AirWave:
Non-Contact Haptic Feedback Using Air Vortex Rings

Sidhant Gupta[1,2], Dan Morris[1], Shwetak N Patel[1,2], Desney Tan[1]

[1]Microsoft Research
Redmond, WA, USA
{dan, desney}@microsoft.com

[2]University of Washington,UbiComp Lab
Seattle, WA, USA
{sidhant, shwetak}@uw.edu

ABSTRACT

Input modalities such as speech and gesture allow users to interact with computers without holding or touching a physical device, thus enabling at-a-distance interaction. It remains an open problem, however, to incorporate haptic feedback into such interaction. In this work, we explore the use of air vortex rings for this purpose. Unlike standard jets of air, which are turbulent and dissipate quickly, vortex rings can be focused to travel several meters and impart perceptible feedback. In this paper, we review vortex formation theory and explore specific design parameters that allow us to generate vortices capable of imparting haptic feedback. Applying this theory, we developed a prototype system called AirWave. We show through objective measurements that AirWave can achieve spatial resolution of less than 10 cm at a distance of 2.5 meters. We further demonstrate through a user study that this can be used to direct tactile stimuli to different regions of the human body.

Author Keywords

Non-contact haptic feedback; air vortex rings

ACM Classification Keywords

H.5.m Information interfaces and presentation: Miscellaneous

General Terms

Human Factors, Design.

INTRODUCTION

Haptic feedback – more generally, the sense of touch – is a critical component of our interactions with the physical world. Numerous studies have demonstrated that haptic feedback can reduce error rates[9], increase efficiency [5], and increase user satisfaction [2] in sensorimotor tasks. Vibrotactile feedback, the use of vibrating motors to create tactile sensations, is one form of haptic feedback that has achieved widespread adoption in consumer devices, having been used to augment the mouse [13], touch screen [11], mobile phones, and game controllers. All these systems
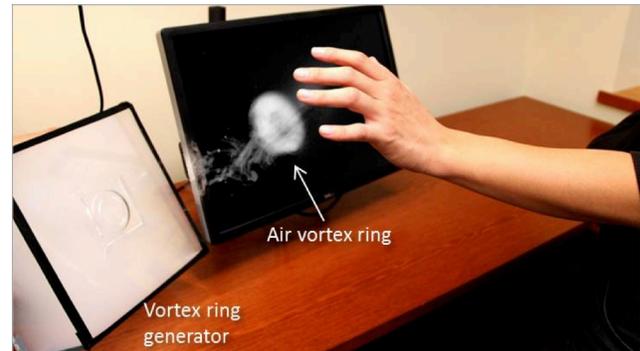
Figure 1: AirWave prototype filled with fog to visualize a vortex ring being used for providing precise non-contact haptic feedback to a user.

assume that because the device is in physical contact with the user, an actuator can be embedded within the input device and provide direct mechanical stimulation. However, this assumption is no longer universal, as non-contact and at-a-distance sensing (e.g., computer vision and speech recognition) is becoming more prevalent in our computing environments. The Microsoft Xbox Kinect, for example, allows immersive gaming and media control through computer vision and speech recognition, which require no physical contact between the user and the computer. This presents a new challenge to haptic feedback systems, and our core research question:

How do we restore haptic realism to virtual environments when the user is meters away from the computer, and is neither carrying nor wearing an interface device?

In order to restore haptic realism to at-a-distance, non-contact interfaces, we investigate the use of *air vortex rings* as a technique for delivering haptic feedback. We describe vortex formation theory and parameterize the design of new vortex generators capable of haptic feedback so that subsequent work can build upon our formulation. We then describe a prototype called AirWave (Figure 1), which provides at-a-distance haptic feedback that requires no physical contact or instrumentation of the human body. We provide an analysis of the spatial resolution of this prototype, and we assess how well vortices are perceived by users when targeted at 8 different locations on the body. In a study with 10 users, we found that the mean error between the intended target point and where users sensed the vortex was less than 10 cm, at a distance of 2.5 m.

The specific contributions of this paper are:

1. A synthesis of vortex formation theory as it applies to Ubicomp and HCI applications. Specifically, we derive equations and parameters that govern the design of vortex generators for at-a-distance haptic feedback systems.

2. The design of a prototype, AirWave, that delivers non-contact haptic feedback at a distance, and an assessment of its *physical* resolution.

3. A study quantifying *perceptual* resolution directed vortices.

RELATED WORK

Contact and Non-Contact Haptics

Substantial research and development has focused on embedding haptic feedback in consumer devices, like mobile phones, game controllers, and touch screens [11]. Embedded devices usually use small, low-cost vibrating motors that have limited bandwidth but can easily be embedded in handheld devices. Alternatively, dedicated haptic interfaces such as the SensAble Phantom[1] can provide rich three-dimensional force feedback, but are larger and more expensive than vibrotactile actuators, and require a grounded kinematic chain (i.e., they must be attached to a table or floor). Researchers have also explored instrumenting the human body to provide always-available haptic feedback. In such systems the body is instrumented with actuators, for example a vibrotactile belt that helps a visually impaired person navigate her surroundings [14].

Relative to these systems that require physical contact with actuators, there has been little research in non-contact or at-a-distance haptic feedback. Most recently, Weiss et al. described a near-surface haptic feedback system that requires minimal instrumentation of the body in the form of a small magnet on the finger, which is attracted to or repelled from a table fitted with electromagnets [23]. Though this requires no contact with the powered part of the system, the feedback is limited to close proximity of the table, and the user is required to wear or carry dedicated hardware.

