Mulsemedia DIY: A Survey of Devices and a Tutorial for Building your own Mulsemedia Environment

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Multisensory experiences have been increasingly applied in Human-Computer Interaction (HCI). In recent years, it is commonplace to notice the development of haptic, olfactory, and even gustatory displays to create more immersive experiences. Companies are proposing new additions to the multisensory world and are unveiling new products that promise to offer amazing experiences exploiting mulsemedia - multiple sensorial media - where users can perceive odors, tastes, and the sensation of wind blowing against their face. Whilst researchers, practitioners and users alike are faced with a wide-range of such new devices, relatively little work has been undertaken to summarize efforts and initiatives in this area. The current paper addresses this shortcoming in two ways - firstly, by presenting a survey of devices targeting senses beyond that of sight and hearing; secondly, by describing an approach to guide newcomers and experienced practitioners alike to build their own mulsemedia environment, both in a desktop setting and in an immersive 360° environment.

CCS Concepts: • **General and reference → Surveys and overviews**; • **Human-centered computing → Interaction devices**; • **Hardware**;

Additional Key Words and Phrases: Mulsemedia, multisensory devices, displays, mulsemedia systems, DIY

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1 INTRODUCTION

Multisensory interaction has been enjoying a growing attention from a variety of disciplines recently. The focus has been on different neuroscientific aspects related to the perceptual channels, on the interactions between them as well as on the factors that influence multisensory integration itself. Among the benefits of multisensory experiences are, for instance, learning and reaction time improvement [10, 96]. However, it is not always clear how to integrate these findings from crossmodal perception with Virtual Reality (VR) or multimedia, where rendering of different inputs has been usually organized separately.

Nowadays, multisensory VR and multimedia promise to become game-changers by rendering a convincing world where users could teleport by engaging all their senses. The design of these systems is focused on optimizing the perceptual dimensions of space and time through the contributions of all the sensory modalities under the realm of mulsemedia - multiple sensorial media [31]. However, in order to achieve the knowledge of how to design an effective mulsemedia system, an

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important amount of research still needs to be carried out, especially for senses that have been usually neglected (e.g. olfaction).

The latter growth in software and hardware technology, especially wearables, has provided mulsemedia researchers with a conceivable spectrum of options. Innovation is getting boundless, wearables are permanently evolving to increasingly complex functions and numerous kickstarter ventures are undertaking projects in various ways to stimulate all the human senses. All these new initiatives are attempting to entice audiences into finally reach market acceptance. Unfortunately, the unprecedented speed of the current development of new technologies determine publications that analyze the current state of technological advancement to become rapidly out of date.

If we take a look at the market evolution for different types of displays, we find that visual displays remain dominant, while the amount of olfactory devices is insignificant [116]. This justifies why alternative sensory interaction modalities have not been sufficiently researched and their influence on the human behavior not yet understood. Many of the commercial initiatives that aimed to engage non-traditional senses failed (e.g. iSmell, Sixense). There have been many research efforts put into compensating this lack of devices by proposing different delivery technologies and systems [13, 52, 56, 102]. Unfortunately, third parties cannot reproduce such work since it is not reported in enough detail. The fact that multisensory displays do not have the same availability as their audiovisual counterparts acts like a barrier for researchers without significant engineering skills who want to understand how different senses can be used in designing interactions.

Our goal is to encourage researchers interested in investigating the effects of multisensory modalities by presenting a set of solutions available now on the market and in the research area. Our focus is on displays developed over the past 5 years that allow us to engage multiple senses either by connecting mono-sensory or bi-sensory devices, or through the multisensory functionality some of them incorporate. We discarded from our survey devices that are not currently available on the market and we present the ones we found relevant through their potential or previous use in multisensory research. Accordingly, Section 2 introduces mulsemedia techonologies. Then, Section 3 presents haptics displays. Section 4 brings displays for olfaction and taste. Section 5 describes an approach for building a seamless mulsemedia solution that decouples mulsemedia application from the respective renderer. We also present the blueprint and prototype of the approach for assembling both regular and 360° VR mulsemedia systems. Section 6 finally ends the article and leads to future works.

2 MULTISENSORY TECHNOLOGIES

Multisensory environments can be deployed by using devices that stimulate various senses at the same time. To this end, a variety of technological elements can be used to construct a multisensory environment [86]. Depending on the senses we want to stimulate and engage, we can choose from different combinations of technologies:

- Haptic devices (force, tactile, vibrotactile feedback), e.g. haptic mice, haptic seats;
- Gustatory devices, although still rare;
- Olfactory devices (desktop and wearable setups);
- Custom built devices (employ different combinations of senses).

These components are mostly used in academic settings, although, recently, the entertainment industry started to be interested in building multisensory environments too. In this paper, we are mainly interested in devices that can be easily integrated by anyone in building digital multisensory systems. Thus, we focus on commercial displays because of their wide availability, but also on research prototypes that either are open-source or provide a high level of detail about their implementation. We think that these prototypes are important to understand the trends and to provide a starting point when thinking about developing multisensory systems.

Additionally, multisensory environments can be deployed by using devices that stimulate multiple senses at the same time. Companies are proposing new additions to the multisensory world and unveil new products that promise to offer amazing experiences, where users can feel odors and the sensation of wind blowing against their face. A good starting point is that of the off-the-shelf alternative of the system described in [51], Feelreal VR[1], which is a VR mask that aims to offer a different level of immersion. It can be attached either wired or wirelessly as a head mounted device (HMD) and provides olfactory content through seven diverse fragrances. Feelreal is equipped with an ultrasonic ionizing system to create water fog, whereas cold and heat can be directed onto the user's head. A Feelreal Software Development Kit (SDK) offers developers many options to add different senses to their applications, while the Feelreal Player has an intuitive GUI that allows users to customize movies. Another multisensory environment is presented by Ranasinghe et al. [81] who integrated a wearable VR system composed of olfactory and haptic (thermal and wind) devices to an HMD in order to stimulate other senses beyond sight and hearing. However, these are but isolated instances of multisensory displays. Most displays target just one of the additional senses beyond vision and audition. Therefore, technologies relating to haptics and chemical senses, and a multisensory development ecosystem are presented in the next sections.

3 HAPTIC DISPLAYS

Haptic technology refers to everything a user touches or is touched by to control or interact with an entity controlled by a computer. Some of these interfaces are energetically passive (a button, a keyboard), whilst some are energetically active (force feedback devices, vibrotactile vests). The techniques, and the key challenges characteristic to this medium are discussed in detail in [20] - a comprehensive survey that presents technologies and examples for enhancing audiovisual content with haptics.

