\Omega$, and a diode (N4007). This circuit enables the control of motor speed by PWM (duty cycle of square wave). An N4007 flyback diode is added to protect the circuit from inductive current that may occur when the motor is stopped.

The current AirVis prototype uses light-weight balls to construct the physical visualization. In pilot studies, different sized balls (diameter of 13, 15, 18, and 20 mm) and different sized transparent body tubes (18×18 and 25×25 mm^2) were tested. The balls weighed 1.04, 1.60, 2.76, and 3.79 g respectively. Identical fan-motors were used for all tests. Pilot studies showed that increasing the ball size required an increase in the power needed to levitate the ball. It is recommended to use a ball that has a diameter similar to the size of the transparent body inner diameter, with less than 6 mm and more than 2-3 mm in difference.



(a) (b) (c)

Figure 3.2: The components of AirVis. (a) The prototype circuitry diagram, showing one of 16 PWM circuits for fan-motors, (b) the AirVis prototype and controller, (c) AirVis consists of a fan-motor array at the bottom of transparent box (body) which generate air flow to levitate balls and provide touch sensation from the top of the box.

The larger diameter of the tube permits air to flow around the ball causing it to spin quickly and create turbulence inside the tube, making it difficult to levitate the ball. Conversely, if the difference in diameter is very small (less than 2 mm) or the ball fits too tightly inside the transparent tube, the ball will touch the inner wall of the tube adding resistance to the air flow that levitates the ball. Based on pilot studies, AirVis is constructed using arrays of balls with 20 mm diameter and transparent tubular bodies which are 200 mm in height with a 25 mm inner diameter following the diameter of the fan-motors in order to minimize air flow leakage.

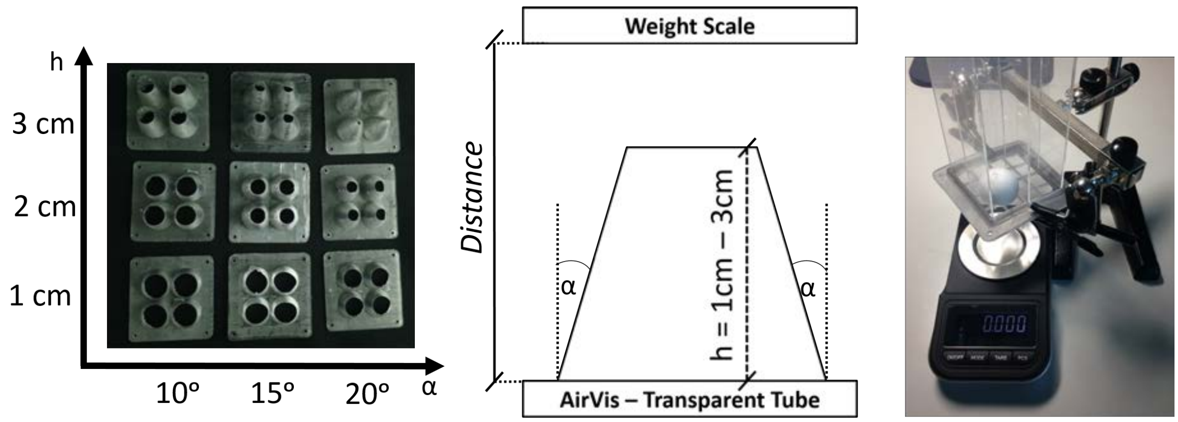
3.3.2 Modular Design

In order to achieve higher resolution in the future, AirVis is designed to be scalable, i.e., the number of fan-motors and its transparent body can be increased and reduced as needed. The 16-channel Adafruit Motor shield is stack-able which allows us to use multiple motor-shields with a maximum number of 32 motor-shields controlled by a single Arduino. This motor-shield characteristic allows AirVis to be expanded to a maximum of 512 motors for a single Arduino.

3.3.3 Air Flow Force

Air-tactile sensation is closely related to air flow force that exits from the top of AirVis (Figure 3.2c). In order to understand how strong the emitted air-flow force is, a measurements of air-flow force were conducted using a digital weight scale with 0.000 gram precision. AirVis was set upside-down and perpendicular to the weight scale. A smaller version of AirVis (2 × 2 pixels) was used, as it was easier to hold it upside down. The distance between weight scale and AirVis can be adjusted to measure the effect of different distance to the air flow force.

Without properly focusing the air, air will be increasingly dispersed from the top of AirVis and the air flow force will decline. Therefore, several nozzles with different height and angle (Figure 3.3a and Figure 3.3b) were developed to focus the air flow force and enhance the



(a) (b) (c)

Figure 3.3: Nozzle effect test, (a) various nozzle with different height and angle, (b) illustration of nozzle dimension with h = nozzle height and α = nozzle angle, and (c) air flow force measurement setup (AirVis is put upside down and perpendicular to digital scale, with changeable distance).

tactile sensation. The measurement was done on one pixel only as can be seen in Figure 3.3c.

Table 1 shows the measurement results of air flow force in multiple conditions. No tube (NT) and with tube (T) conditions were conducted to investigate the effect of transparent tube to air flow force. Subjectively, tactile sensations for both NT and T conditions were similar. However, measurements show that the transparent body/tube of AirVis is important not only as the container for the levitated ball, but also to enhance the air flow force. As for the air flow force with nozzle, the nozzle with a 1 cm height and 10° angle has the best overall air flow force for distances from 3 to 15 cm. However, it is not true if we consider user perception of the air flow. The best tactile perception for distance from 3 to 15 cm is achieve by the tube with 2 cm height and 15° angle. Although air flow force with nozzle is slightly lower for short distances compared to the non-nozzle condition, air-tactile sensations with nozzle are better compared to the non-nozzle condition. Therefore, we used this nozzle for the user study in the following section.

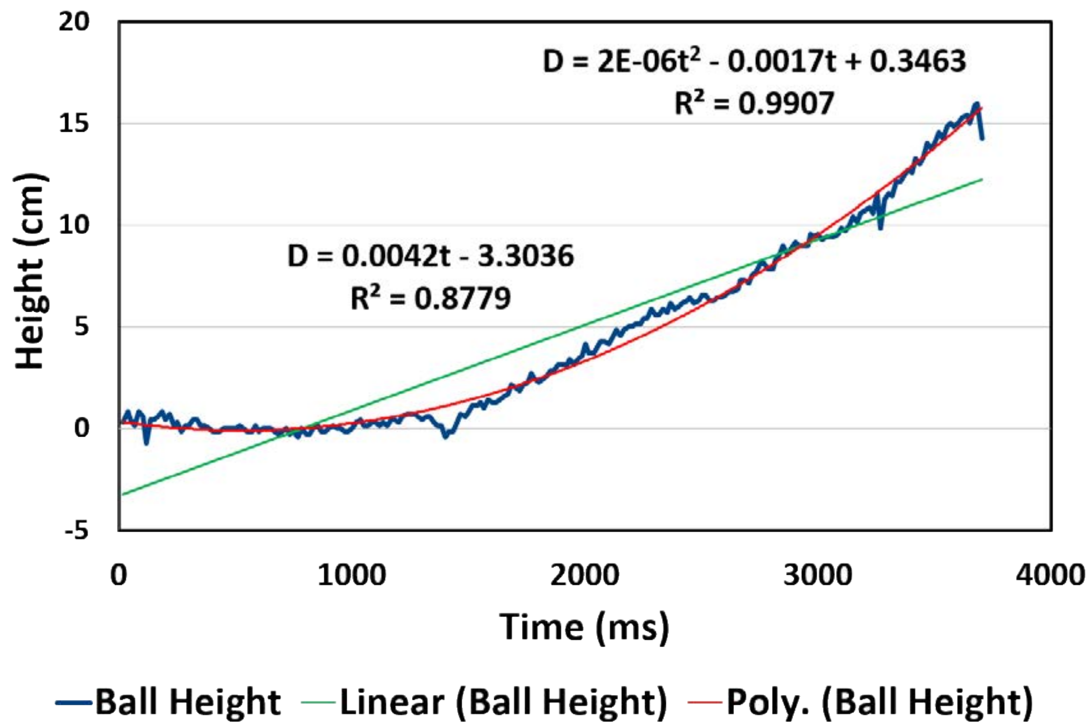
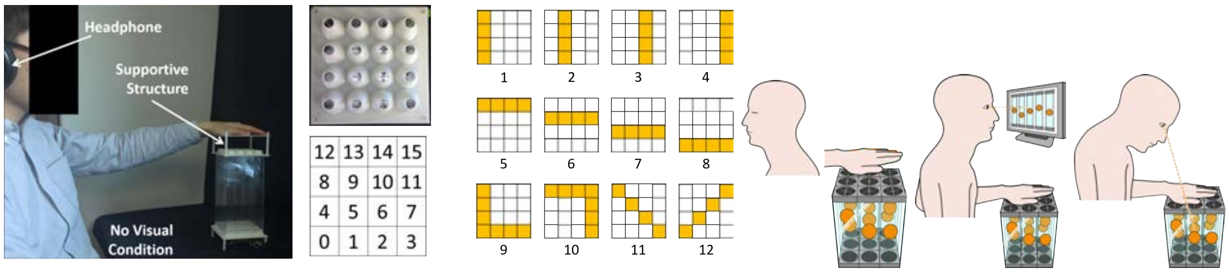


Figure 3.4: Measured average height of the ball (cm) over time (ms) with two regression lines (linear and quadratic)

3.3.4 Ball movement

The individual ball position is controlled by the amount of force and the time the ball is pushed by the air-flow from a fan-motor. In this prototype, a fixed force of air is used to lift the ball, i.e., the maximum force of the fan. Thus, the ball position can be controlled by only varying the time. Several visual pattern can be achieved by varying the time force is applied to each ball. Although this method has a drawback that the ball can not be positioned in a short time and the ball position needs to be reset (i.e., settled at the bottom) before generating each new pattern, this is one of the simplest methods to achieve the levitation of a ball in a desired position.

Figure 3.4 shows the average ball position over time, with two regression lines (linear and quadratic). The relation between ball position and the applied time of air flow was



(a) Setup (b) Pattern (c) NV (d) VM (e) VB

Figure 3.5: Illustration of Experimental conditions. (a) The user wears a Headphone for noise canceling and the hand is supported by a structure in the no visual cue condition (no ball and no monitor), (b) A list of shapes was used in the user studies (12 different patterns consisted of 8 simple lines, 2 composite lines, 2 diagonal lines), (c) The tactile only condition, no-visual cue (NV), (d) Tactile with computer graphic (CG) on monitor as the visual cue (VM), (e) Tactile with levitated balls as the visual cue (VB).

investigated through the measurement of the ball position every 10 ms using an ultrasound ranging module HC-SR04 which was placed 10 cm from the top of the AirVis while the maximum air-flow force was applied to the ball from the fan-motor .This procedure was repeated six times to better validate the measurement data. Based on the regression equation shown in Figure 3.4, around 3 seconds is required in order to levitate ball at 10 cm high which is half the height of AirVis. Theoretically, in ideal conditions with unlimited body height and unlimited time the ball could travel high indefinitely, however this is not the case for AirVis. The equation for ball height over time is strictly limited to our prototype with a 20 cm tall transparent body. Thus, with infinite time, the ball will stop at maximum height of 20 cm.