Recent research has also looked at using high-intensity, beam-formed ultrasonic waves to generate acoustic radiation pressure [8]. The spatial resolution from an ultrasound-based system is superior to what can be achieved via air pressure; however, the state of the art in ultrasonic feedback exerts extremely low force and has a usable range of less than 30 cm. In contrast, AirWave is a relatively easy-to-build approach to long-range, localized haptic feedback.

Suzuki et al. [20] developed a system that provides 3D sensation using an array of air jet nozzles. The air jets are controlled to exert upward force on a device that the user holds. By varying which nozzles release air, the system generates a virtual contour. This approach is also limited in range

because turbulent air jets (similar to a jet from a compressed air duster can) do not maintain their directionality over longer distances. Additionally, this approach requires the user to carry a physical device. From the perspective of fluid mechanics, a vortex ring is also a jet, albeit controlled to produce enough vorticity to allow the fluid to form a toroidal ring, which is an effective way to maintain focused air transmission over large distances.

Vortex Generators

Air vortex rings have been studied extensively and used in numerous applications; for example, they are often used in modeling downbursts that pose hazard to aircrafts. Some children's toys produce crude, turbulent vortex rings. For example, the AirZooka[2] shoots large air vortices that are too big for effective localization. When pointed at a person at the distances used in our prototype experiments, the feedback generated by the AirZooka was felt as a gust of wind on the entire upper body. Another toy, the Zero Blaster[3], couples air vortices with vapor to produce "smoke rings"; however, these rings do not exert any perceivable force on the user.

Kelvin [21] provided one of the earliest descriptions of an air vortex generator in 1867. His apparatus for exhibiting smoke rings consisted of a rigid cubic box, with a 20 cm hole in one side and the opposite side replaced with a flexible membrane. With the box filled with smoke, tapping the membrane produced smoke rings. Modern implementations, including ours, are fundamentally similar; however, the manually actuated membrane has been replaced by an electrically controlled diaphragm (e.g., a speaker).

The use of an electronically controlled membrane has been explored for applications other than haptic feedback. For example, Russell et al. [17,18], inspired by the finding that African cave crickets produce small vortices for communication, developed robots that use directional vortices for communication. Tokuda et al. [22] make use of a fog-filled stable vortex ring to create a flying fog screen onto which visual content could be projected. Instead of a speaker diaphragm, their design of vortex generator is based on a piston-driven system, which is the most popular method of studying vortices in fluid dynamics. Yanagida et al. [24] used a vortex cannon to create an olfactory display. They mounted a vortex generator powered by a speaker membrane on a pan-and-tilt mechanism, infused the vortex with an odor, and directed it towards a user's face. They optimized their vortices for travel distance, and for *minimal* haptic impact: they wanted their users to smell – but not feel – the delivered vortices. In fact each of the systems described here used vortices carefully optimized for an application – communication, projection, and scent delivery, respectively – other than haptic feedback, with different design constraints. Consequently, their designs could not be

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immediately translated to our application, motivating our design of a vortex generator specifically for haptics.

Most similar to our work is a small body of recent research in Japanese language literature that has investigated the use of vortex rings for tactile feedback. Takamori et al. investigated the perception of vortex rings when they hit a user's cheek [6]. They studied how vortex rings disintegrate when they hit a user's face and how it relates to a perceived sensation of 'fluffiness', 'small', 'hard' etc.

Similarly, Takeda et al. have built a vortex canon based on a mechanical piston and speaker design to study both the formation of vortex rings and for imparting tactile feedback on face [3,4]. In [3] they also show preliminary results of how people perceived the impact of a vortex when it hits the face. We significantly extend this body of work by assuming haptic feedback that can be imparted anywhere on the body and not just the face, which requires greater force while maintaining sufficient resolution for targeting. As noted later in this paper, with the face being relatively sensitive, vortices with even small force can also be perceived. Thus, we derive the parameters needed to impart not only the optimal force for all body regions but also maintain sufficient resolution so that different parts of the body could be targeted, including, but not limited to close proximity regions like the left or right side of a user's face.

We began by prototyping a vortex cannon with little formal parametric measurements and understanding of the vortex formation process. We built several prototypes using a speaker as a diaphragm, and experimented with simple hole cutouts in a piece of cardboard as well as various sized glass and plastic bottles to direct the air. We were able to successfully produce vortex rings (visualized using a fog machine) including some that travelled as far as 7 m.

However, like Kruijff et al. [12], we found that air vortices produced in this manner provided only a slightly noticeable haptic feedback even at close range (less than 1 m). It was evident that we needed a more systematic approach to tune generator parameters for optimal haptic feedback.

Unfortunately, the relationship between "perceptible force" and vortex formation has never been formalized in the literature. Many other physical properties of vortices have been investigated, such as stability, air current, and vorticity – parameters that are not necessarily applicable to haptics. We thus present an abbreviated explanation of vortex formation and vortex modeling which other researchers may use in building their own haptic vortex generators. We then evaluate how parameters in the model relate to haptic perception and present a set of design recommendations.

POTENTIAL APPLICATIONS
Non-contact haptic feedback can be used in a variety of applications including gaming, movies, theme park rides and attractions, immersive art exhibits, augmenting notification systems for blind individuals, adding realism to virtual object manipulation, and tele-presence. A detailed dis-
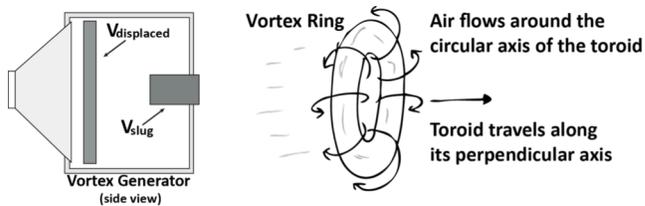

Figure 2: (left) Volume of air moved by speaker equals the volume of the slug used to model the vortex formation. (right) Vortex ring is a toroid where air flows around the circular axis as the entire toroid travels along its perpendicular axis.

cussion of designing vortex-based haptic feedback for each of these applications is an interesting research challenge in itself. As this paper primarily focusses on the fundamental technology, we only briefly discuss how we envision non-contact haptic feedback being used in future applications.

