SensaBubble: A Chrono-Sensory Mid-Air Display of Sight and Smell

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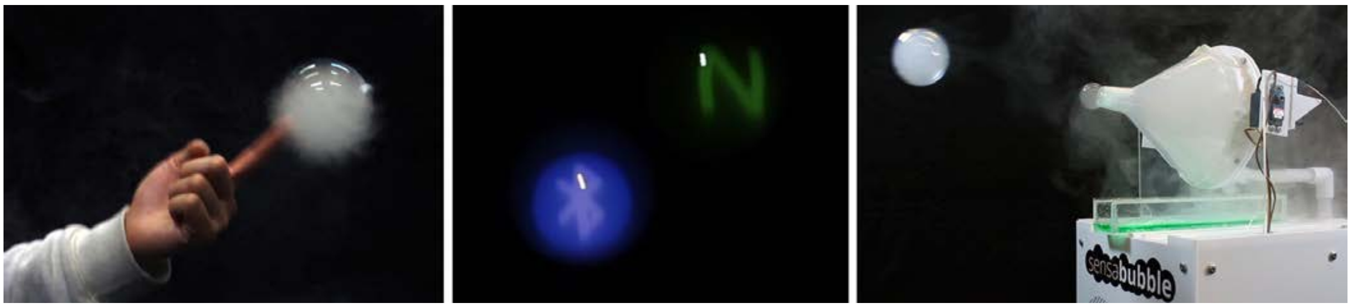

Figure 1 SensaBubble generates scented fog-filled bubbles which have visual information displayed on them. (a) Users interacting with the demo, (b) Bubbles projected with the Bluetooth icon and the letter 'N' (c) The bubble generator.

ABSTRACT
We present SensaBubble, a *chrono-sensory* mid-air display system that generates scented bubbles to deliver information to the user via a number of sensory modalities. The system reliably produces single bubbles of specific sizes along a directed path. Each bubble produced by SensaBubble is filled with fog containing a scent relevant to the notification. The chrono-sensory aspect of SensaBubble means that information is presented both temporally and multimodally. Temporal information is enabled through two forms of persistence: firstly, a visual display projected onto the bubble which only endures until it bursts; secondly, a scent released upon the bursting of the bubble slowly disperses and leaves a longer-lasting perceptible trace of the event. We report details of SensaBubble's design and implementation, as well as results of technical and user evaluations. We then discuss and demonstrate how SensaBubble can be adapted for use in a wide range of application contexts – from an ambient peripheral display for persistent alerts, to an engaging display for gaming or education.

Author Keywords
Ambient displays; Interactive displays; Bubbles; Ephemeral interfaces; Multimodality.

ACM Classification Keywords
H.5.2 Information interfaces and presentation: User Interfaces.

INTRODUCTION
A soap bubble is generally perceived as an object of fascination and beauty, stimulating delight among children and adults alike. For centuries, artists such as Chardin (1699-1779), Millais (1829-1896), and Cornell (1903-1972) have used bubbles as a subject for their work, commonly as a *vanitas motif* to represent earthly pleasures and fragility of life. Similarly, due to their mathematical properties, scientists such as Plateau, Newton and Rayleigh, have long studied their behaviour to better understand the natural world [2]. Our fascination with bubbles is reflected in popular culture, such as the use of the song "I'm forever blowing bubbles" as the club anthem of London football club, West Ham United.

There are therefore compelling reasons to examine how technology can exploit our innate interest in bubbles and enable a variety of augmentations to the already appealing medium of soap bubbles. Interactive technologies that are directly targeted at generating public interest and drawing the user's attention have many applications in advertising and certain forms of education, such as museum exhibits.

Bubbles and bubble-based systems have been previously proposed as a potential display and user interface. Some proof-of-concept prototypes exist [18, 21, 30] but there is no systematic exploration of this space. In particular, bubbles have interesting qualities that could potentially be used to achieve appealing multimodal interactions. Bubbles are visual, tangible and ephemeral, and by enclosing a scent within them, they can also stimulate olfactory senses.

Although there have been olfactory interfaces developed both within academia [3, 17], or within industry [23], there is still a limited use of smell technology in HCI [8]. Often overlooked, the sense of smell is rich, sensitive, and highly evolved. The evolutionary advantages of a highly developed sense of smell have been used to explain the rapid brain development evident in early mammals [26]. Furthermore, humans have an impressively low odour detection threshold that can improve with training [32]. In short, smell has under-explored potential for use in human computer-interaction.

In this paper we examine the design space for bubble-based technology. We describe the bubble parameters that might be manipulated through technology, and we explore the qualities that support pre-attentive and persistent interactions. We also introduce the concept of chrono-sensory experiences where layers of information are presented via different senses for variable length of times, each attracting different types of attention from the user. We then describe our exploratory work in devising a system, called SensaBubble, that generates bubbles with a specified size and frequency, fills them with an opaque fog that is optionally scented, manipulates their trajectory, tracks their location, and projects an image onto them. We report results of an evaluation validating that the intended information is successfully communicated to users through the system. We finish by proposing a variety of application areas for SensaBubble, including education, notification and engaging user experiences.

RELATED WORK

We start by reviewing the literature in three areas of related work: bubble displays, olfactory displays, and variably persistent displays.