3.4 User Study on Effect of Visual Condition on Users' Air-Haptic Perception

The user study was conducted to investigate, 1) user perception of a single-point air-tactile sensation and also of multi-point air-tactile sensation and 2) the effect of different visual condition modes on user air-tactile perception.

3.4.1 Design

We tested the users perceived air-tactile perception in association with three different visual conditions, i.e., tactile only without visual (NV), tactile with visual using computer graphic image on monitor (VM), and tactile with direct visual perception using a ball (VB), as shown in Figure 3.5. The three conditions were conducted in a counterbalanced manner using a Latin Square method. Air tactile sensations were produced from 16 fan-motors that were positioned in an equally spaced 4×4 grid at the bottom of the box.

In each of three conditions, two kinds of air tactile sensation were presented: single-point (16 different points) and multi-point tactile sensation (12 patterns) as shown in Figure 3.5b. The experiment configuration was similar to that used by Tsalamlal et al. [66], where users were asked to put their hand on the supporting structure with palm placed down at the center of the top of AirVis. The prototype was positioned perpendicular to the participants' palm at a given distance. This configuration was chosen to ensure that the palm was kept at a static distance relative to the device. The distance between the top of the prototype and the participants hand could be modified according to the experimental conditions. Three distances of 3, 5, and 7 cm were tested in all the conditions.

Each of 12 patterns was presented in random order and repeated two times. The total number of trials that each participant performed was 3 (conditions) × 3 (distances) × (16 positions + 12 patterns) × 2 repetitions totaling 504 trials.

The independent variables for the study were: Distance (3, 5, 7 cm), Fan position (16 positions) for the single-point mode and Pattern (12 patterns) for the multiple-point mode. The dependent variables were: Detection (if air-tactile sensation was detected), Accuracy (whether the users can tell correctly the position or pattern given), and Perception level (How well the tactile sensation was perceived).

3.4.2 Participant

Twelve participants from 5 difference nationalities were recruited, eight males, aged 21 to 28 ($M = 24.4$, $SD = 2.4$). One participant was left-handed and the others were right-handed. Each was paid US$10. All participants had no previous knowledge or practical experience with non-contact tactile devices.

3.4.3 Procedure

Before carrying out the experiment, participants were briefly told how the device works, the purpose of the experiment, and the procedure experimental procedure. They were then required to fill in their demographic information and their experience with tactile devices. To become familiar with the prototype, participants were allowed to feel several different air-tactile sensation intensities and patterns with all three conditions freely.

For each of the three conditions, the participants were asked to place themselves in front of the desk and to place one of their hands on the supporting structure and wear noise canceling headphones. Research [68] reveals no significant difference in tactile sensitivity between the dominant and non-dominant hands, therefore the participants could freely choose and change which hand to use to receive the tactile sensation.

For all three conditions the participants were required to give their subjective perception level on a 7-point Likert scale. This was repeated until all 16 single tubes and all 12 patterns had been presented. The participants' recognition/detection (JND - Just Noticeable Difference), accuracy (whether participants recognized the pattern correctly), and perception levels (participants' subjective evaluation of their perception for the tactile sensation) were recorded both by the prototype and the experimenter. Participants could take a rest whenever they felt tired.

After completing the trials, participants were interviewed and required to complete a questionnaire about their general impression of AirVis, whether the tactile sensation was strong and clear enough to be perceived accurately, whether the addition of visual perception enhanced the perceptive ability of the tactile sensation, which mode of visual condition was better between the monitor and direct vision of the ball movement, and by how much the participant thought their perception and accuracy improved with three different visual conditions. Participants completed all three conditions, interview, and questionnaire in approximately 2 hours in total (around 35 minutes for each condition, a 10 minute interview and questionnaire, 5 minutes rest).

3.4.4 Results

The data of interest were *stimulus detection*, *accuracy*, *perception quality*, and *subjective evaluation*. Stimulus detection was measured by the percentage of air flow that participants claim to be able to recognize as tactile sensation. Accuracy was the percentage of correct answers given by the participant regarding which tactile pattern was given to them. Perception quality was measured by the participants' subjective evaluation of how clear the tactile sensation was. User evaluation was measured by the participants' subjective evaluation as a tactile device and subjective opinions about their performance during the experiment.

Stimulus Detection

Results show that participants can detect all the air tactile stimulus given for all experimental conditions with different modes of visual conditions and hand position distances, i.e., the air tactile stimulus was strong enough to be detected and recognized clearly by all participants as tactile sensation.

Accuracy

Participants identified the tactile stimuli with 89.02% accuracy on average. The data were analyzed using repeated measures ANOVA. There were significant effects on accuracy from distance between the participants' hands and the tactile source. The detection accuracy was significantly high when the hand distance was 3 cm with the mean of 93.49% for single

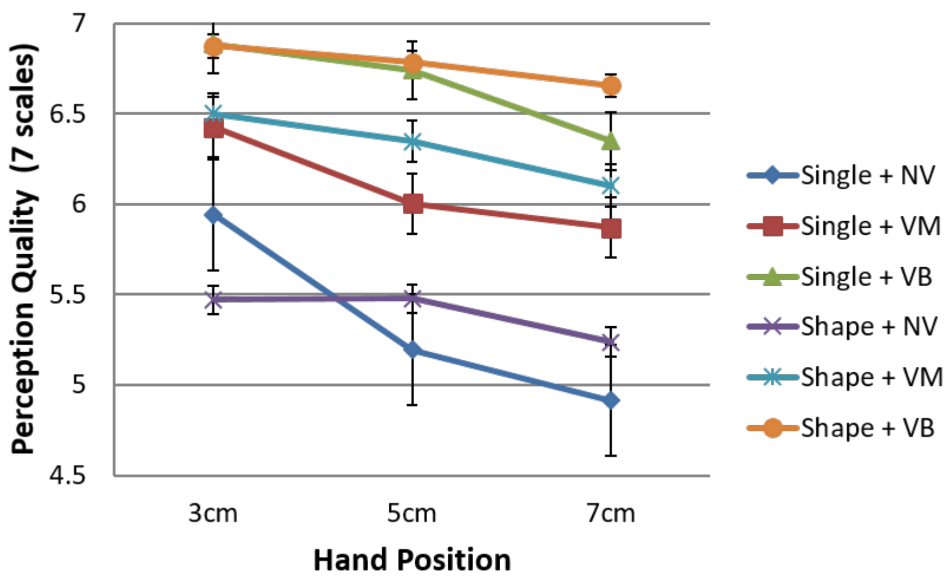


Figure 3.6: Summary of the effect of distance between user's hand and AirVis to the user's tactile perception in percentage, NV = No Visual, VM = Visual on Monitor, VB = Visual using Ball movement.

point detection and 94.14% for pattern detection. Post-hoc comparisons with Bonferroni correction confirmed that increasing the hand distance from 3 cm to 5 cm significantly reduced detection accuracy to 89.61% and 87.31% for both conditions. Further increments in hand distance to 7 cm reduced the accuracy from 84.81% to 84.78% for single and pattern perception respectively. There was no significant difference in detection accuracy between single-point and multi-point perception.

Perception Quality

Perception quality for all conditions with 2 modes × 3 conditions × 3 hand distances was measured. The data were measured in a 7-point Likert scale, then analyzed using repeated measures ANOVA tests. Figure 3.6 shows the summary of perception for all conditions in percentage values.

The perception quality of VB condition showed a mean value of 6.659, while perception values for VM and NV conditions were 6.100 and 5.349, respectively. Post hoc comparisons with Bonferroni corrections confirmed a significant difference between NV and VM ($p < 0.001$), NV and VB ($p < 0.001$), and VM and VB ($p < 0.001$). However, there were no significant differences in perception between single point and multi-point (pattern) air-tactile stimuli with mean perception values of 6.036 and 6.161 for single-point and multi-point respectively. There were no significant differences when the hand distance was increased from 3 cm to 5 cm (mean = 6.349 and 6.092), however there was a significant difference when we increased the hand distance to 7 cm (mean = 5.855) with p value of < 0.001.

Subjective Evaluation

In general, participants gave positive evaluations for AirVis. Nine out of twelve of the participants answered that direct visual perception improved their perception better than representation on a monitor (computer graphic). Figure 3.7 shows subjective user evaluation of AirVis for all participants. One participant suggested that, if AirVis can accommodate different air temperatures, it would improve the devices value and tactile perception. Another participant commented that it maybe interesting to add fragrance/smell feedback together with the air flow feedback.

3.5 Discussion

Overall, the high perception quality of direct vision of ball movement suggests that users prefer to see the actual physical object because it gives the sense of volume and proper proportions. The results suggest that direct visual perception of the balls is better than computer graphic representation on a monitor. This might also be because in the direct visual condition, the users' hand, the air tactile device, and the balls are aligned in one straight line. The device is closer to the users' reach, thus increasing the perception and sense of reality. It is difficult to adjust the viewing angle of the computer graphic representation on the monitor with air tactile sensation and the user's hand.

We confirmed that users can perceive the patterns with high confidence. These patterns

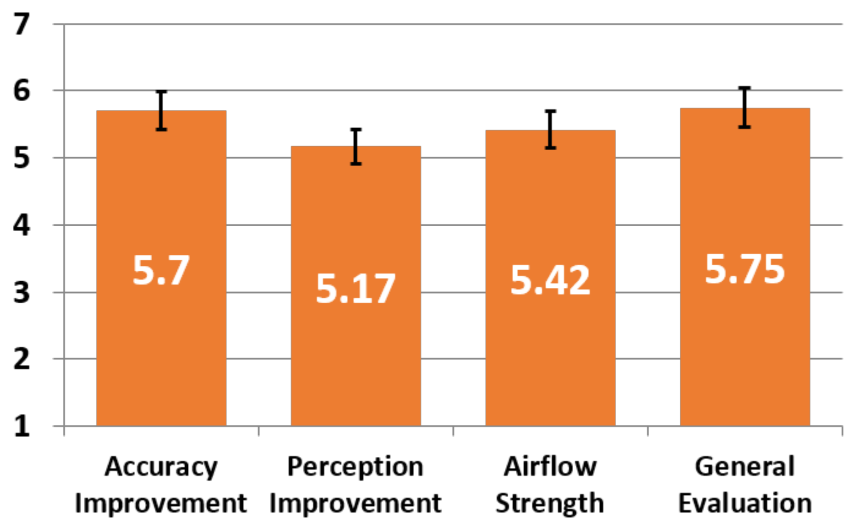


Figure 3.7: Summary of user evaluation on AirVis.

can be exploited in two primary ways. First, these patterns can serve a *utilitarian* purpose where users use the perception of patterns for tactile code (a.k.a braille) or to engage in a learning experience. Given that our device is relatively less expensive compared to ultrasonic or magnetic based devices, our device has more potential utilitarian value. Second, these patterns can serve *hedonic* purposes where they can be used as artistic or cultural expressions, for example, to provide an integrated expression of different colors, smells, and temperatures (e.g., dancing fountain).