3.1 Commercial haptic devices

3.1.1 Wearable. Force feedback gears (that consist typically of vibrotactile actuators embedded into clothes) and suits already have an established business within the area of wearables haptic displays. In the 90s, Auralizer created a system whereby audio waves were converted into vibrations. Likewise, haptic gears such as those presented by Shah et al. [94] and Prasad et al. [77] have been applied in HCI to provide feedback of impact and serve as aid for motorcyclists. This kind of gear was also used as a guide so that robots can steer humans in cooperative works [92]. A vibrotactile vest produced by KOR-FX[2] fits in this category and uses a simplistic approach to transform audio signals into haptic feedback. The audio signal coming from games or media is processed and converted with special transducers into pinpointed high-definition vibrotactile feedback that allow users to feel the on-screen action. Subpac 101[3] is another haptic vest conceptually akin to KOR-FX as mechanism and price. An extra version whereby the equipment can "wear" an existent seat is also ready for use. ARAIG (As Real As It Gets)[4] produces feedback on numerous degrees by incorporating speakers in a collar to create a surrounding effect around the user. Moreover, the user's experience is intensified with vibration and audio feedback, and electrical stimulation by flexing particular muscles and reproducing sensations of touch. The Tesla suit[5] is a full body neoprene suit with

[1] Feelreal VR available at http://feelreal.com
[2] KOR-FX available at http://www.korfx.com
[3] Subpac 101 available at https://subpac.com/subpac-101/
[4] ARAIG available at https://araig.com
[5] Tesla suit available at https://teslasuit.io

"conductive threads that tricks the senses using neuromuscular electrical stimulation." The Tesla suit promises to create "a range of tactile sensations" including vibrations and thermal ones. To do this end, it has several actuators spread through the body to provide comprehensive haptic feedback. Dexmo[6] is an exoskeleton glove for VR developed by [32]. Apart from capturing motion, this product also offers force feedback.

3.1.2 Handheld devices. Vibrotactile mice and joysticks are often used as portable devices through which users experience haptic feedback. One of the first haptic mice to be developed and explored in virtual environments was that of the EU MUVII (Multi User Virtual Interactive Interface) project[7]. The gaming industry is constantly using vibrotactile technology to enhance immersion in video games with examples like the Rival 600 from Steel Series[8] or the Joy-Con from Nintendo[9], which contains an advanced haptic feedback mechanism called "HD Rumble." The controller is composed of actuators that provides users with the feelings of touching objects.

Another proponent, Windy Sight Surfers [79], is "an interactive mobile application for the capture, visualization and navigation of 360° immersive videos." It has a wind accessory composed of two fans attached to a tablet, which presents 360° content. Despite being a prototype, the authors showed that this system can elevate immersion and presence.

3.1.3 Desktop devices. When it comes to desktop setups, displays like Novint Falcon, Phantom Omni or Ultrahaptics are the most popular and easiest to integrate in diverse systems. Novint Falcon was often used in research with different applications: to enhance educational videos [45] or to touch images in the video [9], whilst Phantom Omni was employed to enable users to feel the acceleration associated with videos [19]. Ultrahaptics is another commercial haptic display that employs "focused ultrasound to project discrete points of haptic feedback on user's hands" [8]. This has been successfully integrated with HoloLens in designing mixed reality human-computer experiences, as described in [43]. Ultrahaptics showed promising results in respect of mid-air interactions in cars, decreasing the eyes of the road time, whilst not compromising the driving performance [95].

Wind displays are a particular case of haptic devices in which the sensorial effect is obtained by generating airflow which brushes against human skin. The work of Moon and Kim [54] brought early attempt to create surrounding wind in the user's environment. Following this approach, VirWind[10] tries to create a 3D effect in the environment blowing air from four vertical pole composed of four fans each one.

3.1.4 Haptic chairs. Feel Three[11] consists of a 3DOF motion simulator. It was first created by Kumagai [47] and then evolved to its current state. A half-sphere platform composed of a set of motors and omni directional wheels is responsible for producing motion effects including pitch, roll and yaw.

Roto VR[12] is a platform-based interface that promises to transform the traditional seated VR set-up into a totally immersive endlessly revolving experience - complete with motorized turns, no tangling cables, and a double rumble effect. To some degree, it takes after the conception of Haptic ChairIO [27] including a seat. The Roto VR is designed to make VR experiences even more immersive whilst reducing the effects of simulator sickness. Turning your head will activate the

[6]Dexmo available at https://www.dextarobotics.com/en-us
[7]MUVII project available at https://cordis.europa.eu/project/rcn/57839/factsheet/en
[8]Rival 600 available at https://steelseries.com/gaming-mice/rival-600
[9]Joy-Con available at https://www.nintendo.com/switch/features/
[10]VirWind available at https://www.vrfocus.com/tag/virwind/
[11]Feel Three available at http://www.feelthree.com
[12]Roto VR available at https://www.rotovr.com

motors in the base, while controls located at the players' feet enable movement. Table 1 summarizes the works related to haptic display technologies reviewed from 2013 onwards and concisely provides their main characteristics.

Table 1. Summary of haptic displays.

Device	Description	Haptic effect	Actuators	Software considerations
Kor-FX	Haptic vest - transforming audio signals into haptic feedback	Vibration	Chest actuators	Unavailable SDK but provides a setup guide
Subpac 101	Haptic vest - transmits low frequencies to the body	Vibration	Receptors on skin	Unavailable SDK (Audio input)
ARAIG	Haptic vest - audio, and electrical stimulation of muscles	Contraction	Actuators on torso and shoulder muscles	Unavailable SDK
Tesla Suit	Full body suit haptic feedback system - transcutaneous electrical nerve stimulation and electrical muscle stimulation	Touch and Contraction	Full body actuators except head, hands, and feet	API/SDK, haptic library, and software for creating effects
Rival 600	Gaming mouse	Vibration	Mouse	Engine available
Joy-Con	Gaming mouse	Vibration with fine tactile feedback	Mouse	Haptic engine only compatible with Nintendo Switch
Windy SS	Two fans attached to a tablet	Wind	Airflow	Unavailable SDK
Novint Falcon	Haptic gaming controller	Force feedback	On device actuators	Open source driver library
Phantom Omni	Portable haptic device with 6 Degrees of Freedom	Tactile and force feedback	On device actuators	OpenHaptics SDK compatibility
Ultrahaptics	Ultra-sound based haptic technology	Tactile effects	On device actuators	TOUCH Development Kit
Dexmo	Wearable kinesthetic device	Force to resist grasping motions	On device actuators	Dexterity Engine SDK
Feel three	Motion sphere/chair - pitches, rolls and yaws	Vibration and Motion	Tactile transducers and omniwheels on the chair	Ways to control: individual game support, native support in engines like Unity and Unreal, native support through OpenXR initiative and headset manufacturers, and API
Roto VR	Haptic chair with reverberating system	Vibration	Reverberating shakers attached to the chair	Libraries available
ChairIO	Haptic chair with wind and floor vibration	Vibration and Airflow	Raised floor for vibration and Pan-tilt fan units	Unavailable SDK
Haplet	Haptic device with 1 Degree of Freedom for DIY	Vibration	On device actuators	Open source driver library
VirWind	Four 1.8 meter towers with fans	Wind	Airflow	Unavailable SDK