A key area of application for non-contact haptic feedback is in creating *impromptu* immersive experiences. That is, a system no longer needs to be constrained by having a user maintain contact or carry a special device for delivering haptic feedback. For example, an interactive display window on a street could make the experience both more immersive and entertaining by synchronizing visual feedback with haptic feedback. The same applies to art exhibits in museums, and to impromptu experiences that travel with a theme park visitor.

As a notification system in a quiet waiting room, an automated system could point and "tap" a person's shoulder to discreetly alert them. A similar approach could be used to augment notification systems for blind or deaf individuals.

Stereoscopic visuals and surround audio for movies could be made even further immersive with use of haptic feedback; for example, when a book drops flat on the floor in a movie scene, a viewer might *feel* that thump as a targeted vortex. This feedback would differ and complement feedback from jet air nozzles, used in some theme parks, which feels like a gust of air.

THEORY AND FORMATION OF VORTEX RINGS
An air vortex ring is a toroidal (or a "doughnut") flow of air, sometimes referred to as a "toroidal air vortex" (we use "vortex rings" throughout this paper for consistency). As shown in Figure 2 (right), air flows around the circular axis of the toroid, while the entire toroid travels along an axis perpendicular to the toroid. A vortex ring tends to maintain its shape, size, and momentum as it travels, making a vortex ring less prone to dispersion than air flowing directly along an axis. An example of this phenomenon is a smoke ring.

Vortex rings can be formed by pushing air with a piston through a circular aperture, or hole. How well the vortex is formed depends on the volume of air pushed, the velocity of the piston, and the diameter of the aperture. See [19] for a comprehensive survey of vortex ring physics.
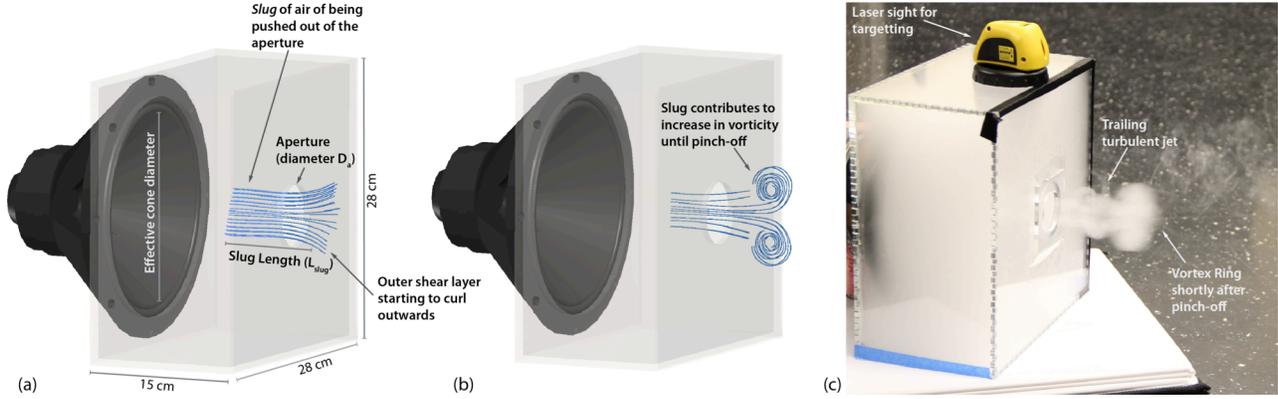
Figure 3: Vortex generator prototype and vortex ring formation process. (a) As the slug of air is pushed out of the aperture, the boundary layer starts to curl outwards as it exits, then (b) vorticity increases until pinch-off, causing the vortex to detach. (c) AirWave prototype filled with fog to visualize a vortex ring shortly after pinch-off.

How a Vortex Ring is Formed

One technique to predict the vortex formation and velocity is the *slug model* [1,19]. The slug model is an approximation; however, we found the performance of experimental measures to be within 4% of predicted, confirming the appropriateness of this model.

Figure 3 shows the process of vortex formation as a *slug* (a fixed volume of air) of length L_{slug} is pushed out of an aperture into a region of still air. As the slug exits, a region of lower pressure is formed around the periphery of the aperture. This causes the outer layer of the slug to separate and roll outwards into a vortex ring. At this point, the vortex as a whole is not moving, but air is "spinning" outwardly. The rate at which the air is spinning is called the *vorticity*. As the remaining slug is pushed out, the air moving outward from the aperture increases the vorticity, until the outer layer can no longer add any more air into the vortex. This can be thought of as reaching the "critical mass", beyond which the vortex ring is detached and the remaining slug becomes unstable, forming a trailing turbulent jet. This detachment is known as the *pinch-off*, and after this point the whole vortex travels away from the aperture, with the air still "spinning" within the moving vortex.