Our open loop control allows the system to position a ball at a desired height for a period of time. A closed loop control design using distance sensing for each levitated ball could provide more precise control over the direct visual perception. With position information, the fan-motor speed can be adjusted to let the balls levitate for a long period of time. The distance sensing could be placed on the bottom or top of the transparent body, however, the bottom (on top of the fan-motor) is preferable in order to avoid visual occlusion at the top of the prototype.

Another way to improve the controlability of the balls is by attaching a transparent string to each ball. The other end of the string is rolled to a DC or stepper motor to control the length of the string. The string and its motor control is placed at the bottom of the system behind the fan motor, thus the concept of activating the fan-motor to levitate a ball and generate air-tactile sensation concurrently is maintained. By using a separate control for positioning and air flow force, we could further allow more robust control over the physical visualization and air-tactile sensation. Additionally, since the ball is attached to a string, it could allow the ball to stay in a desired position even if we put the system upside-down or tilt it to any degree, thus allow more interaction for users, e.g., rotate, tilt, or shake the system. By adding an accelerometer, we could allow the system to show different visual perspectives if rotated or tilted.

While physical visualization of the current prototype is limited, expanding the prototype with more pixels such as 10×10 or 50×50 pixels could allow more variety in the visualization such as for a terrain surface. Combined with a map application this could provide an interesting and useful interaction of the concept of dynamic physical visualization.

Our prototype is currently able to provide tactile stimuli with a strong enough multi-point air-tactile sensation to users. A heating element could provide more variable air-tactile sensations with different localized temperatures for each pixel.

$Dis(cm)$	NT	T	T, 3, 20	T, 3, 15	T, 3, 10	T, 2, 20	T, 2, 15	T, 2, 10	T, 1, 20	T, 1, 15	T, 1, 10
3	67.375	229	N.A.	N.A.	N.A.	113.75	133	87	159	155.5	151.5
5	20.25	197.125	7	73	126.25	124.375	146	120	162.375	162.5	164.25
7	12.875	187.875	7.5	77	134	128.5	133.25	121.5	158.875	163.625	167.25
9	4.75	130.25	8.75	75.75	136	115.25	129.5	109.625	134.75	140.75	146.75
11	0	109.875	2	67.375	131.5	88	114.125	105.125	104.25	113.25	120.75
13	0	96.5	0	61.375	118	79.625	118.75	72.75	91.875	102.75	113
15	0	81.25	0	55	101.625	46.75	88.875	68.75	81.25	88.875	97.125

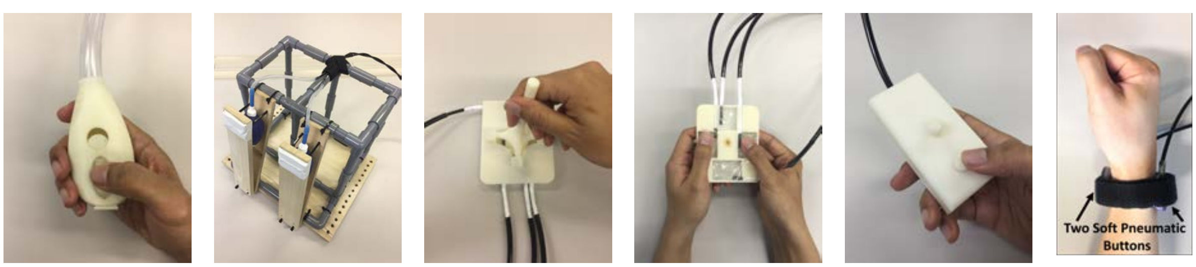
Table 3.1: Effect of different nozzles to air flow force from multiple distances(Dis). Measured using digital scale in 0.000 gram. (NT = No transparent tube, T = with transparent tube attached. T, h, α = with transparent tube, nozzle height(h), nozzle angle(α)).

Chapter 4

NOVEL AIR-BASED MRI-COMPATIBLE INTERACTION DEVICES

4.1 Introduction

Functional magnetic resonance imaging (fMRI) [28] enables medical doctors and researchers to study correlations between brain activation and tasks performed by participants during a brain scan. In addition to the scanned brain images, participants responses and/or behavioral data while performing the tasks are required during post-processing of brain study to improve the detection of brain activity [4]. Furthermore, in a task that requires special stimulation other than visual stimulation, additional equipment is required to deliver the stimulation (signals) to the participants, such as haptic sensations and/or fragrance [43]. However, the



(a) (b) (c) (d) (e) (f)

Figure 4.1: Various air-based devices. (a) 3D printed air-flow based device for tap and slide interaction, (b) a pneumatic pedal device constructed from two pneumatic balls, wood, and PVC tube, (c) pneumatic joystick which can be used to manipulate x-y movements, (d) Pneumatic button with four pressure sensitive buttons, constructed from four air pockets arranged in a 3D printed structure, (e) a two button pneumatic device, constructed using a single air pocket with 3D printed structure, (f) two 3D printed soft pneumatic button put together as wearable soft-haptic device

strong magnetic field of fMRI limits the choice of response and/or stimulation device that can be used. Devices with traditional ferromagnetic materials and actuation/sensing methods are not permitted in the fMRI environment.

Optical fiber-based sensing has been used in various fMRI applications such as force measurement [65], motor response [44], and a music instrument [23] because of its small size, it is not affected by electromagnetic interference (EMI), and presents no electromagnetic susceptibility (EMS). Due to its popularity, there are some commercial providers that offer fMRI-compatible fiber-optic devices for recording participant' responses during fMRI scans [10, 11]. However, these devices are typically expensive[1], requiring specialized control software, limited to recording response only and can not be used to provide stimulation to the participants.

Similarly, air-based (pneumatic) devices are invulnerable to EMI and lack of EMS. Pneumatic-based devices have also been used in various fMRI applications such as robot interaction [13, 17, 77], skin stimulation [18, 72], haptic interface [78]. However, these devices are limited to one configuration and only provide stimulation to participants without sensing and/or recording participants' response information.

We proposes a complimentary method for designing and developing fMRI-compatible devices that are able to both record participant responses and provide stimulation (such as soft tactile feedback and fragrance signal) to the participants in fMRI environment. We explores the use of air properties, especially air-flow and air-pressure for designing and developing various interaction devices for use in the fMRI experiments (see Figure 4.1). We also explores the use of 3D printer, plastic pockets, and off-the-shelf materials to enable fast development and replication of various custom interaction devices for use in fMRI environment.

We conducted informal interviews with several expert fMRI researchers who have been using fMRI for experiment for more that 5 years to find out what possible interaction device functions may be required, which are currently unavailable and which may be made possible

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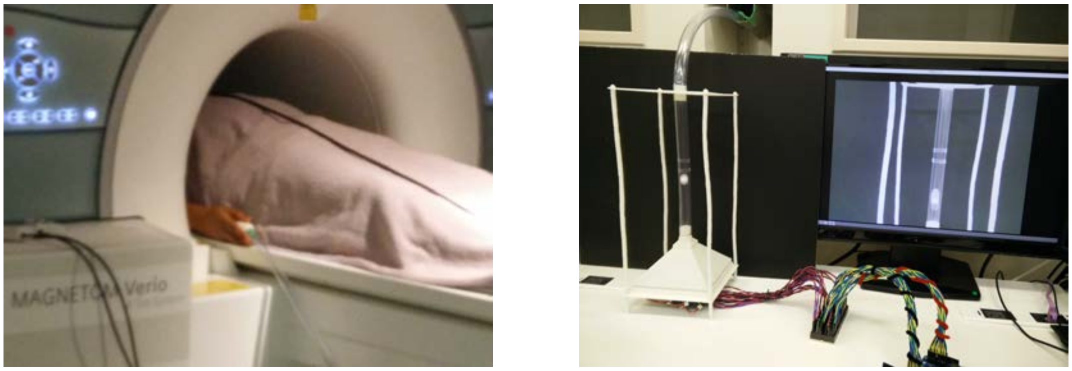
[1] US$2000 - 15000 in 2016, source [11]



(a) (b)

Figure 4.2: fMRI-Compatible air-flow-based system, (a) a participant uses an air-flow-based device to control the ball position positioned outside fMRI room (b) from inside of the fMRI scanner, (b) air-flow-based system consisting of a transparent tube and a ball.

by using the proposed air based interaction devices. We also conducted an evaluation experiment for fMRI-compatibility of the developed devices on a 3.0 Tesla fMRI scanner. The evaluation results show that air-based interaction devices are effective and that they comply with standards for device in fMRI [75].

We envisioned that in the future these air-based devices will allow fMRI researchers to expand their choice of tools in experiments aimed at understanding human behavior using fMRI scanners. These devices could be selected from a standardized library, edited and then be 3D printed, allowing fast and inexpensive testing in pilot studies for new brain studies instead of directly purchasing expensive commercially available devices.

4.2 Related Work

The work presented in this chapter builds on fMRI-compatible devices, pneumatic-based interaction devices, and device fabrication.

4.2.1 fMRI-Compatible Devices

Several researchers have developed various fMRI-compatible devices using pneumatics control [13, 21, 32] and optical-fiber [23, 44, 65]. However, fiber-optic-based devices are limited to only sensing and recording response information. Although pneumatic systems are able to record responses based on changes in air pressure, no previous work utilizes this capability to develop a response device using pneumatic system. Also, there is no prior work that explores the use of air-flow to provide interaction inside the fMRI environment.

4.2.2 Pneumatic-based Interaction Devices

Utilizing pneumatics to develop interactive devices have been exemplified by several researchers, e.g., jamming interface [14], visual display with dynamic button [22], inflatable mouse [35], Pneui [76], robot interaction [60]. However, these devices were developed not to be used inside the fMRI environment, because they require additional components that may contain ferromagnetic materials. Our work is focused on allowing interaction by solely using air-properties and only components that can be put inside fMRI scanners i.e., made from plastic and/or non-ferromagnetic materials. Previous researchers demonstrated the flexibility of pneumatic control devices for interaction and the need to further expand the possible applications in different research areas such as fMRI.

4.2.3 Device fabrication

Pneumatic devices can be built using several methods such as 3D printing [58, 67], manual construction [76], casting or molding [46]. Vazquez et al. [67] have shown that 3D printing is a unified and flexible approach to fabrication and customization of pneumatic devices. They also showed that it is possible to do multi-material 3D printing, however the 3D printer that is capable of print using multiple materials is costly at present[2].