3.2 DIY haptics

Building haptic interfaces has caught the interest of DIY enthusiasts over the past couple of decades especially in order to overcome costly proprietary haptic feedback platforms. Indeed, there are many projects of passionate practitioners that give a step-by-step DIY (Do It Yourself) guide to build vibrotactile displays, haptic gloves or chairs and are available on platforms like Instructables[13].Newcomers to haptic interfaces can benefit from two tutorials [34, 50], which present a detailed road map to guide readers through the physical principles, hardware limitations and stability issues of building haptic interfaces.

Another endeavour worth mentioning here is Haplet, which is "an open-source, portable and affordable haptic device with collocated visual, force and tactile feedback" [28]. This device is based on Hapkit and Haptic Paddle, which present a system for creating haptic effects from 1 degree of freedom device [55]. It allows users to combine their devices with haptic feedback effects. The authors state that "this design can replicate the natural way in which we use our hands to interact with the physical world."

Other devices go beyond vibrotactile notification and render a variety of haptic effects: touch contact, pressure, texture and shapes. In [111], the authors propose a hand-held virtual reality controller that renders fingertip haptics. This consists of an interchangeable wheel that moves in relation to its position in the virtual environment. In [6], the authors present NormalTouch and TextureTouch - two controllers that use different actuation methods to render haptic 3D shape. However, these present limitations in rendering angles, forces and heights. Tactile effects were obtained also via finger-mounted haptic feedback devices. They convey cutaneous force information by deforming the skin on the fingertips [93].

Pseudo-haptic effects can also be used to enhance tactile touch screen interactions. In [16], the authors present Touchy - an interaction metaphor that consists of a symbolic cursor for evoking haptic properties. Changes in its shape and motion might help to convey information on hardness, friction, or the degree of roughness.

4 THE CHEMICAL SENSES: GUSTATORY AND OLFACTORY DISPLAYS

In comparison to vision, audition and even haptics, chemical senses have not been fully explored and there is no clear information yet on how they can be effectively used in human-computer interfaces. A comprehensive review that analyzes the pitfalls and possibilities of digitizing chemical senses can be found in [72]. The authors present key problems with the delivery of digital fragrance and taste and comes up with questions that would be interesting to investigate by the HCI community. Hereby, we acknowledge those issues, while offering insights and solutions into how to build a multisensory environment.

4.1 Gustatory displays

Authentic tasting experiences can be created once we activate the sense of taste, retronasal olfaction, and trigeminal nerve [97]. However, this is very challenging because it implies stimulating all the senses in the right way, with an intensity that feels natural.

Tastes and flavors are complex because most of them cannot yet be generated by stimulating the human palate directly on the tongue, which is able to detect at least the controversial five basic tastes (sweet, sour, bitter, salty, and umami). Other things that surround the tasting experience (e.g. the roasted, the fruity) are related to smell. Sensations of heat (e.g. hot pepper), cold (cool associated with mint), and several food properties such as crunchiness and creaminess, are detected by the trigeminal sense [99].

[13]Instructables available at https://www.instructables.com/

Stimulating and modifying the taste in a digital setup was shown to bring interesting insights in a variety of applications. Cognitive activities and the acting of making decisions are influenced by taste. Obrist et al. [70], for instance, have shown that the five basic tastes have different temporal characteristics. The authors emphasized the importance of understanding the underlying mechanisms of the taste experience because it allows designers and developers to have a common vocabulary when it comes to designing systems. When experiencing sour taste, people tend to proceed based on reason or logic and their actions go slower whilst sweet and bitter tastes lead to instinctual and quicker actions when making decisions. In [106], the authors showed that the sour taste has the potential to promote a riskier behavior.

In terms of devices and systems that stimulate the taste and could be included in multisensory systems, some deal with direct stimulation of this sense and some modify people's experience of taste by stimulating other senses like vision and olfaction. Both approaches shall now be explored in more detail.

4.1.1 Direct stimulation of taste and flavor. As described in [7, 75], basic tastes have been delivered by actuating on the tongue in order to stimulate people's palate. Recently, progress in this area has been achieved with studies like [56, 80]. Lollio [56] has been proposed as a novel interaction method within a game and was built to interact with the user's tongue by pumping specific tastes from a portable and small box to the tip of a lollipop. Its development is described in detail, allowing for replication. One of its limitations is that it delivers taste sensations only on a sweet-sour interval. Digital Lollipop is another experimental instrument that digitally simulates tastes by electrical stimulation of the taste-buds, described in detail by its authors [80].

More complex than Lollio, Digital Lollipop reports taste sensations additional to sweetness and sourness, such as saltiness and bitterness and also proposes a way to control the intensity of sourness. The authors tested their solution in experimental tests, whereby they made significant observations: the interface was uncomfortable over certain values of the current intensity, it was challenging to align the device on the user's tongue, and the subjective opinions provided by participants highlighted that some users were not able to recognize certain taste sensations. Participants' feedback indicated portability and its enhancement with smell emissions were directions in which the device could be improved.

A gustatory device created by Karunanayaka et al. [40] called "The Thermal Taste Machine" produces the effect of tastes by varying the temperature, in bouts, on the user's tongue. The authors reveal that creating and altering the feeling of tastes for "sweet, chemical, minty, fatty, pleasantness, heating, and cooling" had favorable outcomes. Although the design and development process are presented in detail, building these types of interfaces requires a high expertise in the field.

In a related work, Vi et al. [105] devised TastyFloats, a machine where small pieces of food are levitated acoustically and delivered on the user's tongue. As the authors recognize, this system has many issues to be solved before it appears as a steady product, mainly related to speed and quantity. Moreover, the user's environment conditions, temperature, and characteristics of the food also need be taken into account.