Bubble Displays

There are limited examples of bubble displays in prior research. *Bubble Cosmos* [21] examines the attractiveness of illuminated free-floating fog-filled bubbles in entertainment, aiming to provide a fun and aesthetic display. Their system projected images onto the bubbles, and produced a sound and image when bubbles burst. *FragWrap* [18] proposes a scent-mapping system which generates soap bubbles filled with a scent and projects the image of the scent onto the bubble. Their system produces each scented bubble by requesting the scent through voice-activation. *Soap Bubble Interface* [30] allows users to control room lighting by moving or blowing smoke-filled bubbles across a liquid surface. The authors discuss the qualities of material used in tangible user interfaces and explore the use of tangible ephemeral materials such as soap bubbles. *Shaboned Display* [11] uses the expansion and deflation of individual soap bubbles arranged in a matrix on a plane as a variable pixel of an image. This system allows each pixel to exist in a physical form, and users can interactively modify the displayed image by bursting the bubbles. *Information Percolator* [10] generates air bubbles that rise up in tubes of water forming a segmented display that is visible due to the bubbles raising disturbance in the water and reflecting light. Bubble artists such as Fan Yang[1] use various forms of bubbles in their performances, by creating bubbles within bubbles, bubbles of different shapes and long chains of bubbles.

Although bubble displays have been used in many different ways, only *Bubble Cosmos* allows for user interaction with visually-augmented bubbles. We take the direct interaction with bubbles from *Bubble Cosmos* as an inspiration for our work and extend upon it and *FragWrap* by researching the design space arising from interactive bubble-based displays with visual and olfactory augmentation.

Olfactory displays

Olfactory displays have been used in HCI as notification systems, providing ambience in museums and to accompany visuals in films, websites and games [16]. There have been several attempts to commercially capitalize on olfactory displays. In the 1950s, *AromaRama* and *Smell-O-Vision* [28] were intended to give cinema-goers a more immersive experience, and a virtual reality olfactory system, *Sensorama* [9], was patented in the 1960s. Many museum exhibits and fun-parks now incorporate some form of olfactory stimuli to enhance the viewer's experience.

Academic research has also examined potential applications of olfactory outputs. In supporting collaborative awareness, *inStink* [17] uses spice aromas to coincide with the activity of a kitchen in a remote location. *Dollars & Scents* [17] uses scents to represent the state of the stock market. *Olly* [23] releases a scent when there are social media notifications. *Olfoto* [3] investigated the usefulness of smell-based tagging to assist search of digital photo collections.

Basic research on olfactory capabilities have found that humans have the capacity to detect smells as well as other primates, rats, gas measuring instruments, and for certain compounds, even dogs [27]. An untrained subject can distinguish between three levels of odour intensities (not including zero), increased to four with training [7]. Additionally, Lord and Kasprzak [20] found that participants are able to identify their own shirt from nine other identical ones just by smell.

In short, the human sense of smell is powerful, but there are few research systems that explore and examine ways to use it. In our research we take the first steps to explore how smell can be used to augment and prolong a visual stimulus that is mediated by a soap bubble.

Variably-persistent displays

It is well understood that different interaction contexts require different levels of feedback persistence – for example, a calendar application might use a persistently displayed window to alert the user to an upcoming meeting

[1] en.wikipedia.org/wiki/Fan_Yang (Accessed 14 Sept 2013)

(so a user who was temporarily away from their desk does not miss the notification), whereas a transient 'beep' notification may be sufficient for certain types of error such as typing alphabetic characters into a number field. There is substantial research interest in understanding how and when different forms of notification and feedback persistence are used in different interactive circumstances [12, 13]. Our focus in this section is on ambient displays and on their ability to provide notifications that have varying degrees of forcefulness (i.e., the likelihood that they will be noticed) and persistence.

Ambient displays have been deployed in many novel ways, where minimal attention is desired. These displays typically need to be minimally attended yet perceivable from outside of a person's direct focus of attention, providing a level of pre-attentive processing without being unnecessarily distracting.

There are many examples of research on the design of ambient displays within HCI. *ambientRoom* is an interface environment that provides information for pre-attentive processing through subtle cues such as using light, sound and movement of physical objects within a room [15]. Vogel and Balakrishnan [31] explored design principles and an interaction framework for interactive public ambient displays. They proposed a public ambient display system that can assume a dual role of a public ambient or personal focused display depending on context. Sideshow [4] demonstrates techniques for designing for peripheral awareness for notifications.

Döring et al. [6] explored the concept and design space of ephemeral user interfaces (EUIs), which consist of at least one element specifically designed to communicate the state of transience. EUIs can allow the presentation of digital information to be impermanent thus reducing cognitive overload. As EUIs have a temporal existence, they only raise awareness when needed and are natural ambient displays. Examples of materials with ephemeral connotations associated with them that have been used in UIs are such as soap bubbles [30], fog [25] and water drops [24]. These transient materials can be used as input, output or both input and output interaction.

BUBBLE DESIGN PARAMETERS

Bubbles offer a fascinating design opportunity for providing a multimodal ephemeral display. They can be ambient and engaging at the same time. Bubbles also allow for an ephemeral chrono-sensory experience whereby information is presented with different lengths of persistence. To begin the exploration of this design space, in this section we examine the set of bubble parameters that might be manipulated by a system. Parameters like bubble size, longevity and frequency can be readily manipulated by technology. We focus on these parameters, together with brief suggestions for the utility of manipulating each parameter in the following subsections.