Although manual construction such as plastic welding is considered cumbersome and

[2]Objet Eden260V, US$19800 in 2016

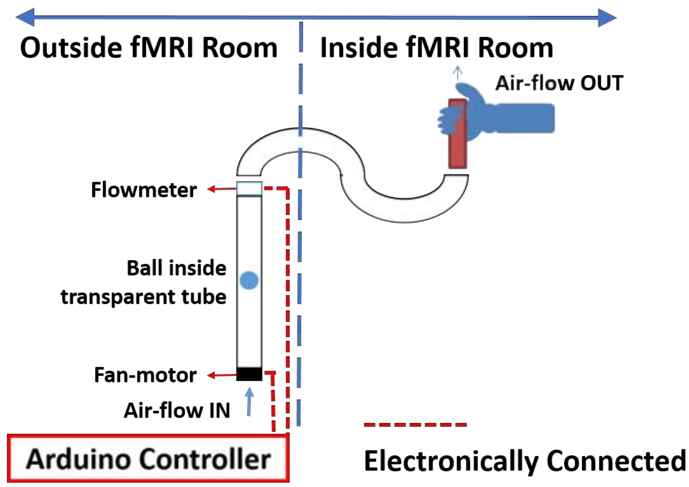


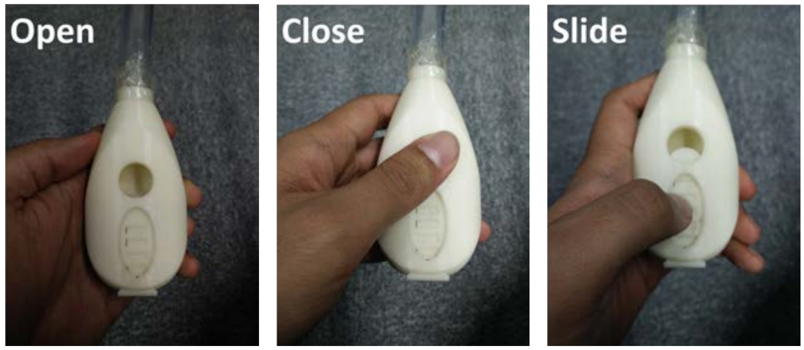
Figure 4.3: Schematic diagram of air-flow based system.

error prone compared to 3D printing, it is one of the fastest methods in fabricating air-pocket for using with pneumatic systems. In this work, we explored a combination of plastic welding and 3D printing to develop various pneumatic chambers (air-pockets) to be used in our interaction devices. Fabricating using plastic welding to allow fast development which are used to provide proof-of-concept of the developed design then refined using 3D printing.

4.3 Air-flow-based system fMRI Input Device

The air-flow-based system is designed to allows simple interactions with simultaneous soft air-tactile feedback to users. In this work, we used the air-flow-based system to allows users to have a soft air-flow sensation and a simple precise control over a levitated ball inside a transparent tube at the same time (Figure 4.2).

Figure 4.3 shows a complete of air-flow-based system. The air-flow-based system consists of a fan-motor, a ball (diameter 8 mm) in a transparent tube (inner diameter of 1 cm, thickness 3 mm), an 8-meter long transparent tube (inner diameter of 1 cm, thickness 3 mm), a flow meter (range 100 mL/min to 1500 mL/min), an Arduino microcontroller and a 3D printed interaction device (Figure 4.1a). The Arduino controller turns on the fan-



(a) (b) (c)

Figure 4.4: Interaction for fMRI-Compatible air-flow-based system, (a) open interaction to lift the ball by allowing air-flow, (b) close interaction to put the ball down by stopping air-flow, and (c) slide interaction for precise control of ball position by controlling the amount of air-flow.

motor generating air-flow through the transparent tube to 3D the printed hand-nozzle device (Figure 4.4) which is held by the user. The hand-nozzle device was developed using a uPrint SE 3D printer with ivory color ABSplus material.

The strength of the air-tactile feedback is correlated with the strength of air-flow that is generated by the fan-motor. Furthermore, in Figure 4.4, position control of the ball can be done in two different interactions, which are an on-off (open-close) interaction and a sliding interaction. Open-close interaction provides a digital-like control, while the slide interaction provide an analog-like control behavior.

Despite its simple setup, this system allows both soft tactile feedback (with just-noticeable differences (JND) in air flow pressure) while concurrently recording user behavior when precisely controlling the ball position, which normally could not be achieved with an optical-fiber-based system. By utilizing data recorded by a flow-sensor, the interaction enabled by this system can not only control the ball position (as shown in Figure 4.2), but also can be used to provide a single-button-like response or an analog slider response (Figure 4.4).

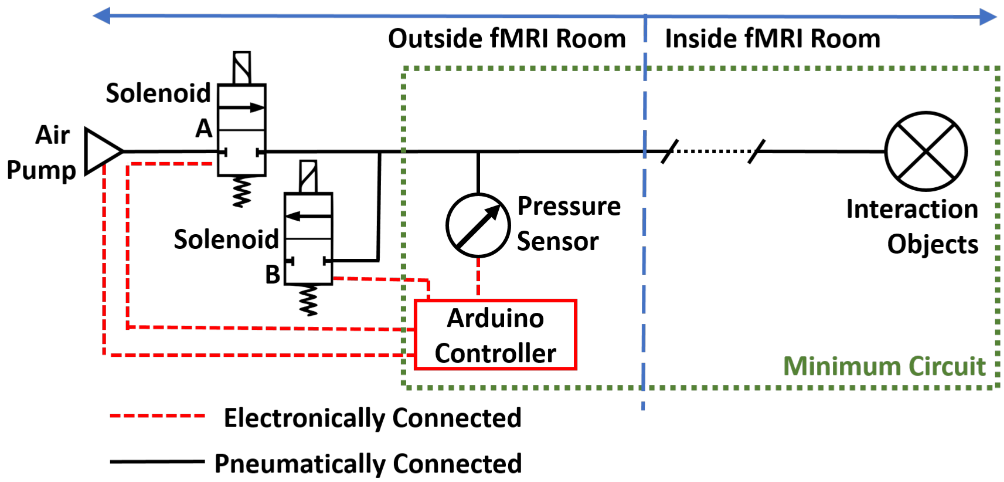


Figure 4.5: Pneumatic and circuitry diagram for general design of pneumatic-based fMRI-compatible devices.

4.4 Novel Air-Pressure-Based fMRI-Compatible Interface Devices

The main design consideration is that, all components that will be put inside fMRI need to be non-ferromagnetic and/or contain no metal/electronic circuit. Thus we focus on utilizing air only without additional component such as potentiometer or LED to our systems. In addition, the device should be able to be operated while the participant is lying down. The pneumatic-based systems that we explored in this work rely on changes in air pressure to record user response information, to generate tactile sensation to users or to send scented air to users inside fMRI scanner.

4.4.1 Design

In this work, we explored three designs to serve three different purposes. The first purpose is to dynamically change air pressure to alter the physical form of air pockets while the sensor continuously reads internal air pressure of the system to allows precise close-loop control. The second purpose is to only sensing user input with pressure sensors, thus further simplify the system. The third purpose is to deliver smell from fragrance chamber outside of fMRI

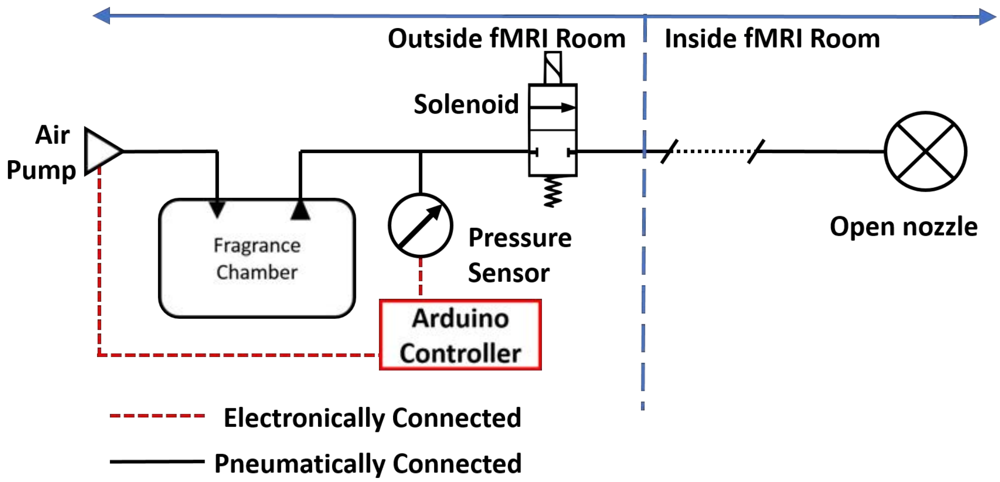


Figure 4.6: Pneumatic and circuitry diagram for delivering smell to users inside fMRI scanner.

room to users inside the fMRI room while air pressure sensor and solenoid control the air flow to user to have a constant pressure.

Figure 4.5 shows the diagram for the first pneumatic design. This first design is for general use which contains an air-pump as pressure source, two solenoid valves, a pressure sensor, and an interaction object (e.g., air pocket or 3D printed air chamber). In the rest state, both solenoids A and B are closed (no air in or out, both solenoids are normally closed). If solenoid A is actuated and B is at rest, the pressure source (air pump) can increases air pressure in the system. If solenoid B is actuated, the system is open, releasing air and thus decreasing the air pressure inside the system.

The second design is for recording air pressure information only. This design is the simplified version of the first design which consist only air pressure sensor and the interaction object as shown inside minimum circuit part of Figure 4.5. Assuming that there is no air-leakage in the system, this is useful to reduce the number of components in the system and to increase the scalability of the pneumatic system (e.g., although in a normal setup, a four-button variable sensing device would require four air pumps, eight solenoid valves, and four

(a) (b) (c) (d) (e)

Figure 4.7: Three basic air pocket/chamber for pneumatic system a four-button pneumatic device, (a) an air-pocket fabricated by plastic welding, (b) a soft button fabricated by 3D printer with flexible material, (c) a hand squeeze device built from off-the-shelf lens blower and teflon tape, (d) a freshly printed four-button flexible pneumatic device with mesh supporting structures, (e) finished 3D printed four-button flexible pneumatic device

pressure sensors, in simplified design, the same device only require four pressure sensors to be functional). This design is limited to interaction objects that can return to its original shape after pressed or squeezed by users. Therefore, interaction object such as air pockets that need to be inflated first before can be used as interaction device can not use this design.

The last design is for delivering smell to users inside fMRI is shown in Figure 4.6. By modifying the design in Figure 4.5, we can use the same components to allow different stimulation for the users. Air pressure sensor continuously reads internal air pressure of the system, if the internal air pressure is lower than required threshold (air-flow that deliver the smell is weak), solenoid valve is switched off and air-pump increases pressure for the fragrance chamber. If the internal air pressure is higher than threshold (strong air-flow), the solenoid is activated allowing the smell to be delivered to the user. By monitoring the air pressure to be close to the threshold value, this system can maintain a stable flow of smell to the user. It is to be noted that this application, if used for a long period of time the fragrance particle will diffuse overtime and making the smell weaker.

4.4.2 Fabrication

We fabricated the pneumatic devices using plastic welding and two different 3D printers (one for rigid material and one for flexible material). The fabrication process using plastic welding is straightforward, affordable, and fast, but have low replicability. Fabricating using 3D printer takes a little bit longer time to design and print, but is very replicable when printing multiple custom devices.