We conclude by remarking that, to the best of our knowledge, there are no commercial options for taste displays that could be easily integrated in any application.

4.1.2 Pseudo-taste, taste and flavor via other senses. Considering all the limitations of the digital stimulation of taste, another approach to it relies on changing food experiences from the interaction mainly with predominant senses [65].

Vision was exploited in this fashion, with promising results. In [69], the authors offer an Augmented reality (AR) system that "modifies the appearance of the food and plate with a projection-camera system." Results showed that sweetness was increased with the increase of the chroma and that altering food's semblance through their proposal changes the five basic tastes.

Another effort in this domain is that of Narumi et al., who propose Meta cookie [66, 67], a pseudo-gustatory display capable of modifying that taste that users feel by overlying "visual and olfactory information onto a real cookie with an AR marker pattern." Results showed that 79% of the 43 subjects felt an alteration in the taste. This taste manipulation using olfactory and visual information was also exploited in [104], where the author looks into eliciting eating behavioral changes by the stimulation of various senses.

Vocktail [82] combines direct stimulation of taste with taste enhancement via other senses. In Vocktail, flavors are created by mixing: taste (resulting from the electrical stimulation of the tongue), smell (scent emitted by micro air-pumps) and vision (RGB lights projected on the real beverage).

Although there is significant achievement in the area, the complex nature of the sense of taste has made gustatory research even more challenging compared to other modalities. In fact, we would argue that many of the gustatory devices are working as conference demos, rather than as a market product.

Basically, the literature provides precious few information in terms of the sensation and display of trigeminal effects. However, according to the review in [97], if one wants to deliver trigeminal effects then one also needs to stimulate the trigeminal sense. In this case, gustatory devices may serve as trigeminal display devices as well. An example could be the ChewingJockey [46] in which the chewing experience during eating can be used to magnify the sound thereby the food texture. Accordingly, Spence et al. [98] state that sight is more effective in terms of foraging than other senses, thus, it can not be neglected when it comes to gustatory devices.

A summary of available DIY gustatory displays for the past five years is shown in Table 2. As most of them are DIY devices encountered in the literature, little information related to the availability of their software is provided.

Table 2. Available DIY gustatory displays.

Device	Description	Flavor effect	Actuators
Lollio	Gustatory interface in a form of a lollipop	Sour and sweet	An outlet that pumps flavors to the lollipop
Digital Lollipop/Vocktail	Electrical gustatory interface in a form of a lollipop	Sour, salty, bitter, and sweet	Eletrodes - electricity on the tongue
Thermal Taste	Thermal actuator installed on the tongue to generate taste sensations	Sweet, fat/oil, electric taste, warm, and reduced the sensibility for metallic taste	Liquid cooler pump with peltier elements
TastyFloats	Machine to hover food particles and deliver to the users' mouth	Sweet, bitter, and umami	Static levitator with ultrasonic transducers and motor drivers

4.2 Olfactory displays

When it comes to digitizing chemical senses, the delivery of ambient scent is the simplest to integrate in any system, thus, the most common application. A series of challenges related to the integration of olfaction in multimedia applications is presented in [30]. To date, digitally-controlled scent displays have been used in a variety of applications: for enhancing the Quality of

Experience (QoE) in multimedia and mulsemedia applications [2, 61, 119, 120], for augmenting the immersion in entertainment/training virtual reality applications [36, 37], for studying its potential in e-learning [1], for studying the connection between smells and autobiographical memories [14] or for analyzing what moods or emotions are triggered by smells [83, 91], or indeed whether olfactory congruence matters in mulsemedia [29]. Obrist et al. [71] researched the effect of ten different classes of olfactory experiences (e.g. mental connections with aromas; smell allowing identification and detection) for smell-enhanced technology. This lead to the identification of interesting opportunities that could be a point of departure towards smell interactions in HCI: (1) smell-enhanced performance regulator; (2) autonomous smell agent; (3) reminder alert with smell; (4) smell-enhanced story telling.

So, how was olfactory stimulation achieved in all these applications? Mostly using "analogue" methods from fragranced shampoos [76], cylindric felt-tip pens [74], ambient odors [103], odorant stimuli provided by Firmenich [22], as well as smelling jars [17, 23].

Odor materials are generally stocked in liquid or solid structure - in the case of the latter, mostly wet with liquid. To deliver the scents, these stored materials need to be conveyed to the user's nose through the air. According to Yanagida [114], computer-controlled olfactory displays achieve this in several ways: "natural vaporization, vaporization accelerated by air flow, heating or atomization."

We argue that research in many scent-related areas (especially related to HCI) was not performed at its full potential because of the lack of "off-the-shelf computer controlled scent delivery devices" [53]. Despite the potential of smell in HCI, over the past quarter of a century, olfaction interaction enterprises failed to achieve their goals. Inspired by Heilig's Sensorama, Smell-O-Vision tried to bring odors in the cinema, however it did not turn out to be successful because audiences preferred a traditional movie experience. DigiScents and its product, iSmell elicited twenty million dollars in venture-capital investment in order to devise a hitherto unleashed product. The idea behind this USB-connected scent synthesizer was based on a database of smells which would collect odors. The device connected to a PC would release some smell from certain websites and electronic mails. Despite being heralded as the beginning of a new "Web revolution," the company did not manage to get the interest of the public and had gone of the business by 2001. Joining the list of products that ceased to exist soon after their release are: AromaJet[14] - used an inkjet technology to transmit smells; Osmooze[15] - was linked up with email programs allowing users to assign a scent notification to specific contacts, Scent Dome - an olfactory peripheral device with potential in learning and gaming.

Vortex Activ USB, another olfactory display that recently disappeared from the market, consisted of four cartridges exposed to four individually controlled fans that were blowing the scent towards the user [1]. A device which operates employing similar principles to that of the Vortex Active USB is Exhalia's SBi4 [59], which will be described in section 4.2.2. One of the drawbacks of systems like the Vortex Activ USB is that because the units are open, scent is continuously released while the CPU fans provide a limited control over the scent direction [53].

Scentee Balloon[16] provided an alternative to this limitation by using sound waves in order to deliver the scents quickly and directed. The Scentee app controls the device and allows the user to manipulate the duration and the strength of the smell. Its drawback was that only one cartridge can be used at a time and that users need to hold the device close to their nose in order to perceive the smell. In [24], the authors use the Scentee Balloon in a recent exploratory study aimed to "guide the design of in-car olfactory interfaces by comparing different olfactory devices based on distance,

[14] AromaJet available at http://www.microfab.com/vapor-generation/aromajet
[15] Osmooze available at http://www.osmooze.com/
[16] Scentee available at https://scentee.com/

volume and speed of scent delivery." However, despite certain advantages, the Scentee Baloon has been discontinued.