Bubble shape

Bubbles can be free-floating, or placed on a surface. Free-floating bubbles allow for interactions in mid-air. However, they do not last as long, as they burst when colliding with the ground. Surface-bound bubbles last longer but interaction space is limited.

Bubble size

Bubble size can be manipulated by varying several factors, including the volume of air used to inflate the bubble, the amount of bubble solution, and the area of the pre-inflated bubble film. Bubble size might be used to control the degree of ambience in a signal, or the urgency of a notification – for example, notification of a meeting occurring in 30 minutes might use a small bubble, while the 5 minute warning might use a large one.

Bubble longevity

The length of time a bubble floats for depends on the temperature and density of the air that it encloses. Bubbles only last as long as their structure is not perturbed by an external object or impurities, or their upper film is not too thin to maintain stability due to evaporation of water from the surface and gravity pulling the film liquid towards the bottom [14]. We define bubble longevity as the time between bubble generation and its popping due to atrophy of the bubble mixture (rather than due to collisions). Bubble longevity can be partially controlled through the composition of the bubble solution.

Longevity could be used to control the degree of visual salience of the bubbles. For example, short-lived bubbles might burst in the periphery of the user's vision, lowering the likelihood of their being noticed, while long-lived bubbles might endure until reaching the user's focal point at the computer monitor or desk.

Frequency and bubble-cloud density

The frequency with which bubbles are emitted can be used in conjunction with their size and longevity to control the size and density of a bubble cloud. This property could be manipulated to effectively manage the salience of the bubble display, with denser bubble clouds particularly appropriate for public displays in large open spaces or functioning collectively as a large display.

Speed and trajectory

The speed and direction of each bubble can be controlled through the use of fans. However, the control of this parameter is crude in that air turbulence is relatively unpredictable and it is difficult to influence only one of several bubbles within a region. This parameter could be controlled using electrostatic fields as in *FragWrap* [18] or using Aireal [29] where air pressure waves can be focused to push the bubble towards a specific location in the room.

Visual properties

There are a number of ways to use a bubble as a visual display. Although a soap film is transparent, a projection onto its surface can be visible if it is vibrated with ultrasound [22]. Bubbles can also be filled with coloured fog or the bubble solution can be coloured.

The most flexible method is to project data onto a bubble that is filled with a translucent or opaque white fog. When combined with camera-based object tracking,

Parameter	*Degree of manipulation supported*
Size	Variable. Reliable production in the range of 7 to 12 mm.
Longevity	Static. We use a single mixture optimized for long bubble life.
Frequency	Variable. Bubbles can be produced at up to one every 4 seconds.
Velocity	Controlled by electric fans.
Visual properties	Accurately tracked, with individual displays on each bubble.
Scent	A controlled mixture of three base scents.

Table 1 SensaBubble's design parameter

individualized data can be projected onto discrete bubbles in a scene. Data projected onto each bubble might be a colour, text, or image. These properties could be used for a multitude of purposes, such as displaying individualized data on a bubble nearest to a particular person (e.g., a personalized advertisement in a bubble), or for colour-coding messages to a user (e.g., migrating from cold colours to hot ones as an event becomes imminent).

Scent

Finally, the air used to inflate the bubble could be scented to enable a persistent trace of the bubble's existence after the bubble has popped. For example, a meeting notification might be announced by generating a single bubble. However, if the user is out of the room at the time the bubble is generated, they might be able to detect the announcement by the scent when they re-enter the room.

SENSABUBBLE IMPLEMENTATION

We designed SensaBubble as a chrono-sensory mid-air display system that generates scented bubbles to deliver information to the user via a number of sensory modalities. SensaBubble introduces the concept of a chrono-sensory output, due to the fact that different components of the system are both short and long-term and detected on different human senses.

Prior to the bubble bursting, the user has to observe the bubble and interpret any image projected onto it in order to receive any information from it. However, after bursting, the scent is likely to be more pervasive and noticeable, and will remain detectable even if the user is absent from the room at the time of initial bubble production. The visually observable bubble is temporally transient, existing for up to a minute, whereas the olfactory aspect of the system's feedback endures for up to half an hour. Table 1 summarises the capabilities of SensaBubble with respect to the bubble design parameters identified in the previous section. The SensaBubble system consists of four main parts: the bubble generator, the scented-fog chambers, the tracker and projector, as described below.

Generating the bubbles

Although it is trivial for a human to make a bubble, the computer-controlled generation of a single specifically-sized bubble filled with scented fog is not. Commercially available bubble-machines tend to generate large numbers of bubbles in rapid succession, typically using an electric fan to blow through an aperture covered with a continuously renewed film of soap. Our experience of trying to use a similar mechanism, as in *FragWrap* [18], to blow a single bubble proved to be unreliable due to both the turbulent airstream created by the electric fan and the slow response of controlling the fan speed.

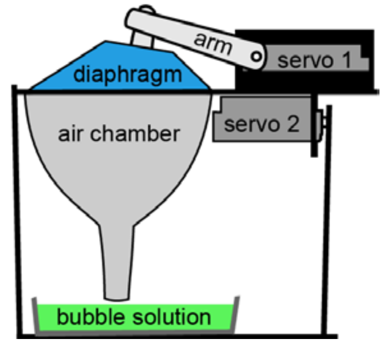

Figure 2 Computer-controlled bubble bellows mechanism.