Formation Number

Gharib et al. [7] showed that pinch-off takes place when the ratio of the length of the piston stroke to the aperture diameter exceeds a critical value. The slug model assumes air inside the chamber is incompressible. Consequently, the volume of air displaced can be characterized as a cylinder with length L_{slug} (Figure 3a) moving through an aperture of diameter D_a. This length and diameter are used to define the *formation number* for which a vortex attains maximum circulation (yielding maximum stability). For a vortex generator with a circular aperture, the stability of the vortex is governed primarily by the formation number:

$$L_{slug}/D_a$$

For non-cylindrical volumes, this ratio can be calculated by defining the volume of the slug to be equal to the volume displaced by a vortex generator inside the chamber (Figure 2, left): (i.e., all of the air displaced is pushed out of the aperture without compression):

$$Slug\ volume = V_{slug} = V_{displaced}$$

$$where,\ V_{slug} = \frac{1}{4}\pi\ D_a^2\ L_{slug}$$

$$L_{slug}/D_a = \frac{4\ V_{displaced}}{\pi\ D_a^3} \quad \text{(Eq. 1)}$$

Eq. 1 is central to optimizing new vortex generators: to relate aperture diameter and displacement volume to vortex stability, one only needs to translate the displacement volume into the equivalent length of a cylindrical slug. For example, in Figure 2 the volume of air displaced by the speaker is $V_{displaced}$ and, thus, can be used to calculate the formation number for a variety of aperture diameters. We refer to the formation number as *L/D* for conciseness.

For stable vortices, this ratio has been shown to range from 1.0 to 4.0 for a variety of aperture diameters [7]. As previously mentioned, we found no prior research that details a range suitable for imparting perceptible haptic feedback. Hence, we experimentally investigate these parameters and their relationship to haptic sensation using our prototype, AirWave.

AIRWAVE: PROTOTYPE VORTEX GENERATOR

AirWave generates vortices by pushing air out of an enclosed box through an aperture. To move air in the box, a speaker is installed such that flexing the diaphragm changes the volume of the box. The rate at which this volume is changed dictates the rate that air enters or exits the aperture.

Construction & Component Characterization

Figure 3 shows the various components of the prototype vortex generator. The enclosing box of $28 \times 28 \times 15$ cm was laser-cut from 6.35 mm thick acrylic to house a 4-ohm, 25.4 cm diameter speaker. It should be noted that our choice of speaker size was arbitrary—instead the main parameter of interest is the formation number. Many different

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speaker sizes can yield the same formation number by adjusting the aperture diameter.

On the opposite face from the speaker, we cut out a 63 mm diameter circular aperture, through which the vortex ring is formed and ejected. We constructed faceplates with varying aperture sizes that could be installed in front of the 63 mm aperture to reduce the diameter allowing us to experiment with various L/D ratios.

A speaker cone's movement is a function of the current flowing through the speaker coil. We found that a current of 3.1 A produced the most movement. Though the speaker is rated at 80 W (4 A at 20 V), we found that raising the current beyond 3.1A only resulted in heat dissipation and no change in the amount the speaker moved. We used an Atmel ATMega 328 microcontroller to control the speaker through a high-current H-bridge implemented using 4 discrete FETs (field effect transistors). This allows the microcontroller to drive the speaker with either negative or positive voltage, which flexed the speaker cone in or out.

To create a slug of air for generating each vortex while ensuring that the heat dissipation did not damage the speaker coil, we applied current only for a short period of time. For 50 ms, we applied a negative current, flexing the cone inwards and drawing air into the chamber. We then reversed the current for 100 ms, which forces a slug of air out of the aperture. We chose the 100 ms delay for the formation phase to ensure that the speaker cone remains flexed throughout vortex formation so as not to pull any air back in when the speaker resets to its natural position.

In order to accurately point the vortices towards a target, we installed two laser line levels (Strait-Line brand). Figure 3c shows the top-mounted laser. Using two laser levels allowed us to form a crosshair and to point the device in a particular direction. We mounted AirWave on a manual pan-and-tilt platform, commonly used to mount cameras.

Operational Characterization
To estimate the volume and velocity at which AirWave displaces air, we need to measure the distance and speed with which the speaker cone moves. We built a simple device consisting of 2 metal contacts at the end of a probe mounted on a set of vernier calipers. A small piece of conductive foil was placed on the speaker cone so that it shorted out the two contacts on the end of the probe when it made contact. Using this shorting event and the accurate displacement measure from the calipers, we could determine the exact duration and displacement of the cone's movement. To verify the integrity of this measurement approach, we initially compared it to a high-resolution motion capture system and found it to be accurate within 1 mm.

At 3.1 A, we found the cone displacement (h_{cone}) to be 1.14 ± 0.015 cm and the time (t_{cone}) for the cone to travel from flexed-in to flexed-out to be 12 ± 0.11 ms, averaged over 50 measurements.
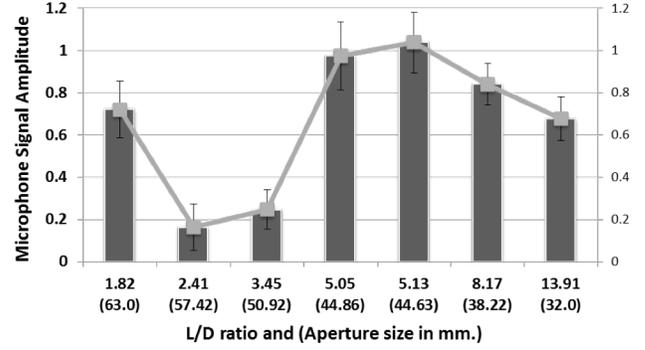

Figure 4: Trend of pressure exerted on a microphone as a function of aperture sizes and associated L/D ratio. Higher amplitude indicates higher relative force. An aperture of 44.63 mm diameter with L/D of 5.13 was selected as optimal.

Thus, for the AirWave prototype, the volume of air displaced by the speaker cone can be computed as:

$$\Delta V_{displaced} = \pi \, r_{cone}{}^2 h_{cone} = \pi \, (10^2)1.14 = 358.14 \; cm^3$$

Here r_{cone} is the radius of the diaphragm. It should be noted that although the speaker has a radius of 12.7 cm, the diaphragm itself is only 10 cm, excluding the surrounding 2.7 cm of flexible membrane.