Fabricating by Plastic Welding

In a condition where 3D printing is not available, plastic welding offer a fast way to develop a prototype for air-pocket used in pneumatic systems. We used plastic welding method to develop a simple air pocket by heat pressure molding off-the-shelf 0.3 mm thick polyethylene sheets (plastic) into a square and attaching a pneumatic tube on one end of the pocket. Although this method is error prone (e.g., it is difficult to form an airtight pocket in single try), it is one of the fastest and most cost cost-effective ways to fabricate a custom-sized air-pocket. To ensure the air pocket was airtight, we used airtight tape (teflon tape) and heated it with a heat gun to close any possible openings. Using this simple method, we were able to increase the fabrication success rate of this method. The fabricated air pocket can sustain internal air pressure of 4.5 PSI before breaking. One example of air-pocket that developed by this method is shown in Figure 4.7a. This air pocket can be used as an on-off button and also a pressure sensitive button.

Fabricating by 3D Printing

Although plastic welding can be used to fabricate air pockets, its choice of geometry and shape is limited and difficult to reproduce the same result multiple times. Therefore, we combined the air pocket that we fabricated using plastic welding with rigid 3D printed part to improve variation of pneumatic device that we can develop.

In order to make the appearance of the air pocket more appealing, we 3D printed a

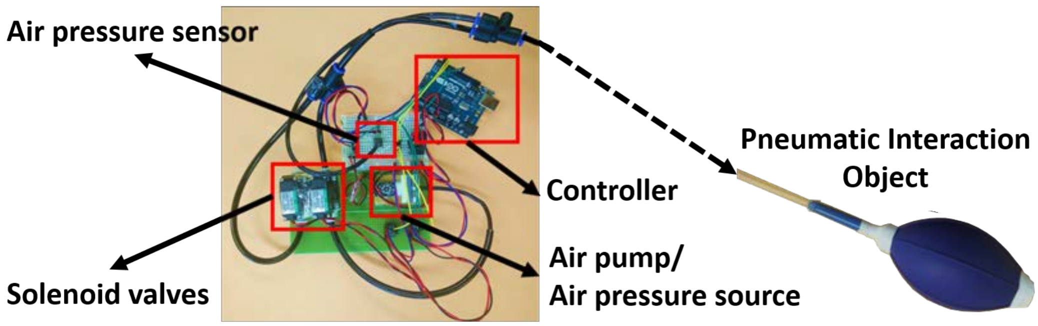


Figure 4.8: Complete Pneumatic System.

case for four air pockets (Figure 4.1d) using a uPrint SE printer with ivory color ABSplus material. This allows the four air-pockets to work as a four-button pneumatic device. Using the same 3D printer, we also 3D printed a handle for the joystick device (Figure 4.1c). Since the 3D printed part is used only as container, we designed so that it does not have any over-hanging geometry in order to reduce any support material in printing result. By avoiding over-hanging geometry, the fabrication process will become faster because it eliminates the need to remove supporting material and cleaning process.

For soft and flexible parts of the system, we used a FORM2 printer with flexible resin[3], to fabricate soft and elastic part of our system, for example a soft pneumatic button (Figure 4.7b). Although flexible resin from formLabs can not elongate as much as TangoPlus used in [67], it has a higher tensile strength which allows the printed parts to be more robust from breaking. Additionally, in this 3D printer there is no supporting material. In order to print any overhanging geometry, FORM2 uses mesh like supporting structure to hold the geometry (see Figure 4.7d). One feature of this 3D printer is that, it allows printing a hollow geometry without any internal support structure. Therefore, there is no need to clean the internal part of the printed result. However, naively printing hollow structure will result in failure of the 3D printed structure. In order to print overhanging and/or hollow geometry,

[3]A more detailed information of this material can be found in http://formlabs.com/products/materials/flexible/

the geometric should be tilted/positioned in such a way (around 15 to 20^o) that each layer of the 3D printed structure can support the hollow part without any supporting structure.

4.4.3 Applications

In this section, we will illustrate some potential applications of fMRI-compatible pneumatic-based interaction devices. Figure 4.8 shows the pneumatic system that we used for all of the following application. The pneumatic system consist of an off-the-shelf MIS-2500-015G air pressure sensor from Metrodyne with a pressure range of 15 PSI (68.95 mbar) [1] to monitor the pressure levels, two 2-way solenoid valve (model EXA-C6-02C-3) to regulate the system pressure.

Pedal Simulation

Figure 4.9 shows a pedal interface constructed from woods, PVC tubes, and two lens blower which are the same items used for hand squeeze device shown in Figure 4.7c. With two pressure sensitive input devices connected together, the pedal device can simulate interaction for acceleration and brake in car simulation. The pedal can detect when the user accelerate

(a) (b)

Figure 4.9: (a) Pedal simulation device which consisted of acceleration and brake pedals, (b) Experimental setup inside MRI device.

or brake, or detect whether the user make a slow acceleration/brake or fast. Currently, there is no pressure sensitive pedal device available commercially, thus this device open an opportunity for brain researchers, to better investigate human behavior when driving, i.e., not only investigate whether user press acceleration or brake, but also investigate how strong the user need to press the pedals, or when the user make a mistake, how much pressure the user already applied to pedal before realizing the mistake.

Wearable Wrist Haptic Feedback

We develop two flexible pneumatic buttons (Figure 4.7b) and put them together to make a wearable wrist haptic device. Since the buttons are made from flexible material, increasing internal air pressure of the pneumatic system can elongate the button giving a soft pressure feedback. This wearable haptic device can be used by brain researchers to study human reaction to haptic feedback that generated by smartwatch on the wrist. Since normal smartwatch can not be used inside fMRI environment, this pneumatic wearable haptic device is a good alternative to reproduce smartwatch haptic feedback inside fMRI. Wearable wrist can be expanded by using more pneumatic buttons.

4.4.4 Interviewing MRI researchers

In order to understand whether the prototype was useful for the researchers, we interviewed four expert researchers who work closely with fMRI devices. We asked three questions:

Q1 Can the proposed device be used as a response device for fMRI research?

Q2 Is any possible new device needed by fMRI researchers?

Q3 Would any new fMRI study be possible if these devices were available?

The researchers responses to the device were generally good because the prototypes provided richer information compared to fiber optic response devices which can only provide binary (on-off) information. They agreed that the prototype can be used as an alternative cost-effective response device for their future work using the fMRI device.

For Q2 and Q3, two researchers answered that they need a joystick-like response device, as the fiber-optic one is currently very costly. The other researcher answered that a balloon like device that can detect two handed interaction as well as the pressure from each finger would help build an understanding of human motor interaction. Another researcher responded that if the pressure is linear to the deviation of the pressed surface of the device, it can be used to detect head movement adjustment for fMRI research.

4.5 fMRI-compatibility evaluation

We conducted an experiment to evaluate the fMRI-compatibility of the pneumatic device. A device needs to satisfy three characteristics to be called fMRI-compatible. First, it must be safe to use and not do any harm to the users in any way. Second, the device should not affect the scanned image of the fMRI. Third, the device must be able to work properly within a high magnetic field while the fMRI is running [23, 78].

The prototypes were designed to be compact, soft and free from any para-magnetic material so that they will not be affected by the magnetic field of fMRI. Even if the prototype hits the users in an accident, it will not harm the users in anyway. In order to be used for fMRI environment, a minimum of 7 meters in tube length is needed as the participant needs to use the device from inside the fMRI room. Therefore we used tube with 10 meters length to allow more movement.

The experiment was supervised by an fMRI researcher/expert. As shown in Figure 4.10, we placed the pneumatic response device on the fMRI bed together with an fMRI phantom (an object used to evaluate the fMRI device that responds similarly to how human tissue and organs act) [56]. The fMRI has different scanning sequences for different purposes. We used a sequence that used the whole frequency range of the fMRI device so that if the device did not effect any of the readings, the device can be said to be fMRI-compatible with any scanning sequence.

(a) (b)

Figure 4.10: Experiment in the fMRI room and result images. a) The pneumatic device was put on the fMRI bed to be tested, b) a view of the pneumatic device while the fMRI was running.

We conducted three types of MRI-compatibility tests, which are i) Structural image scan comparison, ii) Noise image scanning sequences, and iii) Echo planar imaging test. These three tests were conducted for three conditions. The first condition was scanning with the phantom only, this was to provide the baseline scanned image of the fMRI that is not affected by any device. The second condition was scanning with the phantom and the prototype in the off condition. This was done to investigate whether the prototype material affected the scanned image. The third condition was scanning with the phantom and the prototype in the running condition. This condition was done to test whether the prototype had any effect on the scanned image from the fMRI. All experiments were conducted using a 3T Siemens scanner.

4.6 MRI-Compatibility Results

4.6.1 Structural image scan comparison

Structural image scan is a straight-forward test to investigate whether there is any noise or disturbance in the scanned image. As can be seen in 4.11, the scanned images for all three conditions are nearly identical without any visible noise. By visually investigate these three

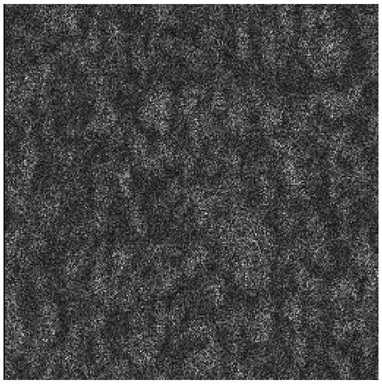
(a) (b) (c)

Figure 4.11: Structural image scan result. (a) without the pneumatic device, (b) the pneumatic device inside the fMRI scanner off condition, (c) the pneumatic device inside the fMRI scanner on condition.

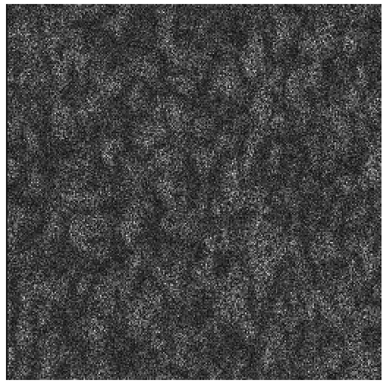
images, we can suggest that the pneumatic response device does not give any artifact to the structural image of MRI.

4.6.2 Noise image scanning sequences

The noise scanned images from the three conditions are shown in Figure 4.12. One criteria to define that the scanned image is free from disturbance is that the image should show random noise. If there was any disturbance in the scanning process, the image should show a white line (vertical/horizontal) on the image. During scanning in the third condition, we also tested whether the scanning process affected the performance of the pneumatic response device by monitoring the pressure sensor reading. We found that during the scanning process the fMRI did not affect the pressure sensor reading (i.e., the sensor reading worked properly). Based on the resulting images and the sensor readings, the fMRI researcher concluded that the pneumatic response device has no effect on the scanned images and that it was fMRI-compatible.