Our experiments and design prototypes demonstrated that there is a lot of controlled feedback involved in manually blowing a bubble, with the speed and strength of the blow varying dynamically as the bubble forms. Thus, we took inspiration from bubble artists, who have used various techniques of creating bubbles of different sizes and shapes. Bubble artists usually produce their bubbles by blowing through a straw or a tube, allowing them to easily control the size of their bubbles. This inspired us to create a bellows system, simulating the human lung blowing into a straw. We used a funnel where the stem mimics the straw and the conical mouth mimics the lungs or air chamber. The top of the funnel is covered with an air-tight fabric that is pushed and pulled with a servo to simulate the diaphragm contracting and expanding during inhalation and exhalation. We mounted the funnel onto a laser-cut platform which pivots at the top of the air chamber. Servo 1 controls the actuation of the diaphragm and servo 2 controls the pivot angle of the bellows (Figure 2).

Computer-controlled generation of a single bubble

Using the bellows mechanism, we are able to reliably create a single bubble on demand and accurately regulate the size of the bubbles by controlling how much air goes into a bubble before it leaves the tip.

The bellows method reliability partly comes from the two-stage approach to blowing the bubble. Firstly the bubble is slowly inflated, by actuating the arm so that it goes through a specified angle in a certain amount of time. The amount of angle actuated by Servo 1 determines the size of the bubble. Secondly, we provide a short quick 'puff' to the bellows to disengage the bubble and send it away from the

Bubble Size	*Number of bubbles successfully generated*	*Sample size*
Small (7 – 8 cm)	92	100
Medium (9 – 10 cm)	93	100
Large (11 – 12 cm)	83	100

Table 2 Reliability of bubble generation.

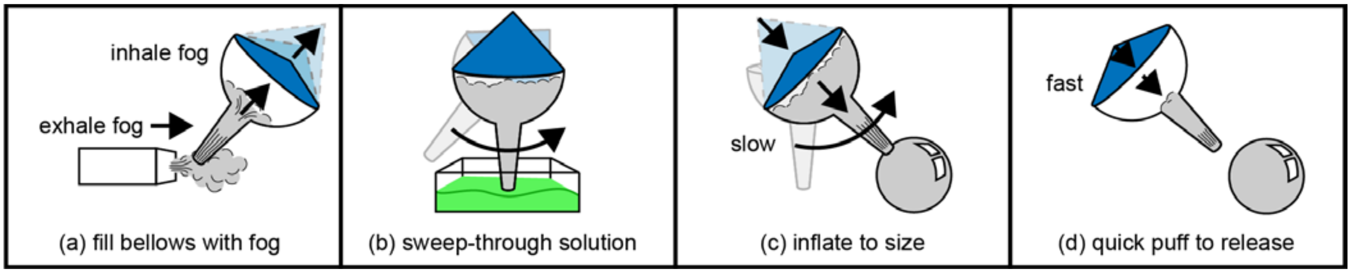

Figure 3 Steps for generating a bubble.

nozzle (Figure 3d).

The pivoting action actuated by Servo 2 allows the bubble generator to perform two other functions that are needed for SensaBubble: inhaling the fog, and immersing the tip of the bellows in the bubble solution. As shown in Figure 3, the pivot can assume three different positions: the first position, whereby the bellows can inhale the fog; the second, where it sweeps-through the bubble solution so that a film of solution is formed on the bellows tip; and finally the third, where it creates and releases the bubble.

From our tests in the lab, we are able to consistently create a single bubble, achieving accuracy of 93% with medium sized bubbles (9 to 10 cm diameter). We are also able to create 3 different sizes with this mechanism. The test involved blowing 5 sets of 20 bubbles, with a short pause between each set to check the bubble mixture depth. Results of this test are shown in Table 2. Measuring the diameter of a bubble was not trivial. We performed our measurements of the bubble sizes by colliding several bubbles of each size onto a vernier calliper.

Bubble solution

The mixture of the bubble solution is fundamental to the longevity and manipulability of bubbles. We found that commercial 'off-the-shelf' bubble solutions were unsatisfactory, as bubbles would burst in the air shortly after generation. Ideally the bubbles produced by SensaBubble should last until they touch the ground or until the user chooses to pop one in the air. We therefore experimented with three different bubble recipes with help from the Soap Bubble Wiki[2] (Table 3), and tested the average time for a bubble to burst when created on a surface. We settled on Solution 2, consisting of equal parts water, glycerine and dishwashing liquid, as it had the desirable properties of both longevity and leaving a limited amount of residue on surfaces where bubbles have popped.

Solution	*Formula*	*Time to burst*
1	Supermarket	15-30 seconds
2	Water, glycerin, dishwashing liquid (ratio 1:1:1)	3-4 minutes
3	Water, glycerin, dishwashing liquid, lubricant (ratio 1:1:1:1)	4-5 minutes
4	1 liter water, 40 ml dishwashing liquid, 1.5 g guar gum, 1 g baking soda, 0.5 g citric acid.	1-2 minutes

Table 3 Bubble solution formula longevity

Creating the scented-fog

Fog sources

We also experimented with several methods for creating a scented fog to fill the bubbles:

- *Dry ice*: Bubbles can be filled with the fog released from dry ice. However, the fog created is heavy, curtailing the time the bubble remains air-borne and does not allow the bubbles to float in air.
- *Ultrasonic fogger*: Bubbles filled with fog produced by an ultrasonic fogger are lighter than those filled with dry ice, however their density is too low to be reliably tracked by the Kinect.
- *Fog machine:* Fog machines produce warm and dense fog allowing the fog-filled bubbles to float for a longer period of time and be easily tracked.
- *Electronic cigarettes and radio-controlled train models*: These use a heating element wrapped around a fiberglass wick, which vaporizes a vapour liquid within the wick. This produces relatively dense fog from a small package, however at a much slower rate than fog machines.