APERTURE SIZE SELECTION
Using the AirWave prototype, we evaluated 7 different apertures with diameters ranging from 32 mm to 63 mm, to understand the relationship between a vortex's effectiveness at imparting feedback and vortex generator parameters. These apertures correspond to L/D ratios between 1.8 and 14 (calculated using the volume displaced and Eq. 1); this range includes both stable vortices (<4.0) and highly turbulent ones (>10) [1].

To objectively compare the relative force exerted by vortices produced using different apertures, we place a microphone 1 m away from the vortex generator. By taking measurements too close, we risk measuring the trailing jet or the initial turbulence as the vortex forms, while too far would make vortices more susceptible to trajectory deviations reducing repeatability of measurements, thus 1 m was deemed to be a reasonable balance. Since a microphone is essentially a pressure transducer with a fixed area, we can use the signal amplitude to estimate relative force. It should be noted that the microphone is not calibrated to measure force directly, and thus only relative comparisons can be made. This suffices for our purposes as we want to maximize subjective human perception, which increases monotonically with exerted force.

Figure 4 shows the trend of peak microphone signal amplitude averaged over 50 measurements as the L/D ratio increases, controlled by decreasing aperture Error bars indicate the 95% confidence interval. Higher signal level indicates greater pressure exerted on the microphone diaphragm. Apertures diameters of 44.63 and 44.86 mm exhibited the largest responses from the microphone, with 38.22
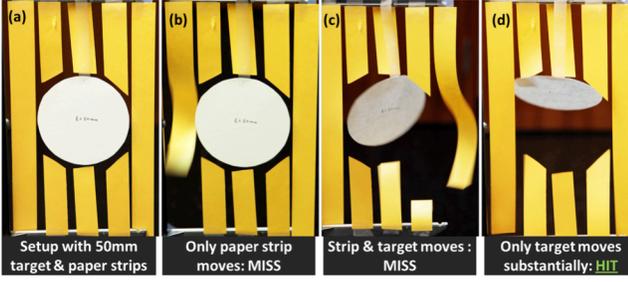
Figure 5: (a) Setup of targeting experiment to validate spatial resolutions at varying distances. 50mm target (white) at 2.5m is shown. (b) and (c) show miss/failure cases due to deflection in paper strips. (d) Hit/Success only when no paper strips deflect and only the target moves >4 cm.
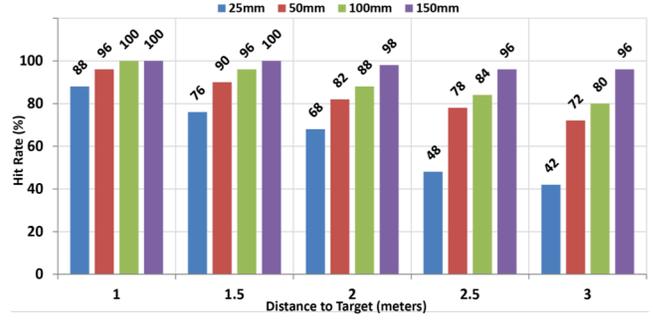

Figure 6: Hit rate (%) for target of varying radius sizes placed at varying distances for 50 measurements per target per distance is shown. At 2.5 meters, AirWave can reliably (84%) be used for targeting areas with a resolution of only 10 cm.

mm yielding the third-largest response (significantly lower).

To validate the applicability of these measurements to haptic feedback design, we performed an informal evaluation with 5 participants. We used each of these three aperture sizes to project vortices at each user's hand at a distance of 1 m, and participants subjectively rated the sensations. All participants indicated that the feedback from the 44.63 and 44.86 mm apertures yielded significantly more pronounced feedback than the 38.22 mm aperture, but could not reliably differentiate between the larger two apertures. This corresponds well to the results we obtained using the microphone.

We selected the 44.63 mm aperture for further study because a smaller aperture creates a smaller vortex. A smaller vortex may have finer localization, which is desirable for a number of haptic applications. For this aperture diameter, the formation number for vortices produced using AirWave can be computed using Eq. 1 as follows:

$$L_{slug}/D_a = \frac{4 \, \Delta V_{displaced}}{\pi \, D_a^3} = \frac{4 * 358.14}{\pi \, 4.463^3} = 5.129$$

Low vs. High L/D Ratio
An interesting observation is that at either end of the L/D spectrum we tested, the vortices seem to produce at least some perceptible force. We asked the 5 users to compare the feedback from largest and smallest apertures to our selected aperture. At a low ratio of 1.8 (63 mm aperture), the vortices produced are stable and large, however the force of feedback was barely perceptible. We attribute this to the large surface area of the vortex, which not only reduces resolution but also diminishes the force due to its large contact area. On the other end, with high ratio of 13.91 (32 mm aperture), the vortices produced are mostly turbulent and result in a long trailing jet. Participants characterized the feedback as diminished compared to the selected aperture (44.63 mm). Interestingly, they described the feedback from the selected aperture as a "ball" or "clump of air" hitting them, while the higher L/D ratio was described as a "diffused jet" of air.

In summary, we found that an L/D ratio between 5 and 6 produced the most desirable results. A ratio of about 4 or lower produced barely perceptible feedback. Perceptible but less pronounced vortices can be produced with L/D ranging up to 8. A ratio greater than 10 reduces both the perceived force and focus of the haptic feedback that vortex rings impart. This is consistent with findings presented by Baird et al. [1] that with $L/D > 10$, the turbulent jet created loses translational momentum.

Velocity of Vortices and Applicability of the Slug Model
Next, we validated how closely the measured vortex velocity relates to that computed using the slug model.