(a)



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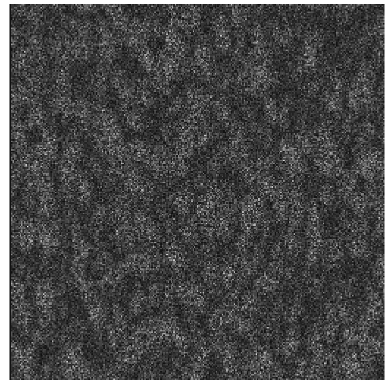

(c)

Figure 4.12: Noise image scanning sequences result. (a) without the pneumatic device, (b) the pneumatic device inside the fMRI scanner off condition, (c) the pneumatic device inside the fMRI scanner on condition.

4.6.3 Echo planar imaging test

Compared to the other two test, EPI test is meant to measure the difference and loss of Signal to noise ratio (SNR) on different scanning conditions. Thirty-four axial slices were acquired for echo-planar imaging (EPI) with TR/TE value of 2000/30, FOV = 24cm, flip size = 80, acquisition matrix size of 96x96, and voxel size of 3x3x3mm.

Additionally, the image quality were measured using time-variant signal-to-noise ration (tSNR), which is the ratio between temporal mean and the temporal standard deviation of a time-series. The results confirmed that the pneumatic devce is fMRI compatible with tSNR decreased by less than 2%. The system also proved to be able to used to obtain a clear brain scan images with similar activation to hand device.

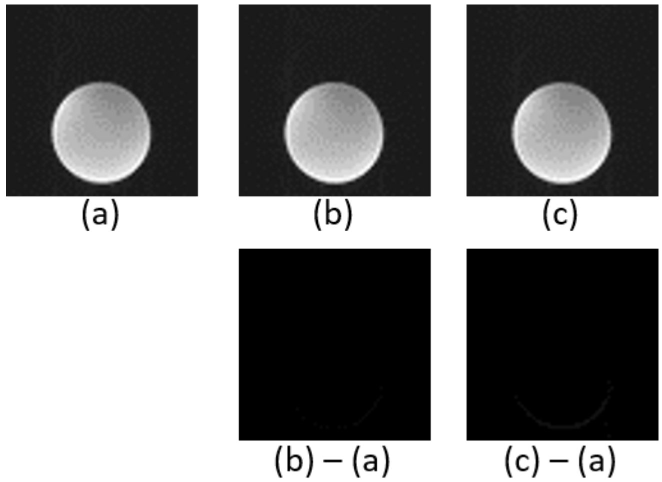

Figure 4.13: EPI scan result. (a) without the pneumatic device, (b) the pneumatic device inside the fMRI scanner off condition, (c) the pneumatic device inside the fMRI scanner on condition.

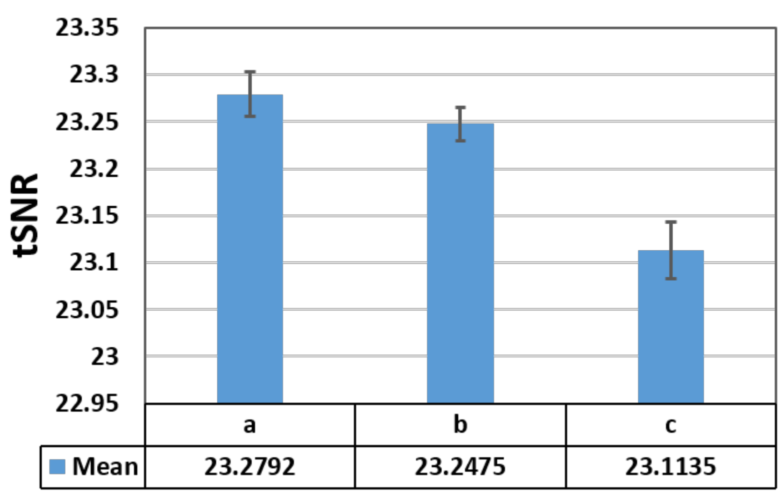

Figure 4.14: tSNR results. (a) without the pneumatic device, (b) the pneumatic device inside the fMRI scanner off condition, (c) the pneumatic device inside the fMRI scanner on condition.

Chapter 5

AIR-BASED GAME INTERACTIONS

5.1 Introduction

Playing computer games is an enjoyable activity that is loved by many people. One integral game component that contributes to great player experiences is game input devices. Keyboard and gamepad are two most commonly used input devices in video games.

However, the traditional input paradigm only supports binary and directional input and thus, interaction bandwidth can be limited. This paper explores a novel parameter, i.e., *air pressure*, for game input. Air pressure supports continuous value, as opposed to binary input in keyboard or gamepad. This continuous value is particularly intuitive in games where there is a range of possible values, e.g., hitting a drum with different forces produces different sound. To explore the feasibility, we developed *AirDevice*, a device that supports air pressure input.

We explore the usefulness of *AirDevice* for game interaction in two custom-made games. Our comparison with keyboard and gamepad found that *AirDevice* outperformed other devices in immersion and fun, was well-accepted by participants, and can achieve equal performance after five trials of training. This suggests that air pressure can serve as a promising input for game interaction and can provide new forms of play. We conclude by discussing future directions and possibilities of air-based game interaction, and the possibility to extend it for exergames or health games alike.

Our contributions are threefold:

1. We propose a novel input device for games called *AirDevice* that supports air pressure input.

2. We demonstrate how air pressure can be utilized in games by developing two custom-made games and by showing how the act of squeezing can add a new dimension of play to games.

3. We discuss future challenges and opportunities of air-based game interaction.

5.2 Related Work

Our work is related to two areas: game interaction and air-based interaction.

5.2.1 Game Interaction

Gamepad and keyboard (+ mouse) are two most commonly used input devices in video games. Apart from these devices, there are abundant efforts from researchers to provide new ways to interact with games such as the use of gaze [57], body movements [5], and physiological signals [48] such as facial input [37] or heart rate [49]. One most recent development is the idea of using brain-computer interfaces (BCI) through electro-encepalogram (EEG) signals to control gaming [70]. Similar to these efforts, this work aims to expand the interaction bandwidth of video games and proposes *AirDevice* that utilizes air pressure as a new form of game interaction.

5.2.2 Air-based Interaction

The idea of using air for interaction has been used in the area of haptic stimulation. For example, researchers have employed mid-air feedback for virtual reality applications [61]. Hachisu and Fukumoto [20] leverage the property of air suction for a haptic interface. There also work on using the freeform quality of air to develop shape-changing interfaces [14, 76]. In sum, air has many good qualities for interaction which has not been explored in the games domain. These works focused on providing feedback/output, little study have investigated the use of air for input interaction, especially for game interaction. This work aims to fill the gap.

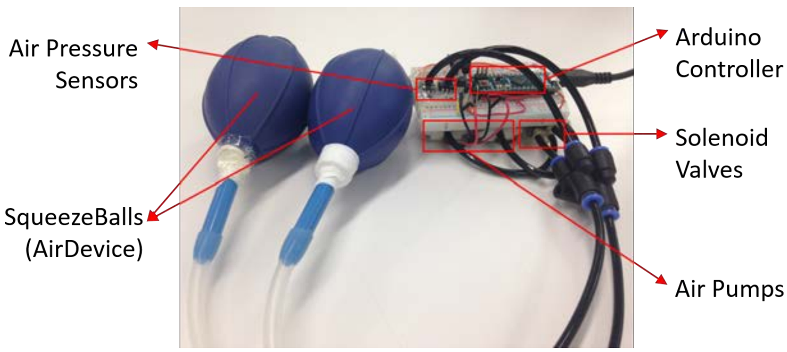

Figure 5.1: Complete system of *AirDevice*.

5.3 Development of Air-Based Interface

The goal of *AirDevice* prototype is to develop a game input device that is able to provide continuous data input. To achieve continuous data input, an off-the-shelf squeeze ball was chosen. The squeeze ball was chosen because it has a form factor that can fit comfortably to user hand and easy to provide push and squeeze interactions. Given that there is no leak in the *AirDevice* system, push and squeeze interaction increases internal air-pressure of *AirDevice*, and release interaction will return the internal air-pressure to its initial pressure level. Additionally, the material of the squeeze ball is soft and rubber-like, enabling the

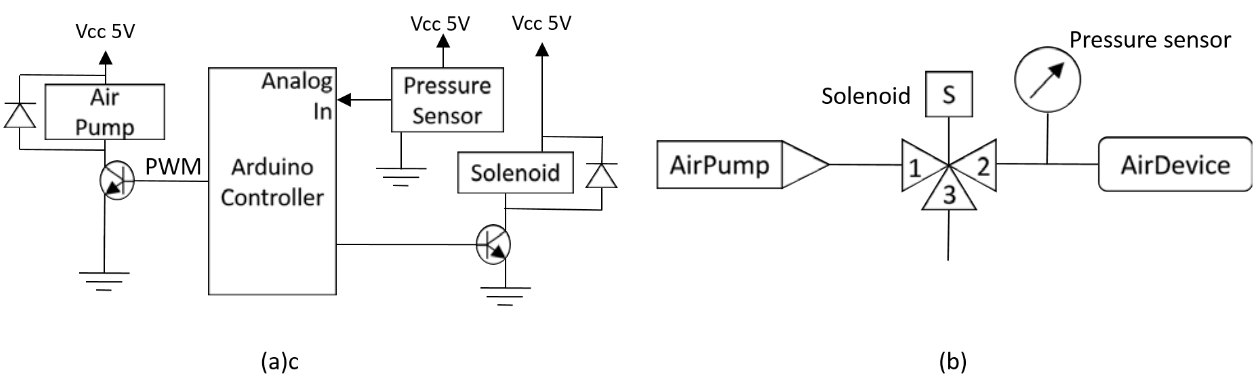

Figure 5.2: Diagrams of *AirDevice*, (a) electronic diagram of *AirDevice*, (b) pneumatic connection of *AirDevice*.

ball to return to its initial form after squeezed and released, thus eliminating the need of air-pump to continuously giving air in order to inflate the ball to its original shape.

5.3.1 Hardware Components

AirDevice (Figure 5.1) consists of an air-pressure sensor (MIS-2500-015G [1]), one three-way solenoid valve (S070 series), a micro air-pump as air pressure source, and a hand-sized ball-shaped soft container (Figure 5.3c) as the interaction device. Figure 5.2b shows the pneumatic connection of all of the *AirDevice* components. All electronic components such as air-pump, air-pressure sensor, and solenoid are electronically connected to (see Figure 5.2a) and controlled by an Arduino Micro (ATmega32U4). Arduino Micro has a small form-factor and can work as generic keyboard and mouse without additional driver thus it is convenient to be used for developing input devices. Air-pressure sensor is connected through analog pin. Since the Arduino maximum current output for each pin is 40mA and power requirement for air-pump and solenoid are higher, both components are connected through digital pin with additional NPN transistor and a diode in order to control the high current load.

5.3.2 Working Principle

In general, Airduino read the internal air-pressure information from the sensors continuously. Changes in the internal air-pressure of *AirDevice* can be utilized for input interaction. There are two way to use the air-pressure information, first, use the raw pressure data directly for a continuous input, second, by defining pressure threshold, the system can be manipulated to behave a certain way if a certain pressure level is achieved.