Scenting the fog

Many commercially-available scents are oil-based or water-based emulsions. To produce a scented fog, we need to select a fog liquid which can easily dissolve the scent liquid. If the resulting solution is homogenous, the fog will have the smell of the scent used. We found that scents specifically meant for vaporizing via heating worked very well with the fog machines.

SensaBubble's scented-fog setup

We decided to use fog created from the fog machine as it allowed us to rapidly create several bubbles that float in the air concurrently. With this method, the bottleneck to bubble creation is the action of the bellows, rather than fog generation.

In SensaBubble we used three fog machines, each containing a different scent. All the fog machines are individually controllable by a computer. The fog from these machines is channelled through a mixing funnel leading to the nozzle of the bubble bellows. This method allows the three scented fogs to be mixed as desired to form more than three scent combinations.

[2] soapbubble.wikia.com (Accessed 1 August 2013)

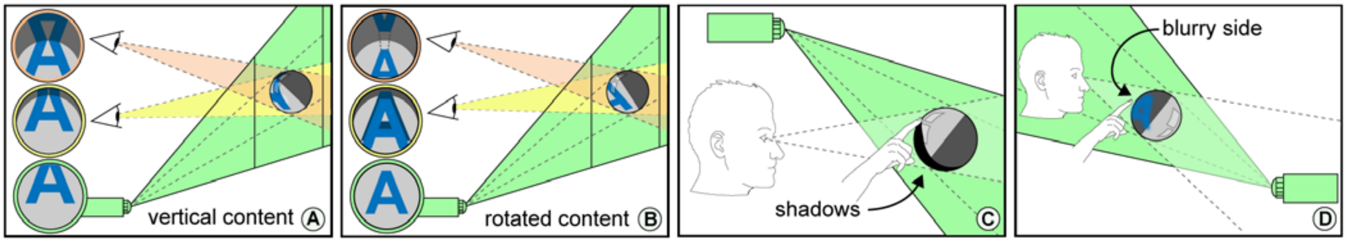

Figure 4 Projector angle options.

Tracking the bubbles

Accurate tracking of the generated bubbles is necessary for individualized data to be projected onto each bubble. We used a Kinect to track the bubbles and an off-the-shelf projector. For tracking to succeed, the bubble needs to be 'visible' to the infrared camera of the Kinect. Our initial trials showed that the visibility of the bubbles was greatly affected by the density of the fog enclosed inside them. A bubble containing very little or no fog is almost invisible to the Kinect, and therefore cannot be tracked.

For bubbles that can be detected by the Kinect, there is another aspect to consider. The fog density also affects the structured light field emitted by the Kinect. When a bubble contains fog with low density (but more than what is required to be visible), the structured light field is disrupted, making depth information from the Kinect unusable. Bubbles with a thin fog are therefore visible to the Kinect, but *not depth-trackable*. This limitation does not occur if the fog inside the bubble is sufficiently dense.

We implemented two bubble tracking systems within SensaBubble, experimenting with solutions to both depth-trackable and non-depth trackable bubbles.

Non-depth-based tracking

Bubbles with low fog densities are seen by the system as circular regions without any depth information. While one solution would be to simply increase the fog density inside the bubble, this affects the projected content visibility (as discussed later). Hence, we developed an alternative tracking mechanism.

We utilized image segmentation to identify the relative position of a low-density fog bubble. Any circular region of the depth map, wherein depth information is not available, can be assumed to correspond to a bubble in most common usage scenarios. Image segmentation is greatly simplified because the algorithm only needs to segment regions without any depth information. However, the main challenge is determining the 3D position of such bubbles. The most obvious approach is to estimate the depth of each bubble based on its relative size on the depth map. This is relatively simple because SensaBubble already reliably controls the size of each generated bubble. The resultant tracking is satisfactory but α-β noise reduction filters become necessary to reduce jitter. A more complex approach using two stereo cameras, or two orthogonally positioned Kinects, was considered. However, the results of the first approach were satisfactory enough and thus the second approach was not explored further.

Depth-based tracking

Bubbles with sufficiently high fog density are opaque enough for the Kinect to reliably determine their 3D position. On the other hand, image segmentation (i.e. identifying what is and what is not a bubble) becomes more challenging. This is because a bubble is not any different than a common object (e.g. a plastic ball) that appears in the depth map.

To approach this issue, our tracker first uses background subtraction to remove static objects from the depth map. Next, skeletal tracking is used to detect users and demarcate regions that are potentially the users' bodies. For the remaining depth map, we use OpenCV-based blob-tracking and contour mapping to identify regions as bubble candidates. A similar process is independently carried out for the regions identified as users' bodies. This allows the tracker to also detect bubbles in front of a user. The regions where a user's body is located are also scanned for depth-based discontinuities. These discontinuities would indicate the presence of a bubble occluding a part of the user's body. For all the discontinuous regions identified, the algorithm performs similar steps (blob-tracking and contour mapping) for identifying bubble candidates.