Surprisingly, the difficulty signaled by Kaye in [41] remains prevailing, more than one decade later: most commercial off-the-shelf computer controlled olfactory devices never reached the market or if they did, they have not lasted long. Although there are exceptions to this observation (such as Exhalia's SBi4 device, which is still being commercially produced), convincing users that digital olfaction is desirable is only one of the stumbling blocks. Problems in respect of inauthentic odors or unnatural experiences also play an important role, together with the general lack of knowledge about how to use and which kinds of scents are adequate for use in mulsemedia.

Although most commercial attempts to create smell devices have not been successful to date, research laboratories have continuously explored the potential of this area. In [113], the authors presented a wearable olfactory device for olfactory stimuli according to the position of the person. Based on spatial localization sensors, this device was used to create an odor field in a virtual reality space. Another interesting system was proposed by Yanagida et al. [115]. This olfactory display consists of "a nose tracker and a scent projector scent projector composed of an air cannon, a scent generator, and a 2 degrees-of-freedom platform that is controlled so that the air cannon aims just under the user's nose." In [64], the authors addressed the limitation of the gas-based scents in olfactory displays by developing an apparatus that deals with liquid odor. They built a system capable of real time scent blending and, based on it, they developed a cooking game to evaluate any change in presence experienced by the participants. In [52], a new type of olfactory system was introduced. In this case, the scent was distributed to the user through four ventilators that were fixed on the corners of the screen. This showed potential for further development of novel interactive multimedia systems, but has as main drawback the fact that it cannot generate multiple scents simultaneously. Although the authors provide significant proof of work for all the above devices, the development steps are not described in detail to allow for replication by other researchers.

4.2.1 DIY low cost olfactory devices. It is remarkable that a number of papers have been written to propose reproducible olfactory systems, thus benefiting a larger part of the research community. Addressing the limitations of olfactory research in immersive virtual environments, Herrera and colleagues presented an effective and affordable desktop olfactory display that relies on vapor to deliver smell effects [35, 36]. The authors used affordable components (the device is estimated to cost 55$) and provide detailed information about the design process and the software used to control the olfactory device, that could easily be replicated by other researchers.

Hajukone is another open source low cost olfactory design, this time in a wearable format [53]. It was built as an alternative to research devices that are not presented in full detail to allow reproduction. Thus, it makes use of electronic elements that are fairly easy to find in the market. As opposed to the device described in [35, 36], Hajukone supports multiple scents that are emitted through ultrasonic transducers. InScent [25] is a "miniaturized open source wearable olfactory display that allows users to receive personal scent notifications." Similar to Hajukone, it allows replicability through 3D printing. At only 102g, inScent has 8 cartridges, each of them containing scents to deliver over 70 "scentifications." Amores and Maes [3] describe the development of a prototype that users can wear called "Essence". The aim was to create an attractive and light olfactory device for applications that can deliver different strengths of smell related to the user's bio data. This work is further expanded to "Bioessence", a device that can be attached to the user's clothes in a form of clip or necklace [4]. It can release the limit of three scents and passively captures vibrations representing the beating of the heart and the respiration through clothes.

Salminen et al. [89] present an "olfactory display prototype for emitting and sensing odors." They used an intersurgical mask attached to a VR headset that covers part of the user's face. It was then connected to a vent hole that comes from an aromatized container or a device receive scents.

Hasegawa et al. [33] depict a system to control the spacial distribution of aromas through an ultrasound-driven approach, guiding a vaporized scent to the user's nostrils. This technique could be useful not only in this particular case, but also for removing remaining odors while presenting multiple olfactory experiences sequentially.

4.2.2 Commercial computer-controlled scent emission devices. When trying to build a multisensory system, researchers also have the possibility to employ a commercial solution for olfaction display. Although most of the commercial devices disappeared soon after their release, there are still some available that were the subjects of different experiments described in research papers.

SBi4[17] from Exhalia is one of these commercial devices, which uses airflow to vaporize and delivers (by default) one of four fragrances at the time. In [59], the authors stated that SBi4 is "more reliable and more robust than the other devices on the market" and the scents are more realistic. However, there are some considerations which researchers need to keep in mind when working with this olfactory display:

- Its cartridges are made from scented polymer balls, which allow the scent to linger less than other types of cartridges (e.g. Dale Air Vortex[18] employs fragrances based on alcohol drenched onto cotton cushions). As documented in [62], due to natural vaporisation, odors from SBi4 cartridges can be detected in advance of any fans running. Thus, the authors' recommendation is to let two days pass after the opening of a cartridge before using it in experiments.
- SBi4 can be connected to a USB port and allows the creation of Java code to manipulate the device's activation. However, this allows the control of a single fan.

SBi4 was used in numerous studies that investigated the QoE in desktop systems enhanced with olfactory content [59, 61, 63, 121].

Another option from Exhalia is uScent[19] collection that delivers odors in rooms of different size (depending on the model). These devices work with one cartridge and they be programmed remotely using the platform[20] provided by the developers.

An ultrasonic USB essential oil diffuser called "The Keylia"[21] is offered by Aroflora. As its name suggests, this device diffuses essential oil, operates at intervals of 10, 30 or 60 seconds, and starts emitting the aroma as soon as it is connected to the USB port of any kind of machine supporting USB.

Olorama[22] is another technology that could offer researchers new ways of integrating the sense of smell into their projects. This solution combines hardware, software and essential oils in the synchronization of audiovisual scenes with scents. The wireless olfactory display fits both a small room or a big cinema and uses airflow to vaporise only one odorant cartridge at a time. Developers promise a simple and quick integration and provide Unity and Unreal code as example.

A summary of DIY and commercially available olfactory displays for the past five years is provided in Table 3. Despite media excitement, most of the olfactory displays launched thus far are proof-of-principle prototypes. Although it seems hard to convince users that digital olfaction is

[17]Exhalia SBi4 http://www.exhalia.com/fr/
[18]DaleAir available at http://www.daleair.com/dispensing/
[19]uScent available at http://www.exhalia.com/us/produits/espaces-olfactifs/uScent/
[20]i-Scent available at http://i-scent.fr/login
[21]The Keylia available at https://bit.ly/2SmjG1o
[22]Olorama available at http://www.olorama.com/en/

desirable, a potential explanation behind the restricted prosperity of this technology is the lack of correlation between hardware and software developers and interaction experts. The work put in developing these devices is often not detailed, thus it cannot be reproduced by third parties. Whilst the dialogue between these stakeholders will undoubtedly intensify when a mulsemedia killer app

Table 3. Summary of DIY and commercially available olfactory displays.