As the speaker flexes, the time it takes the displaced air to move through the aperture is the same time it takes the speaker cone to flex, which is given by t_{cone}. Thus, the velocity of the cylindrical slug through the aperture is:

$$Slug \; velocity = v_{slug} = {L_{slug}}/{t_{cone}}$$

Velocity measurement equations presented by Baird et al. [1] and more recently by Mohseni [15] both indicate that the vortex translational velocity (v_{vortex}) (i.e., the rate at which the whole vortex travels away from the device) can be approximated as *half the slug velocity*. With a 44.63 mm aperture:

$$L_{slug} = \frac{4 \, V_{slug}}{\pi \, D_a^2} = \frac{4 * 358.14}{\pi \, 4.463^2} = 22.89 \; cm$$

$$v_{slug} = {0.2289}/{0.012} = 19.07 \; m/s$$

$$v_{vortex} = v_{slug}/2 = 9.53 \; m/s$$

To measure the actual translational velocity, we computed the time delay between when the voltage to the speaker was applied to generate a vortex and when it hit the microphone placed 1 m away.

Over 50 measurements, we found the average measured velocity of a vortex to be 9.17 m/s, a 3.7% error from the velocity calculated using the model equations, thus suggesting that the slug model is well-suited for designing vortex ring generators similar to AirWave. For completeness, we

performed these measurements with other aperture sizes as well and found that when $L/D > 10$, the slug model failed as the measured velocity differed by as much as 80%.

PHYSICAL RESOLUTION OF AIRWAVE

Many applications of non-contact feedback will benefit from imparting feedback to particular regions of a user's body, requiring a spatial resolution on the order of a few cm. We thus conducted a lab experiment to quantify spatial resolution of the vortices produced by AirWave. To maintain ecological validity, we took no steps to control potential environmental disturbances. For instance, doors were opened and closed as people used the lab space, and a nearby AC vent was unaltered and produced air drafts occasionally, as one would expect in any indoor space.

To estimate the resolution of haptic feedback created by AirWave, we created circular test targets of various radii that were placed at 5 different distances from the vortex generator. The radii were selected to roughly correspond to different regions of the body. For example, with 25 mm resolution one can specifically target an adult human cheek, and with 50 mm resolution one can target a typical hand.

For each test, a paper target was hung using a thin piece tape so that it would move when hit with a vortex. Additional strips of paper were also hung around the target to see if a vortex partially hit the target or completely missed it (Figure 5(a)). For the latter case, we would see minimal movement of the target and one of the paper strips move (Figure 5(b)). Using a laser sight, the AirWave device's aperture was manually pointed at the center of the target. It should be noted that accurately pointing the device does not imply that the vortex accurately hits the desired location, due to the variability in its size and trajectory.

An attempt was considered a "hit" (success) only when two conditions were met: (1) the target moved *substantially* (i.e., greater than 4 cm, Figure 5(d)), and (2) none of the paper strips around the target are visually deflected. This meant that if a vortex partially hit the target and partially hit the paper strips around it, it would be classified as a "miss" (failure) as shown in Figure 5(c). For consistency in the amount of deflection, we made use of a laser beam-crossing detector placed 4 cm away, like those commonly found in security systems. We repeated the experiment for each target size at 5 different distances from the vortex generator. We note that the size of vortices produced is not varied as the aperture size is kept fixed to the selected 44.63 mm.

This experiment captured two properties of the vortex rings: (1) the stability of the vortex ring trajectory (i.e., how often the vortex ring traveled straight), and (2) the size of the area on which it exerts force, which depends on the size of the vortex and the distribution of the momentum within it. Thus, the effective size of the region onto which sufficient force is exerted does not necessarily equal the size of the vortex.

Figure 6 shows AirWave's resolution at various distances. As expected, the hit rate drops with increasing distance, especially for the smallest target (radius 25 mm). As the vortex ring travels, its momentum decreases due to air resistance, and its size slightly increases as the vortex disperses. More importantly it becomes increasingly susceptible to deviation from its otherwise straight path. For example, air drafts in a room can cause the vortex ring to move, creating variability in hitting a target.

We summarize the results of this experiment as follows: at a short range of 1 m, we found that our prototype accurately targets a region of 50 mm 96% of the time, and at 2.5 m, it reliably targets a region of 100 mm 84% of the time. 2.5 m is a typical distance between a user and today's video game systems, and the 100 mm resolution offered by the prototype at this distance is sufficient for targeting specific regions of a human body.

Though the targeting results are promising, it is not necessarily the case that mechanical precision corresponds to *perceptual* precision, which is the ultimate metric for interactive applications. We therefore tested how well users could perceive the feedback at this distance in terms of both presence and spatial targeting (*i.e.*, which part of the body was hit).

PERCEPTUAL RESOLUTION OF AIRWAVE

Experimental Procedure

We recruited 10 participants (5 female) aged 23-32 (median 25) and had them stand at a fixed distance of 2.5 m from the AirWave device. We ensured that the participants were positioned behind the 2.5 m mark so that each vortex traveled *at least* that distance. Participants wore noise-isolating headphones playing pink noise, and closed their eyes so that sound or vision could not be used as a cue that a vortex was created and where it was targeted. While the sound generated by the speaker is low, we wanted to test the pure haptic sensation in the most conservative of conditions. Moreover, we did not want the user to utilize complementary streams of sensory input that might amplify perceived sensations. We confirmed that participants could not see or hear the device in operation before the experiment.

No special instructions were given for clothing during recruitment, and as one would expect in a naturalistic setting, clothing ranged from users wearing half-sleeved cotton t-shirts to full-sleeved fleece pullovers. However, we did request that users remove outerwear such as jackets prior to start of the experiment.

We chose 8 body locations as depicted in Figure 7. A vortex was directed at each location 5 times – a total of 40 vortices per participant. The ordering of the 40 vortices was randomized, and the entire experiment took about 20 minutes per participant including setup. The experimental procedure involved the experimenter using the laser crosshair and the pan-tilt platform to manually point the AirWave's aperture at one of the 8 locations.