In both cases of tracking, the Kinect can only provide 30 depth map frames per second. For all intermediate projector frames, we implemented a prediction algorithm based on a second order model of the movement of the bubble (velocity and acceleration). This allowed us to estimate intermediate positions based on previous trajectory parameters. The prediction of the position allows us to reduce latency between the real-world position of the bubble and the position at which the projector projects content for it. During trial runs (and subsequent studies) of the system, we observed that the tracking is stable enough for the projector to smoothly track the bubble and continue projecting on it till it pops.

Projecting onto the bubbles

Projecting information on the bubbles involves a few considerations and resulting trade-offs. The presence of the fog inside the bubbles results in light scattering. Also, the angle and direction of projection play a significant role in the perceived quality of the contents projected onto the bubble. Other factors related to line of sight between the bubble and the projector such as shadows (e.g. if a user stands between a bubble and the projector) or projector glare (e.g. when the projector faces towards the user) also need to be considered (Figure 4).

Light Scattering
For a bubble without any fog, the two opposite surfaces of the bubble will partially reflect the projected light passing through them. Since the reflection-transmission ratio is very small, the reflection will be clearly visible only if the incident projection is brighter by several magnitudes. Thus, the presence of the fog is beneficial in terms of improving visibility of the content. However, there is a trade-off involved. With the presence of the fog, the light hitting a bubble is scattered as it travels through the bubble. While the image on the side facing the projector remains crisp, it becomes blurred by the time it reaches the side facing away from the projector.

Therefore, it is important to consider the position of the user. For a user located on the same side as the projector, the visibility of the content is not critically affected by fog density. However, if the user is positioned such that they see the back surface of the bubble and the content is text-based, the bubble needs to be smaller and also contain less fog. With increasing fog densities and larger bubbles, the blurring of image on the back side increases (Figure 5).

This trade-off is not so restrictive if only a single colour is used to represent the information. In this case, the blurring seen in large and dense bubbles is beneficial. The system can leverage the resulting scattering to make bubbles look homogeneously coloured when viewed from any position.

Projection and viewer's angle
Most off-the-shelf projectors are designed to produce an off-axis projection volume to facilitate mounting. This projection volume has to be modelled as a system parameter to ensure correct projection onto the bubbles. If the projector angle is not considered, this can result in contents being only partially visible. Figure 4a shows an example where contents are always presented perpendicular to the floor. The top part of the letter 'A' is on the part of the bubble that is not visible from the projector's point of view and thus will not be visible to either locations of the user.

One solution is to align contents to the projector, ensuring that the whole letter is centred in the plane of the bubble that the projector can illuminate, to maximize image quality (Figure 4b). Then, the location of the user plays an important role in the content's visibility. A user aligned closer to line of sight of the projector will have better visibility than a user aligned at a further angle. Taking these elements into consideration, we can suggest two different scenarios where text-based contents (i.e. text as opposed to colours) are presented.

The first one would be to place SensaBubble above the user (Figure 4c), ensuring a small user-to-projector angle and that the user's viewing plane of the bubbles is the same as the projector. This setup maximizes visibility, but it can cause users to cast shadows on the bubbles when they reach in to interact with them. In the second setup (Figure 4d), the users and the projector are located at opposing sides, ensuring a small user-to-projector angle and that no shadows are cast onto the bubbles. However, since the user

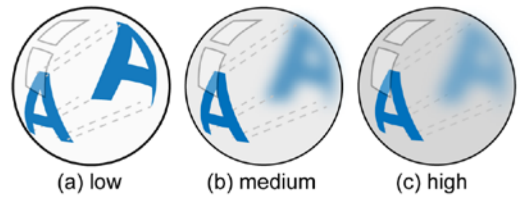

Figure 5 The effect of fog density on the projected image. The smaller letter to the left is on the 'front' surface of the bubble and the larger one to the right is on the 'back' surface.

will be viewing the 'back' surface of the bubble, readability could be affected. Also, as the user is looking almost directly at the projector, projector glare can be a source of irritation.

Thus the setup of the system has to be determined by the nature of the application. For example, we can use the setup in Figure 4c for applications that need high content visibility but interactions will have to take into account the shadow cast by the user's hands. Alternatively, for applications that are highly interactive but where visibility is less critical, we can use a setup similar to Figure 4d.

Directing the bubbles
Basic control over the trajectory of the bubbles has been implemented with the use of computer-controlled electric fans. Currently these are used horizontally to determine the distance the bubble is blown away from the generator, and also vertically from floor-level as a method of lengthening the time in the air.

SYSTEM OVERVIEW
Combining the elements of scented fog generation, computer-controlled bubble blowing, bubble tracking and projection, creates the complete SensaBubble system (Figure 6). An Arduino is used to control the two servomotors in the bubble generator in order to create bubbles of a given size and frequency and to monitor and trigger the three fog machines for the release of specific scented fog mixtures when required. The bubbles are tracked by the Kinect, as discussed in the previous section. The x, y, z position of the bubble is relayed back to the computer which then projects onto the surface of the bubble the necessary visual information. When a bubble is burst, the Kinect recognises the absence of the bubble and notifies the software. This system was used for user evaluations as described in the following section.