Device	Scent characteristics (e.g. type, number, delivery)	Availability	Software considerations	Remarks	Wearable
DIY - low cost devices					
Hajukone [53]	• Six cartridges • Any liquid scents • Ultrasonic vaporization	Open source affordable device (low technical skills)	• Proprietary API • PC and wireless (iPhone, Android)	+ No release of scent through evaporation	Yes
inScent [25]	• Eight cartridges • High viscosity liquid scents • Vaporization by heating	Open-source affordable device	• InScent framework (Android background) • Remote control via Google Cloud Messaging	+ Small and lightweight	Yes
Essence [3]	• One cartridge • Liquid scent	Summary description of the design process	Proprietary API	+ Lightweight, fashionable	Yes
Bioessence [4]	• Three cartridges • Liquid scents • Ultrasonic atomizer	Detailed description of the design process	The accelerometer sends data to a smartphone application (Android) via BLE; the information is sent to the cloud-based Global Vitals API which returns heart and breathing rate measurements; the application uses the physiological information and the user input to release scent accordingly	+ Delivers up to three scents + Self-contained solution for physiological sensing	Yes
Reproducible olfactory display [36]	• One cartridge • Liquid odorant • Airflow vaporization	Detailed description of the design process and odorants selection	API SDK software to control the duration of scent emission	+ Simple	No
Midair Ultrasound Fragrance Rendering [33]	• User tracking sensor • Sponge pad and a diffusing fan • Airflow vaporization	Detailed description of the design process	Not available	+ If the emitted gas velocity is greater than the air flow, it does not work properly	No
Commercial Devices					
Olorama	• Ten to twelve cartridges • Liquid odorant • Airflow vaporization	Commercially available off-the-shelf	Provides wireless control & integration is performed with Unity and Unreal code	+ Wall mountable	No
Exhalia SBi4	• Four cartridges • Solid odorant • Airflow vaporization	Commercially available off-the-shelf	• Graphical interface available • SDK provided for various programming languages and platforms	+ USB operated and powered desktop device	No
uScent	• Collection of devices that promises to fit rooms of different size. • Each of these devices work with one cartridge	Commercially available off-the-shelf	It can be programmed remotely using the i-scent platform	+ Various size (uScent 85, uScent 50, and uScent 25)	No

is found [31], this does not preclude undertakings in these areas, one of which is that of building a mulsemedia environment, which we detail next.

5 BUILDING A MULSEMEDIA ENVIRONMENT

Constructing a mulsemedia environment is not only about choosing powerful and compelling sensory effects devices and plugging them in. Firstly, most multimedia applications do not support mulsemedia devices natively. Secondly, although some devices use some sort of connectivity and communication standard, it is nonetheless not straightforward, as multimedia applications do not know how to handle them. Finally, there is still a concern with issues that stem from classic multimedia - synchronization between content and sensory effects rendering, processing, masking effects, concerns when introducing a network to bind applications and devices, etc [31, 57, 87, 88]. It would be appealing to integrate the devices using IoT (Internet of Things) approaches if it was just to turn on/off the devices which is not the case with mulsemedia systems, however.

This section presents two different mulsemedia scenarios and prescribes information on how to build them from scratch. Guidelines for building and putting the devices together and weaving heterogeneous technologies to integrate applications to hardware are provided. Before advancing though, some particulars with regard to software and hardware are discussed and solutions are suggested.

5.1 The need for mulsemedia middleware

A plethora of situations, conditions, and constraints has to be considered when dealing with mulsemedia systems [18, 31, 57, 87]. When it comes to devices, heterogeneity emerges as a notorious issue. Not because of the lack of standardization in mulsemedia. One could argue that the MPEG-V standard (ISO ISO/IEC 23005-3:2016)[23] would allow interoperability at hardware level without ruining performance if the suppliers employed its binarized mode. However, they still prefer to use their own method or perhaps due to the fact that they just want to avoid paying royalties to the MPEG group. This latter option would be acceptable if there was an open standard, which is also sorely missing.

Putting aside standardization, general frameworks for IoT such as Hydra, GSN, Node-RED, among others [68], could cope with heterogeneity at the hardware level. On the other hand, these are not completely ready mulsemedia solutions. The rationale for us saying so is because: (i) they do not process Sensory Effects Metadata (SEM); (ii) they tend to work on the basis of request/response model, that is, they are reactive applications, which sometimes is detrimental to the performance required when using certain types of sensory effects depending on the applied protocol [88]; (iii) as they work on a request/response model, there will always be a delay between a multimedia application and an IoT platform, which is the response time; and (iv) they are not concerned with synchronization with other media such as AV. At the same time, they might be useful if connected to mulsemedia middleware or frameworks that take those responsibilities into account such as in [48], which is restricted to an specific video platform.

In light of this, Saleme et al. [87] discuss major technical mulsemedia challenges and give practical guidance on how to deal with hardware and software diversity when integrating mulsemedia components. The first challenge is related to the multifunctionality that mulsemedia solutions have to provide to heterogeneous multimedia applications to support them and the reusability of components of applications to work with the entire mulsemedia ecosystem. The second one has to do with reactivity and timeliness so that mulsemedia systems work as users expect in terms of responsiveness and reliability. The last challenge caters for manageability and configurability

[23]MPEG-V standard (ISO ISO/IEC 23005-3:2016) available at: https://www.iso.org/standard/65396.html

considering complex architectures composed of heterogeneous entities. The solution presented is the PlaySEM Sensory Effects Renderer (SER), the most important component of PlaySEM's platform, a detached set of software to work with multisensory applications and heterogeneous hardware [84, 85, 87, 88].

Rather than simply advising any mulsemedia middleware or framework beforehand, there is a need to understand mulsemedia software, as follows.

5.1.1 How do mulsemedia systems work? From the point of view of Waltl et al. [108], mulsemedia systems work like this: (i) there is a main AV media and its SEM which is stored in a physical media or an online service; (ii) there exists a media processing engine to deal with those resources, reading, adapting and processing them to deliver the respective sensory effects; and (iii) there are the devices in the user's environment, ready for producing multi sensory effects such as vibration chairs, wind fans, smell emitters, etc. Complementarily, Santos et al. [90] envisioned event-based mulsemedia scenarios whereby occurrences in the user's environment triggers a response. For the sake of example, when a user experiences an explosion in a game, a sequence of actions such as bright lights, feeling of heating, smell of burnt artifacts, and so on, should be delivered.