Users responded only if they felt a vortex hit them, and were instructed to point to the perceived center of the impact. To measure how well the users perceive the location of the feedback, we measured the distance between the point where the users indicated they felt it and our laser crosshair using a digital vernier caliper; we will refer to this as *targeting error*. Though the vortex never hits a point as small as the spot to which users pointed (with a single finger), having users give us a specific point allows for consistent and objective measurement that captures system performance *and* user perception.

"No response" from a user indicated that the vortex impact was not perceived, and we counted these scenarios as a "miss". Thus, to measure how often users perceived the feedback, we kept track of the hits and misses to yield an overall hit rate.

Experimental Results

Spatial accuracy and hit rate

Figure 7 summarizes the mean targeting error and standard deviation, across all users for each region on the body. Larger values of distance indicate that the perceived feedback was farther away from the targeted point. It should be noted that for all body regions, the average targeting error is lower than 10 cm, similar to our finding that at 2.5 m (Figure 6).

The average *hit rate* (i.e., the proportion of tests where users reported perceiving a vortex impact, irrespective of where it was felt or targeted) across all users was 93.75% (σ=5.17%). When the chest or torso region was targeted users always felt a perceptible impact. This is expected given that the average variability in targeting is under 10 cm and these regions of the body are wider than the other 6 regions.

The lowest number of perceptible hits for any participant was 33 out of 40 (82.5%), and occurred because the participant wore a thick fleece pullover. We note that in some instances, we could visually see the vortex moving the fabric of the fleece, but the participant did not react, indicating no perceived impact. Most misses were in the shoulder region as the chest and torso was relatively flush with their clothing. This is a promising result, as it suggests that the force imparted by the AirWave prototype is strong enough to impart feedback even through thick clothing more than 8 out of 10 times.

Body region accuracy

From a quantitative perspective, the variability in distance measures and the overall hit rate with the participants was consistent with the findings from the targeting experiment in previous section, suggesting for example that AirWave can target the left shoulder without stimulating the right shoulder or torso. However, many applications will aim to target a body *region*, rather than a specific point. Accuracy at the region level is not a direct function of targeting precision, due to variations in individuals' proportions and subjective perception. Therefore, we also assessed our results in terms of AirWave's ability to target specific body regions.

To measure *body region accuracy*, we categorized the user's perceived point of impact into one of the 8 body regions. Thus we recorded not only the quantitative distance measure, but also any mismatch between the region of body the vortex was directed at and the region to which the user pointed. For example, directing a vortex at the right shoulder and the user pointing close to the right cheek was categorized as a mismatch. It should be noted that a mismatch could potentially occur even if the distance is less than 10 cm (particularly for slender participants). Figure 7 details the body region accuracy across users for each body region.

We found through this categorization that the face regions performed somewhat poorly, with average left and right cheek region accuracy of 77% (σ=25%) and 86% (σ=25%) respectively. This is expected as our resolution is no better than 10 cm and vortices targeted to the left cheek were perceived on the right cheek and vice-versa. Similarly, the chest region, with an average accuracy of 78% (σ=15%), was often miscategorized as either left or right shoulder.
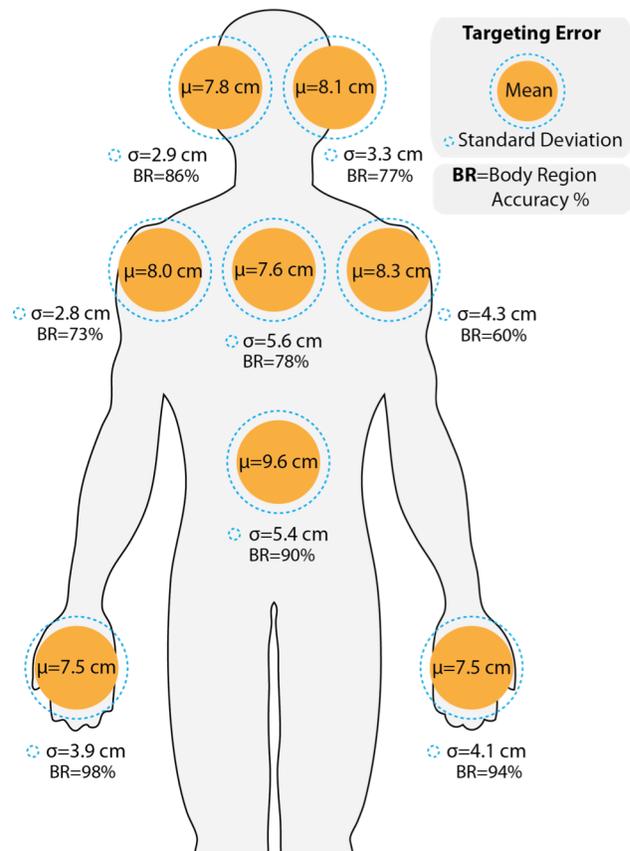

Figure 7: Mean targeting error and standard deviation for 8 body locations across 10 users, at a distance of 2.5 meters, showing a typical resolution less than 10 cm. Also shown is the hit rate categorized by body region.

This was especially the case for users with a slender build (for 3 of 5 female participants, the chest region accuracy was 60%).

The lowest performance corresponded to the left and right shoulders, with region accuracy of 60% (σ=21%) and 73% (σ=31%) respectively. On further analysis, we found that 37% of left and 61.5% of the right shoulder mismatches were categorized to left and right cheeks respectively. That is, vortices directed at a user's shoulder were frequently perceived as hitting the face (on the same side). We believe this can be explained by the observation that users' shoulders were clothed, while neck and face regions were not. If a vortex hits the upper region of the shoulder and brushes against the neck or face, the perceived feedback on the bare skin would be relatively greater than the clothed region.