USER EVALUATION
Ultimately, the goal of SensaBubble evaluations will be to determine how users' react to it and interact with it, in

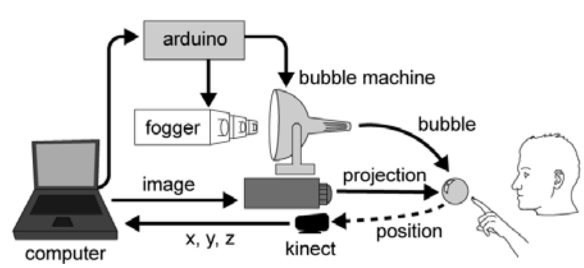

Figure 6 System overview.

specific contexts. However, before deploying the system in field settings, it is necessary to evaluate whether (and the degree to which) the elements of its design are successful. Therefore, the research questions we wish to answer in this user study concern the user's ability to extract different types of information from the system, rather than any summative judgement of its overall effectiveness for supporting or enhancing a particular task or activity.

Specifically, in this section, we evaluate the human legibility of data projected on the bubbles' surface, as well as the ability to recognize different bubble sizes. Legibility of projected data is a fundamental requirement, if users' are to gain any information from SensaBubble. Similarly, the generation of bubbles of different sizes is substantially worthless if problems such as depth-size ambiguity remove the user's ability to reliably determine their size.

As the bubbles are moving objects, we decided to use the *Transport Medium* font, which is a sans serif typeface used for road signs in the United Kingdom and numbers, letters or words from vision acuity tests. We used a random selection of numbers and single letters taken from the Snellen eye chart and words taken from the Bailey-Lovie reading charts. As the Bailey-Lovie reading charts do not have two or three letter words, we identified these words from part of longer words in the charts.

All six users were either staff or students of the university. They all went through a vision acuity test and stereoscopic test before carrying out the tasks. All the tasks were conducted with the bubble floating about 1m away from the users. The order of the trials was randomized across the users for each task. We performed four different tasks – bubble size, icon, text and number recognition.

Bubble size recognition

Bubble size can be used to inform urgency. Users were required to distinguish between the three bubble sizes created by SensaBubble. The users were shown the bubble sizes in a practice session. One bubble was generated at a time and users identified its size – small, medium and large. Each size was repeated 5 times for a total of 15 trials. The system was hidden from the participants' view and white noise was played through headphones to hide the noises involved in the bubble generation.

Legibility of projected data

We carried out three types of legibility tasks: icons, text and numbers. Icons can be used for notifications, and numbers and letters or words can be used for data information. The order of these three tasks was performed in a Latin-square design with one bubble released at a time with the projected content. In all of these tasks, a projected distraction screen was used to cover any residual projection of the data through the bubble onto the opposite floor or wall. The results are shown in Figure 7.

Icon Recognition

We tested how well users identified icons displayed on a bubble. The users had to identify 3 types of orange, blue and multi-coloured icons where each type was repeated 3 times for a total of 27 trials. The icons used were: *Orange* – RSS feed, Ubuntu, and VLC player, *Blue* – Bluetooth, Dropbox and Twitter bird, and *Multi-colour* – Apple, CNBC, and Windows.

Text and number legibility

Two separate tasks were undertaken to determine text and number legibility. In the first task users were required to read text (from single character letter and 2 to 4 character words) and in the second, numbers (from 1 to 4 digit numbers) on bubbles. Every character or number type was repeated 3 times for a total of 36 trials each. We only acknowledged a successful result if the users correctly identified all the characters or numbers on the bubble. We applied a repeated measures ANOVA on the percentage accuracies for character type and found significant differences in increasing the number of characters displayed on the bubble ($F_{(3, 15)} = 37.0$, $p = 0.001$). Pairwise comparisons with Bonferroni corrections reveal significant differences between two groups: 1-char, 2-char and 3-char, and 4-char ($p<0.005$). We applied a repeated measures ANOVA on the percentage accuracies for digit type and found significant differences in increasing the number of digits ($F_{(3, 15)} = 287.3$, $p < 0.001$). Pairwise comparisons with Bonferroni corrections reveal significant differences between two groups: 1-digit and 2-digits, and 3-digits and 4-digits ($p<0.001$). Although the users were generally poor in correctly recognizing text or numbers with more than two characters or digits, they were able to correctly recognize some parts of it.

Associative memory-smell task

Separate from the bubble size recognition and data legibility tasks, we also performed an associative memory-smell task with 6 users. The users were asked to smell three different scents (apple, cinnamon and peanut) and associate them with a related person (mother, father or a friend). After the association step, we presented the scents to the users in a fixed order (determined by Latin-square design)

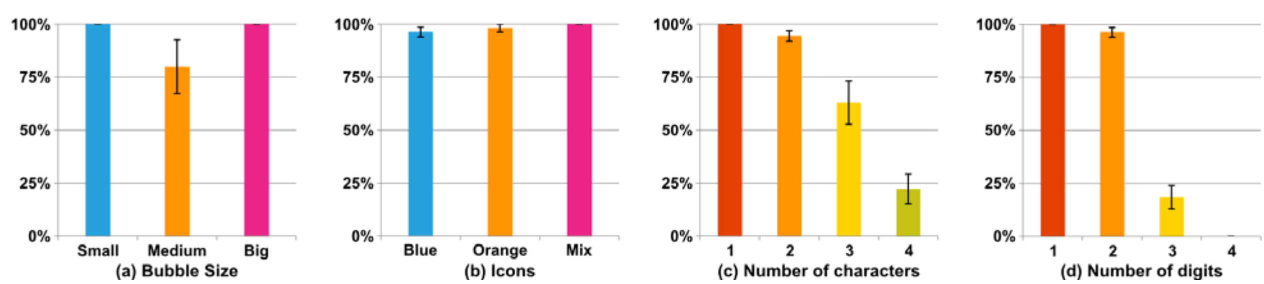

Figure 7 Results of user studies. Y-axis represents percentage accuracy.