5.1.2 Which mulsemedia applications does the literature bring? SEM needs to be reproduced in the user's environment, changing metadata to real sensory effects rendered by the devices. Indeed, from the perspective of hardware abstraction, the MPEG-V standard champions that mulsemedia content can be created without knowing where it will be delivered. Authoring tools and approaches have helped towards this end [21]. This has allowed indeed the creation of a range of off-the-shelf mulsemedia systems such as in [5, 11, 44, 85, 107], whereas other envisaged scenarios [12, 100, 117] have also been thought. Cho [11] came up with Sensorama that works in timeline and event-based, although it is a static list of events that has to be manually triggered. Waltl et al. [107] created SEMP[24] which is a media player with an embedded mulsemedia engine capable of reproducing sensory effects content annotated with MPEG-V. Kim and Joo [44] devised the Sensible Media Simulator boasting a web interface based on the proprietary technology Flex from Adobe which runs within different web browsers. The first version of the PlaySEM platform, composed of a SER[25] and a Sensory Effects (SE) Video Player[26], was developed by Saleme and Santos [85]. It brought the concept of separation of concerns to mulsemedia systems, that is, different system components have varied responsibilities and can work separately so that its parts can be reused with other applications such as videos and music players, VR, games, and so on. Bartocci et al. [5] presented a similar concept of decentralization to separate concerns whereby they use a hardware controller to deliver sensory effects, but, allow the reuse of its controller with other multimedia applications. Suk et al. [100], Choi et al. [12], and Yoon [117] are all endeavors to promote architectures and conceptual frameworks for delivering sensory effects. Sulema [101] proposed a programming language for processing of multimodal data in order to allow the development of mulsemedia applications for several areas including education, health, among others. Jalal et al. [39] proposed an IoT-based architecture for mulsemedia presentation for home entertainment environment in which they used not only the PlaySEM SER [85], but also the PlaySEM SE Video Player. In [15], Comsa and colleagues introduced the concept of 360° Mulsemedia envisaging a conceptual Mulsemedia Delivery System for 5G networks, while Luque et al. [49] designed and implemented a solution that integrates sensory effects to a hybrid (internet-broadcast) television system but use their own standard to write SEM. Even though there have been many efforts when it comes to mulsemedia

[24]SEMP available at http://sourceforge.net/projects/semediaplayer
[25]PlaySEM SER available at https://github.com/estevaosaleme/PlaySEM_SERenderer
[26]PlaySEM SE Video Player available at https://github.com/estevaosaleme/PlaySEM_SEVideoPlayer

systems, most of them were built for particular aims. It means that integrating heterogeneous multimedia and mulsemedia software and hardware remains a challenge albeit there have been caveats, which are discussed next.

5.1.3 What would a seamless solution look like? Mulsemedia systems are indeed complex and deal with uncustomary requirements whilst producing, transmitting, integrating, and presenting sensory effects under multifarious constraints and conditions. Ideally, a rational mulsemedia solution should reproduce multimedia and mulsemedia content without code refactoring, connecting to heterogeneous multimedia applications and devices on the other side. A feasible solution would be decoupling multimedia applications from mulsemedia renderers - software responsible for producing sensory effects in the user's environment - thus making a bridge between virtual and real worlds. From this perspective, mulsemedia renderers ought to offer an assortment of options for heterogeneous multimedia applications to reach them. Furthermore, these renderers shall also have the ability to work with sensory effects devices from different brands taking into account their distinct protocols of communication and connectivity and proprietary commands for activating them. In this fashion, multimedia applications could keep their interest in processing AV content, which is already rather demanding, whereas new issues arisen from mulsemedia such those described in [87] like SEM processing, communication with devices, synchronization between software and hardware, delay, among others, would be dealt by mulsemedia renderers.

Given the presented circumstances, instead of reinventing the wheel, which might be time and effort demanding, we would advise either the use of the evolved PlaySEM SER [87] or the combination of a mulsemedia system to deal with mulsemedia issues and an IoT platform to cope with hardware heterogeneity. Of course, it will depend on the need and many other particulars of each situation. Therefore, works like Jalal et al. [39], which integrated heterogeneous applications and devices using the first version of PlaySEM [85] in an IoT architecture, are also plausible possibilities. In a nutshell, the reason why we support PlaySEM SER [87] is that it supports multi-communication and multi-connectivity protocols, is multi SEM standards ready, and allows the accommodation of new technology relying on its set of architectural and design patterns. To communicate with multimedia applications, it offers a communication broker that supports timeline and event-based approaches. Its configurable mode provides ways to tailor communication with different software and hardware, and compensates potential delays stemming from devices, for instance, the time elapsed when a fan starts until it hits its maximum power. The works of [38, 39, 84, 85, 87, 88] have presented results of the PlaySEM SER's flexibility, responsiveness, and adaptability to work with different variables.

5.2 The art of DIY

Focusing on devices once more, not so long ago, building your own hardware was expensive because this construction required the skills of many different workers including exterior suppliers [73]. The advent of open hardware such as Arduino, BeagleBoard, and Tinkerforge, and 3D printers has boosted the process of making your own device. However, one may ask "Why DIY if there exist off-the-shelf mulsemedia devices ready to be used?"

The so-called DIY has been broadly applied to academic research like many devices mentioned throughout this article. In a wide sense, Wolf and McQuitty [112] provide the main reasons why people opt for DIY instead of commercial products and they include "lack of product availability, lack of product quality, economic benefits, need for customization, fulfillment of craftsmanship, empowerment, community seeking, and need for uniqueness." Obviously, it has upsides and downsides. Noticeable advantages of building your own mulsemedia device are explicit in the reasons why people choose DIY such as the lack of some product, which is commonplace when it comes to research, the need for customization and the final cost. Behind the scenes, there are also the feelings of accomplishment, control, and enjoyment when doing your own stuff [112] or even being the first to do it. On the other side, drawbacks include also the cost, which can be affected by the price of raw or semi-raw materials to build the device or can require specialized materials, and the DIYer's available time. Pearce [73] includes the very early stage of open-source scientific hardware as a downside as well as the fact that commercial devices may have a longer lifespan.

The decision to build your own device will depend on the setup and obviously on the project's main goal. In fact, sometimes it is necessary to employ a pinch of hands-on, which does not mean simply to put materials together, but it is an art that requires many different skills and is indeed time-consuming. In the next section, we present scenarios where environments are built from commercial and DIY devices.