For the solenoid, in off condition, nozzle 1 and 2 of the three-way solenoid is connected but not with nozzle 3, thus allowing air-pump (if powered on) to increase the internal air-pressure of *AirDevice*. Conversely in on condition, the nozzle 1 of the three-way solenoid is disconnected from nozzle 2 and connected to nozzle 3 (which is connected to environment), thus allowing the air to escape reducing internal air-pressure of *AirDevice*. By increasing

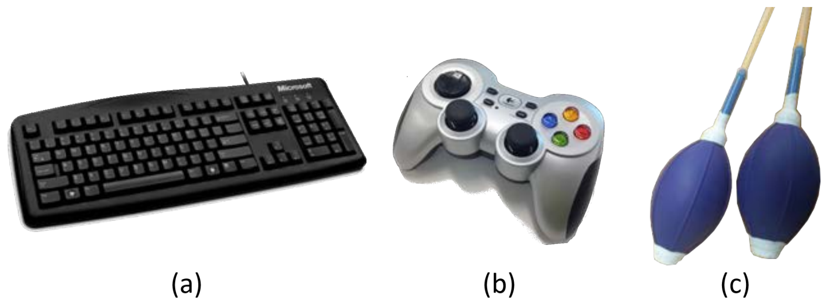

Figure 5.3: a) Keyboard, b) Gamepad, c) *AirDevice*.

and decreasing the internal air-pressure, these two conditions can be utilized to regulate the internal air-pressure of *AirDevice*.

5.4 User Study

We are interested in evaluating the effectiveness of *AirDevice* as a game input device. We are also concerned about whether the participants' preference affects the immersion level. We compared immersion and usefulness level of each participant on three different input devices (keyboard, gamepad, *AirDevice*) for playing two specific games. We also recorded participants' performance to investigate whether devices affect the performance.

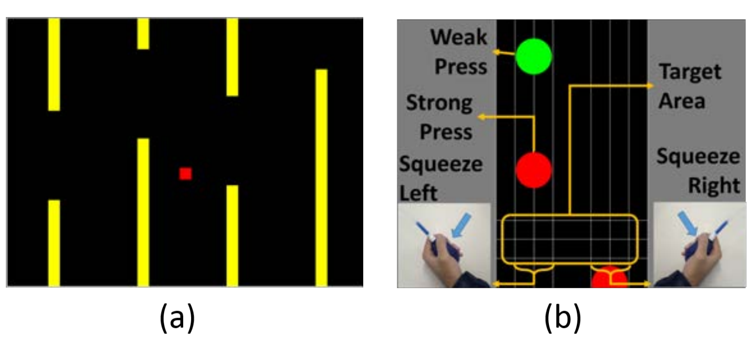

Figure 5.4: Interface of the simple games; (a) flappy bird (copter) like game, (b) two-line rhythm game.

5.4.1 Game Selection

Figure 5.4 shows two simple games based on popular commercial video games, chopter/flappy bird (Game 1) and rhythm/guitar hero (Game 2), which were developed to demonstrate the capability of *AirDevice* as a game input device. Both games were chosen because of their simple task and interaction method, also they were able to be played well using both keyboard and gamepad. Thus, these games were good choices to evaluate the usefulness of *AirDevice* as a game input device.

Game 1 requires participants to avoid the yellow obstacle by squeezing the *AirDevice* to move the red-square up and release to move the red-square down. Interaction is the same for keyboard and gamepad (push a button to move the red-square up and release to move it down).

Game 2 requires participants to squeeze *AirDevice* with appropriate pressure levels. The game recognizes two pressure levels (weak and strong). In the game, participants will be presented with two types of circle as the target. Figure 5.4b shows the interaction for Game 2, when red circle arrives in a target area, the participants are required to squeeze with strong pressure, likewise, the green circle for weak pressure. Since keyboard and most gamepads are unable to accommodate pressure sensitive input, participants need to press four buttons for left red, right red, left green, and right green circles.

For game 1, we recorded time elapse from game start until the red square hit the yellow obstacle or reach time limit (60 seconds) as the participants performance. For Game 2, we recorded the number of targets missed by the participant and divided it by a total number of targets as the error rate. These performance parameters were recorded in the background and did not show to the participants.

5.4.2 Participants and Apparatus

Twelve participants (6 females, M = 28 years, SD = 3.72) were recruited. Two participants play video games for five to ten hours a month while the rest play less than two hours a

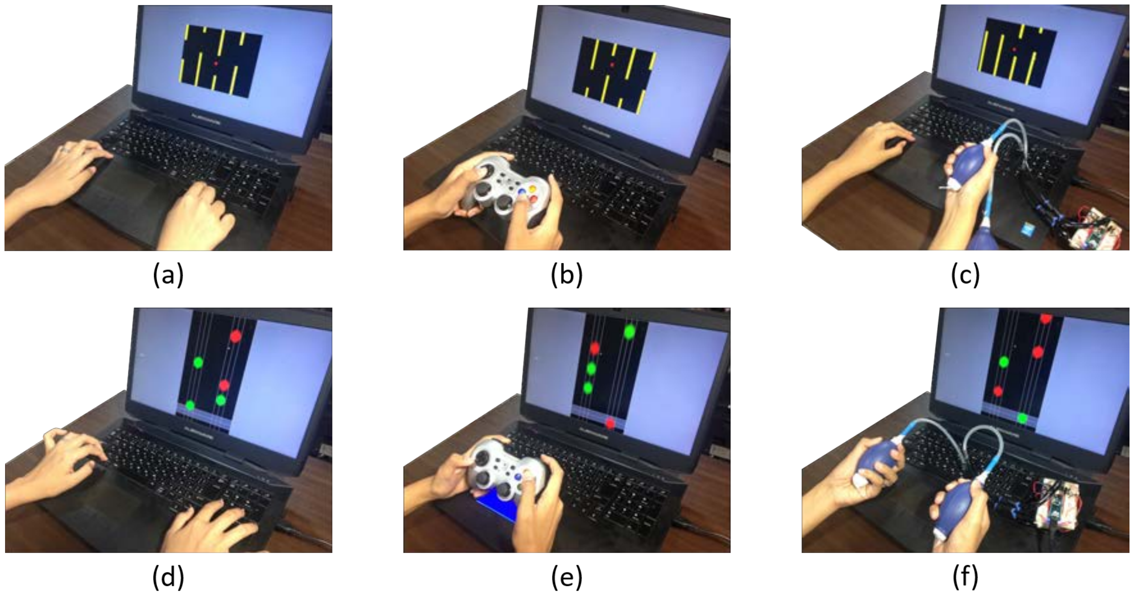

Figure 5.5: Experimental setup; (a) playing game using keyboard, (b) playing game using *AirDevice*.

month. All participants have experience using keyboard and gamepad for playing games.

Experiment was conducted using a notebook PC with 64-bit Windows 10, Intel i7-4710MQ processor, and 32 GB RAM. Participant used three input devices shown in Figure 5.3 to play both games.

5.4.3 Design

The experimental manipulation was *Device* (keyboard, gamepad, or *AirDevice*). The participant's preference for a particular input device was a pseudo-independent variable (*Preference*). The dependent variables were immersion which was measured using the IEQ (Immersive Experiment Questionnaire) [33], a 31 items questionnaire with five-point Likert scale items, USE (Usefulness, Satisfaction, and Ease of use) questionnaire [40], a 30 items questionnaire with five-point Likert scale items, and player performance parameters (scores and error rates).

The IEQ can provide an overall measure of immersion as well as five factor of immersion, which are *cognitive involvement, emotional involvement, real world dissociation, challenge, and control*. We hypothesized that playing the game using *AirDevice* would achieve higher immersion rating compared to playing using keyboard or gamepad. The USE questionnaire provides a measure of *usefulness, ease of use, ease of learn, and satisfaction*. We hypothesized that *AirDevice* would achieve at least equal or better usability rating compared to keyboard and/or gamepad as a game input device. We measured player performance across five repetitions. We hypothesized that *AirDevice* can reach similar performance as other devices within these repetitions. Specifically, we seek to understand how fast can users learn to use *AirSqueenze*.

5.4.4 Procedure

Participants were first informed about the objective and procedure of the study, and how to play both games with each device. Participants were allowed to familiarize with the control of all three devices. After that, participants were asked to play the games in six conditions (2 games x 3 devices) as shown in Figure 5.5 in counter-balanced order using Latin square. Each game was limited to one minute and repeated five times, resulting in approximately 30 minutes excluding rest time. Participants were not informed that their performance would be recorded, to ensure participants to focus on the device and the game without worrying about score or competition. Participants were asked and allowed to take a rest whenever they feel tired. After all of the conditions were done, participants were required to complete the IEQ and the USE questionnaire and open-ended questions regarding *AirDevice*, including their preference of device for playing the games. All procedures took around 1.5 hours.

5.5 Results and Analysis

We investigated immersion, usefulness, and user performance for different game input devices. All data conformed to two requirements for parametric evaluation namely, normal distribution using the Kolmogorov-Smirnov test and equality of error variance using Levene's test. For the ANOVAs, we tested sphericity using Mauchly's test and used a Greenhouse-Geisser adjustment when the Mauchly's test was significant; this adjustment can result in fractional degrees of freedom.

5.5.1 IEQ

Table 5.1 shows results for each IEQ components (total immersion, cognitive involvement, emotional involvement, real world dissociation, challenge, and control). The results show that the participants achieve higher total immersion when they play with *AirDevice* (M = 97.61, SD = 12.98) regardless of their preference compared to keyboard (M = 90.97, SD = 10.11) and gamepad (M = 94.46, SD = 6.49). The results also shows that participants who prefer to use *AirDevice* (M = 102.47, SD = 4.39) achieve higher total immersion regardless of the *Device* used for playing the games, compared to participants who prefer keyboard (M = 84.91, SD = 4.54) or prefer gamepad (M = 95.67, SD = 4.34).

We conducted a two-way repeated measures ANOVA with IEQ parameters as the dependent variables: *Device* (3 levels, within-subjects) × *Preference* (3 levels, between-subjects). The result showed that there was main effect on *Device* ($F_{10,76} = 2.466, p = 0.013, \eta_p^2 = 0.245$,

Table 5.1: Total immersion and its components when playing using Keyboard(K), Gamepad(G), and AirDevice(A).