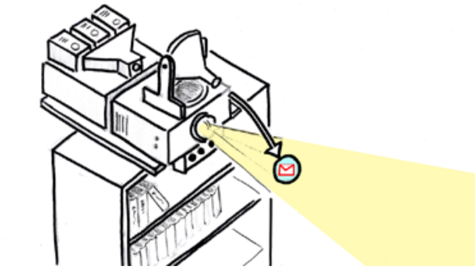

Figure 8 SensaBubble Alerts indicating arrival of new email.

and asked the participants to identify the person with whom they associated the test scent with. Each scent was repeated 3 times for a total 9 trials. Between each trial, the participants were asked to smell coffee beans to cleanse their olfactory palette. Out of the six users, three got all the trials correct. Two users made only one error and the last user made four (this was later explained by the user as mixing up his associations for the mother and father). We had an average accuracy of 88.9%. Within the 6 errors, the errors consistently occurred for the apple and cinnamon scents and none for the peanut scent. Thus a cautious selection of scents, much like that of complementary colours, may be required for easy distinguishability.

DISCUSSION

The SensaBubble system is currently able to reliably produce bubbles that the system can track and users are able to interact with. We have found icons to be readily identifiable, along with two digit numbers or two characters. The odour-identification task demonstrated that we could associate odour with a predetermined notification. Although only 6 participants were used for the user evaluations, the results have paved the way for future work on chrono-sensory displays. Following are a number of considerations that will be important for the designer of future chrono-sensory bubble displays.

The bubble tracking works in well-lit environments, but the projected image on the bubbles is clearer in a darker environment. If used in bright light, we recommend using a high lumens projector. Our experience of using a narrow field of view projector means that the range of bubble flight that we can cover is currently relatively small. This could be improved with a short throw projector if we required a wider field of view near to the projector itself. Likewise, the issue of focusing the projector on the bubble would be solved with the use of a laser-projector.

We also found that the participants could easily read text up to 2 characters long. Text longer than this was not always clearly readable. This follows from the fact that the bubble's reflective surface area and the distance of the bubble from the user are factors that impact the readability of the text. However, this is not an absolute limitation of the system. Since we envision the system to be a notification system, the content displayed on the system is more likely to be iconic or low on character count.

In a mixture of odourants, it has been found that we are generally unable to identify more than 3 or 4 individual components due to perceptual blending in olfactory processing [19]. The rate and magnitude of adaptation in olfaction occurs in an exponential decay that depends on the duration of exposure and concentration of the odourant [5]. Thus, careful localization of scented bubbles would help to prevent mixing and hence misidentification of scent notifications.

APPLICATIONS

There are many applications areas in which a system like SensaBubble could be applied, four examples of which are presented below.

SensaBubble Clock

SensaBubble Clock is inspired by clocks that mark out each hour with a chime and by incense clocks identify each hour with an aroma [1]. On the hour, SensaBubble clock releases the number of scented bubbles corresponding to the hour. The scents communicate morning coffee break, lunchtime, afternoon tea break and dinner time with a flurry of scented bubbles. Additionally, passersby can request the time by gesturing, which releases a stream of bubbles with each bubble containing an image of the time.

SensaBubble Alerts

In a workstation setting, SensaBubble creates a bubble to notify the user of a new email or social network service update. Each bubble is released in the periphery of the user's workstation and contains a corresponding icon displayed on its surface (Figure 8). The user can 'select' the notification by bursting the bubble, which shows details of the notification on the computer display. Scents can carry additional information, such as a perfume for a partner.

SensaBubble Maths

SensaBubble Maths is a fun educational game for kids, incorporating smell as feedback on their success. In SensaBubble Maths, several bubbles are generated and the user is required to burst the correct bubbles. The first bubble shows the result of the equation (e.g. 9). The second bubble shows the operator of the equation (e.g. +). Then the following bubbles will be a random generation of numbers including a combination that fits the equation, (e.g. 7, 5, 4 and 1. When the system detects that two bubbles have been burst, it releases a bubble with a question-mark icon, filled with a perfume if the burst bubbles were correct (e.g. 5 and 4), or a rotten eggs odour if incorrect.

SensaBubble Keep-Em-Up

SensaBubble Keep-Em-Up is a game whereby players try to keep bubbles in the air and within a play area as long possible by wafting their hands. The number of seconds is displayed on the bubbles. More bubbles are released as time passes. Different bubbles can have different scores associated with them, displayed as an icon on each bubble.

CONCLUSION

The paper introduced SensaBubble, a *chrono-sensory* mid-air display system that uses visual and olfactory stimuli to deliver information. A scented fog-filled bubble allows for the containment of a smell until the bubble bursts. The applications discussed in this paper demonstrate the diverse opportunities that SensaBubble offers as an interaction technology. We believe that SensaBubble encourages a new way of thinking about multi-sensory technologies. The aesthetics of a bubble-based system allows a rich design space for user interaction in terms of ambience, ephemerality, tangibility and multi-sensory experiences.

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