We confirmed through informal questioning that the feedback was more pronounced on bare skin than clothed regions. This was also confirmed with the observation that vortices targeted at participants' (bare) hands were almost always perceived correctly: right 98% (σ=6%) and left 94% (σ=11%).

These results suggest that for applications wishing to target a body region, the physical target point and perhaps the vortex intensity should be adjusted with the target region in mind. For instance, while imparting feedback on the shoulder, the target should be kept lower to counterbalance the possibility of a vortex brushing against the neck.

False positives
Another interesting finding was that there were *no* "false positives" across all participants. The time between vortex events was randomized, and even when long periods elapsed, users never reported an event until the vortex was fired. This suggests that the feedback from AirWave was easily distinguishable from ambient air flow. One user mentioned early in her session, that she felt air draft from a nearby AC vent and was unsure if it was a vortex. However, after feeling a few vortices, she characterized them as a "ball of air" that felt much different from air drafts.

DISCUSSION, LIMITATIONS, AND IMPROVEMENTS
Our results suggest that air vortex rings represent a promising approach to at-a-distance, targeted haptic feedback. In this section, we provide additional detail and insights that may improve future designs in this space, and we discuss some limitations and challenges.

Steering Vortices
In the prototype implementation we presented, AirWave was mounted on a manual pan-and-tilt platform for directing vortices at a target. An automated version of this platform could easily be used instead, which can further be combined with a tracking system to automatically target the vortices, similar to the approach used in [24].

Though straightforward, we believe moving the entire vortex generator can quickly become slow and cumbersome.

We thus experimented with an alternate method to steer vortices, where instead of panning and tilting the apparatus, we attached a short, flexible tube – which can be directed by physically bending the tube – directly before the aperture opening. We did not notice any significant change in the vortices produced, however the feedback diminished when we tried to use longer (10 cm) tubing for added directionality. Further investigation is required to validate the effect on vortices produced and potentially make use of longer tubing.

Sound Produced During Operation
Speaker-based prototypes generate a "thump" sound when the speaker diaphragm flexes to eject a vortex. One way to mitigate this is to insulate the chamber with noise-absorbing foam. We tested the latter approach, and observed that with foam noticeably reduced the sound, with no adverse effect on perceptible force (since insulation does not affect the volume of the air moved or the movement of the speaker). Alternatively, application designers could take advantage of this sound and mask it by incorporating it into other audio-visual elements of their application.

Vortex Velocity and Feedback Delay
The vortex translational velocity falls off as the vortex travels, due to air resistance. At 1 m, the measured velocity of our current setup is 9.1 m/s; however this drops to 3.7 m/s at a distance of 2.5 m, thus creating a delay of ~410 ms after the vortex is ejected. Thus, the total delay taking into account the speaker cone movement is ~470 ms. Applications may need to model this delay: in a sports game, for example, the visual animation of when a ball hits the player could be timed with the associated haptic feedback, taking into account the propagation delay.

Of course, the delay can also be substantially reduced by increasing the velocity at which the vortex is ejected either through increasing the length of the slug (moving more air) or decreasing the time required to move the diaphragm by using a higher-speed speaker coil.

Estimated Force on Impact
Though we have focused our experiments on perception of force rather than on absolute force, we performed an additional experiment to coarsely estimate the force exerted by a vortex, to allow readers to loosely compare to other haptic feedback modalities.

To estimate force, we directed AirWave at a 0.1gm-resolution, 500gm-maximum mechanical scale. At a distance of 1 meter, we found the peak force to be ~18gm or ~176.6mN, and at 2.5 meters, ~9gm or ~88.2mN. We note that these estimates do not take into account the air resistance experienced by the weighing surface tray and thus slightly underestimate the actual force.

Variations for Enriching Feedback
This work is primarily focused on exploring the viability of air vortices for haptic feedback. However, the attributes of the air a vortex carries can also be altered to achieve inter-

esting haptic sensations. For example, we filled the Air-Wave device with hot air and observed that the vortex it ejects felt warmer when it hit bare skin. Similarly, a cooling effect could potentially be achieved with cold air. This approach is not limited to temperature changes; for example, a fine mist of water or alcohol can be injection during vortex formation (commonly done in fluid mechanics research to introduce a coloring dye for studying vortices) to produce interesting moisture or cooling sensations.

Similar to the approach used by NakaiZumi et al. [16] to alter the vortex velocity in an olfactory display, we can generate multiple vortices in succession, as well as vortices with variable timing. For example, generating two vortices in rapid succession can produce a "double tap" sensation. Additionally by varying the current applied to the speaker, the volume of air displaced could be controlled.

Finally, we believe it may be possible to create many interesting haptic sensations by leveraging tactile illusions, similar to those exploited by Israr et. al's tactile display [10].

DESIGN RECOMMENDATIONS AND CONCLUSION

One of the key takeaways from our synthesis of vortex theory is that when building a new vortex generator with similar displaced air volumes, designers need not constrain their design around an exact aperture size, but rather around our recommended L/D ratio of between 5 and 6 for optimal haptic sensation. We recommend one should work backwards from this suggested ratio and find the aperture that fits the system's constraints.

Another important design criterion to note is that we do not make use of a cylindrical tube at the end of the aperture like that found in generator designs used in [12,24]. In our experiments, we found that using them noticeably diminished the feedback irrespective of the aperture and tube diameter.

Our initial results both validate the effectiveness of our approach and provide a basis for future analyses and improvements. Using these findings and a few off the shelf components, researchers and application designers can begin to explore this new and exciting haptic modality that does not require the user to be tethered to a system or carry a specialized device.

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