	Play with K						Play with G						Play with A					
	Prefer K		Prefer G		Prefer A		Prefer K		Prefer G		Prefer A		Prefer K		Prefer G		Prefer A	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
TI	98.8	6.30	79.6	21.72	94.5	21.45	95.1	4.67	87.7	20.82	100.6	17.42	93.1	12.87	87.5	13.44	112.3	12.68
Cog.I	33.6	1.52	26.4	6.78	29.4	5.97	31.4	2.88	29.6	5.22	32.0	6.06	31.2	3.56	29.2	3.83	35.7	3.86
Emo.I	17.6	4.51	13.6	5.61	16.3	5.02	16.3	3.03	14.4	6.71	17.6	3.91	16.1	5.82	16.2	3.97	21.2	4.40
RWD	21.4	1.82	17.1	5.78	21.9	5.82	22.2	1.92	19.0	5.63	23.2	4.57	20.6	2.67	18.7	6.13	25.4	4.01
Cha.	9.8	1.92	8.0	2.06	10.6	2.37	9.6	2.07	8.4	2.55	9.9	2.33	9.8	1.64	9.1	2.03	10.9	1.91
Con.	16.4	0.89	14.4	4.82	16.4	5.17	15.6	2.51	16.2	4.06	17.9	4.18	15.4	3.13	14.3	2.45	19.1	3.25

Total Immersion (TI), Cognitive Involvement (Cog.I), Emotional Involvement (Emo.I), Real World Displacement (RWD), Challenge (Cha.), and Control (Con.)

Table 5.2: Mean scores of USE components

	Keyboard		Gamepad		AirDevice		ANOVA	
	M	SD	M	SD	M	SD	F	η_p^2
Usefulness	2.65	0.21	3.27	0.08	3.34	0.16	6.348**	0.366
Ease of Use	3.30	0.25	3.93	0.18	4.04	0.18	5.499*	0.333
Ease of Learn	3.19	0.26	3.67	0.24	3.98	0.23	6.359**	0.366
Satisfaction	2.62	0.31	3.35	0.18	3.80	0.19	8.152**	0.426

$*p < 0.05, **p < 0.01$

Wilks $\lambda = 0.570$). However, there was no main effect on $Preference$, while the interaction effects were marginal ($F_{20,127} = 1.548, p = 0.076, \eta_p^2 = 0.166$, Wilks $\lambda = 0.485$). In terms of immersion components, main effect of *Device* was found for cognitive involvement ($F_{2,42} = 6.213$, $p = 0.004$, $\eta_p^2 = 0.228$) and total immersion ($F_{4,42} = 3.094$, $p < 0.05$, $\eta_p^2 = 0.228$). Also there was interaction effect of *Device* and $Preference$ on cognitive involvement ($F_{4,42} = 3.094$, $p < 0.05$, $\eta_p^2 = 0.228$). There was no main effect nor interaction effects for emotional involvement, real world dissociation, challenge, and control components of immersion. Post-hoc pairwise comparison using Bonferroni's test shows that significantly different results were found between keyboard and $AirDevice$ for cognitive involvement ($p < 0.05$) and between gamepad and $AirDevice$ for the total immersion ($p < 0.05$).

These post-hoc results suggested that playing using $AirDevice$ can improve users' immersion level significantly compared to the gamepad. Although the difference between $AirDevice$ and keyboard was not significant, the result was marginal.

5.5.2 USE questionnaire

Table 5.2 shows participants' ratings regarding the interaction devices' usefulness, ease of use, ease of learn, and satisfaction. Overall, the results showed that mean values for $AirDevice$ was higher than keyboard and gamepad in all components of USE.

A one-way ANOVA showed that there were significant difference on which device to use for playing the games on the combined components of USE ($F(8, 38) = 2.200$, $p < 0.05$, $\eta_p^2 = 0.317$, Wilks' $\lambda = 0.467$). Significant difference also found for Usefulness, ($F(2, 22 = 6.348$, $p < 0.01$, $\eta_p^2 = 0.366$), Ease of Use ($F(2, 22) = 5.499$, $p = 0.012$, $\eta_p^2 = 0.333$), Ease of Learn ($F(2, 22) = 6.359$, $p < 0.01$, $\eta_p^2 = 0.366$), and Satisfaction ($F(2, 22) = 8.152$, $p = 0.002$, $\eta_p^2 = 0.426$). Post-hoc analysis using Bonferroni's test showed that there were significant differences between keyboard and gamepad for Usefulness ($p < 0.05$), between keyboard and *AirDevice* for Ease of Learn ($p < 0.05$), between keyboard and gamepad for Satisfaction ($p < 0.05$), and between keyboard and *AirDevice* for Satisfaction ($p < 0.05$).

These results revealed that the value was relative to the usefulness of the devices for the specific games, not for general use or games. The results suggested that *AirDevice* was easier to learn to use and provide higher user satisfaction when used for playing the games compared to the keyboard. Nevertheless, it is important to note that this result applies only to our games or alike but not the general games.

5.5.3 Player Performance

Figure 5.6 shows participants' score for Game 1 and error rate for Game 2 for five repetitions while using keyboard, gamepad, and *AirDevice*. Two-way repeated measures ANOVAs were

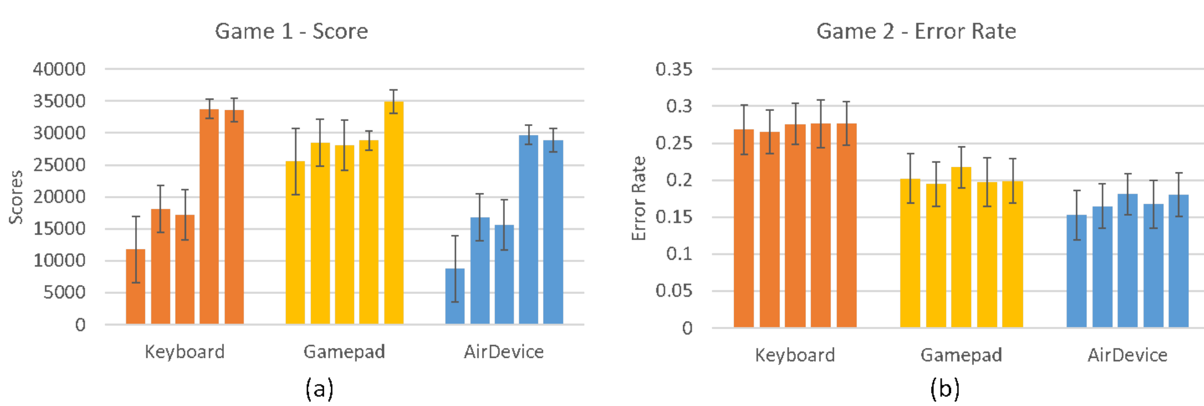

Figure 5.6: Performance parameter for repetition 1 to 5, mean score (a), error rate (b).

run for game 1 score and game 2 error rate as dependent variables, and with *Device* (3 levels, within-subject) × *Repetition* (5 levels, within subject) as independent variables.

The ANOVA result for game 1 showed that there were main effect of *Device* ($F(2,22) = 5.666$, $p = 0.01$, $\eta_p^2 = 0.340$) and *Repetition* ($F(2,22) = 5.809$, $p = 0.001$, $\eta_p^2 = 0.346$) to the score, however there was no interaction effect found. Post-hoc pairwise comparison revealed that there were significant difference between gamepad and *AirDevice* ($p < 0.005$), repetition 1 and 4 ($p < 0.05$), repetition 1 and 5 ($p = 0.01$), repetition 2 and 5 ($p < 0.05$), repetition 3 and 4 ($p < 0.05$), and between repetition 3 and 5 ($p < 0.05$). These results suggested that participant's learning curve for keyboard and *AirDevice* were same, and participants can achieve similar performance for all *Device* after the fourth repetition, thus four repetitions was adequate for participants to learn how to use *AirDevice* to achieve similar performance with gamepad interface.

For Game 2, ANOVA showed that there was main effect on *Device* only ($F(2,22) = 19.354$, $p < 0.001$, $\eta_p^2 = 0.366$). This suggested that the error rate was highly impacted by the device difference. Pair-wise comparison with Bonferroni's test suggested that both gamepad ($p < 0.005$) and *AirDevice* ($p < 0.001$) have significantly lower error rate compared to keyboard. This implies that playing game 2 using *AirDevice* can achieve similar performance as playing the game using gamepad.

5.6 Discussion and Future Work

Our study confirmed that although preferences has an effect on user immersion, playing games using *AirSqueeze* achieves higher levels of immersion and USE scores compared to keyboard and gamepad. We also confirmed that four repetitions are adequate to learn how to play games using *AirSqueeze* to achieve scores on par with gamepad. These results suggest that air-pressure can be utilized as a game input device that can promote deeper immersion when used with certain games.

Currently, *AirSqueeze* is connected to PC through a cable and has limited space for movement. We can add greater freedom by applying wireless connections to *AirSqueeze* instead of cable connections. *AirSqueeze* can also be used to further expand current gamepad devices by redesigning the shape of *AirSqueeze* so it can be attached to the back of a gamepad as an add-on device to enable squeezing interactions in gamepads and other game input devices.

Chapter 6

GENERAL CONCLUSION AND FUTURE DIRECTIONS

6.1 Summary of Contributions

This dissertation presents three studies which focus on leveraging the use of air for designing and developing air-based devices for interactions, and understanding interaction between user and the air-based devices.

Study 1 concerned with the capability of air-based interaction devices to concurrently providing multiple feedbacks for multimodal interactions. In this study, we developed a prototype that is able to generate physical visual feedback as well as non-contact tactile feedback in a single device. We proposed a straight-forward method to allows both feedbacks to be generated simultaneously. The developed prototype achieved desirable results both in term of device performances and user subjective assessments.

In Study 2, we proposed a specialized use case of air-based device where specific capabilities of air-based device that is able to not only provide multiple feedbacks but also able to receive and record interaction information. We proposed novel air-based devices that leverage the use of air-flow and air-pressure that are compatible to use inside MRI, an environment with strong magnetic field and high magnetic interferences. We confirmed that our proposed designs and prototypes are promising approach to further expands human interaction research through a brain study using fMRI.

From Study 1 and Study 2, we observed that air has a lot of potential as a medium for designing and developing interaction devices. In this dissertation we would like to add one more parameter for the design of the air-based interaction devices, which is engagement. In Study 3, we further improve the design of air-based device to be engaging, thus allowing users to enjoy using the air-based device compared to conventional interaction devices. We confirmed that user performance and satisfaction is higher for game interaction with air-based devices. We also confirmed that, although users were able to familiarize themselves with air-based devices very fast (within 2-3 trials). Based on these results, we discussed several design guidelines to further improving the air-based device for an engaging interaction devices.

The outcome of this dissertation are:

1. An understanding of air properties for designing input interactions and haptic feedbacks.

2. Several new air-based interaction devices.

3. Practical guidelines for interaction device design for multi-modal, MRI, and game interactions.

In summary, this dissertation contributes to the field of interaction technology. The conclusion drawn and methodologies proposed will benefit future research studies that explore the use of air-properties for interaction devices, and also future brain researches that utilize air-based devices.

6.2 Future Research Direction

Throughout the project, the main design insight we have achieved is that instead of developing interaction devices only, it is important to identify one specific application that can really leverage the advantages of the prototype. We come into conclusion that air-based devices have a huge advantages and potential for fMRI-compatible response devices. Thus, in the future we will conduct research studies on further investigating and developing various response devices that are needed by brain researchers and MRI researchers. By doing so, we believe, the MRI-compatible air-based device can expand the possible research direction in the field of brain study that are previously very limited.

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