5.3 Assembling a regular mulsemedia system

Many heterogeneous mulsemedia scenarios have been elaborated and have been portrayed in Section 5.1.2. Most frequently, they present a regular mulsemedia system, which we classify as being composed of non-wearable components. Evidently, there are some exceptions in which they can be combined, producing compelling results. However, we put them aside for the time being in order to make it easy to understand how to build your own mulsemedia environment.

Figure 1 depicts a generic design blueprint as a suggestion to make a regular mulsemedia system, which can be adapted accordingly. There is a computer where a `Multimedia Application`, capable of reproducing `AV Content` and `SEM`, runs. This computer is also connected to `Speakers`, to reproduce high-quality audio, and to the internet through a `Wi-Fi Router` so as to download the content and communicate with the `Mulsemedia Renderer` (see its role in Section 5.1.3). The latter, in turn, is running on a portable computer, and will process `SEM` and deal with heterogeneous

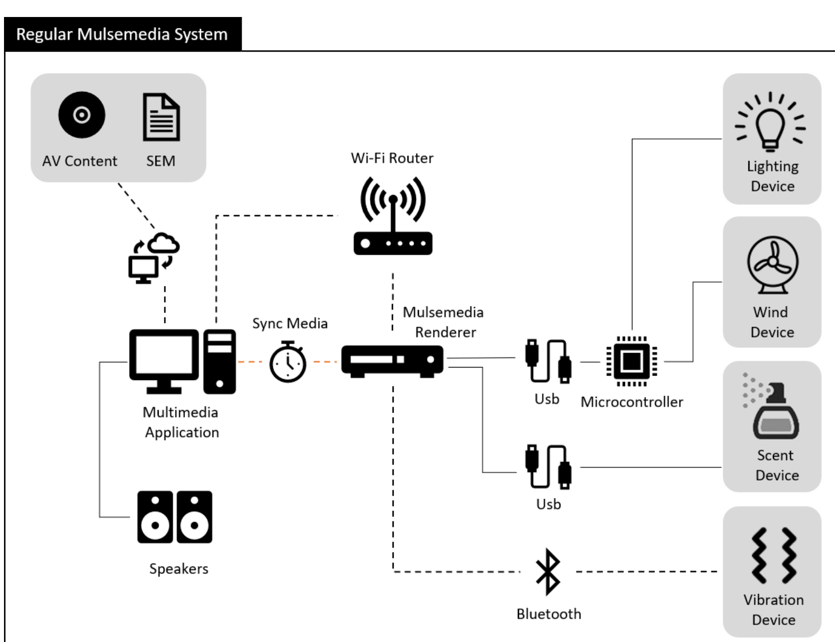

Fig. 1. Regular mulsemedia system's design blueprint suggestion.

devices to render sensory effects such as a Lighting Device, a Wind Device, a Scent Device, and a Vibration Device. The first two are connected via wire to a Microcontroller, responsible for handling the devices, which in turn, is linked to the Mulsemedia Renderer via Usb but using a traditional serial connection. The Scent Device supports connection to the Mulsemedia Renderer directly via Usb. Finally, the Vibration Device uses the Bluetooth protocol to be reached by the Mulsemedia Renderer.

The aforementioned suggestion comes together with Table 4, which presents a list of software and hardware to be placed in the scenario described and their approximate cost.

Table 4. Regular mulsemedia system's setup suggestion.

Type of component	Component	Ver.	Goal	Cost (≈)
Multimedia Application	PlaySEM SE Video Player	1.1.0	Play AV content on a screen, read SEM data, and convey it to the mulsemedia renderer.	£0.00
AV Content and SEM	Whatever video annotated with MPEG-V SEM	N/A	Provide the system with AV Content and SEM (lighting, wind, smell, and vibration effects).	£0.00
Speakers	Trust PC Gaming Speaker System with Subwoofer	GXT 38 2.1	Play high-quality audio.	£65.00
Wi-Fi Router	TP-LINK Archer C50	V3	Connect the multimedia application to the mulsemedia renderer and devices.	£35.00
Mulsemedia Renderer	PlaySEM SER	2.0.0	Receive SEM, convert it to hardware commands, synchronize media, and handle devices.	£0.00
Microcontroller	Arduino Uno	Rev3	Receive commands from the mulsemedia renderer and activate physical devices accordingly.	£10.00
Lighting Device	Addressable LED Strip	N/A	Render lighting effects in the environment using whatever individually addressable LED Strip in sync with the mulsemedia renderer.	£20.00
Wind Device	ARCTIC F12 Ultra Low Noise Cooler	120mm DC12V 0.07A	Blow airflow to create wind effects in sync with the mulsemedia renderer.	£5.00
Scent Device	Exhalia Scent Diffuser	N/A	Emit scents in the environment from cartridges in sync with the mulsemedia renderer.	£165.00
Vibration Device	Android Smartphone	6.0+	Vibrate the smartphone fastened to the user's torso or limbs in sync with the mulsemedia renderer.	£100.00

In order to produce this mulsemedia environment, the components need to be interwoven so as to form a system. First, the PlaySEM SE Video Player and the PlaySEM SER should be downloaded and installed following their *readme* instructions. There is a simulation mode in which they can be tested without using real physical devices. The former will be run on a personal computer that can be either a laptop or a desktop station. The latter is suggested to be set up on a portable device, although it will work if it is used on the former's machine. Wherever they are, they must be connected to the TP-LINK Archer C50 router.

After that, the devices should be integrated into the system. To this end, an Arduino Uno is suggested because its inputs and outputs can be easily programmed. Moreover, it is not expensive and can be connected directly to an USB port. A program to read the content received from the PlaySEM SER and to control the colors of an Addressable LED Strip, and the intensity of wind from the ARTIC F12 Ultra Low Noise Cooler must be created. The PlaySEM SER provides an open-source code to follow as an example to do so. It is worth noticing that both devices need an external power supply not to overheat and burn the microcontroller. Schematics to do this are widely found on the Internet. At this point, there may be a need to buy some electronic components such as transistors, resistors, diodes, capacitors, soldering tools, and power supplies or batteries.

Subsequently, the `Exhalia Scent Diffuser` needs to be plugged in. This process is straightforward with the `PlaySEM SER` and rules the need for an SDK out. This scent device also needs fragrances cartridges to work which can be bought directly from the company or created with oil essence and cotton. Finally, to create vibration effects, an `Android Smartphone` running a program listening to Bluetooth connections is needed. It will receive commands from the `PlaySEM SER` and promptly turn on/off the vibration function on the smartphone, spread on the user's body. Taking into account its current popularity and ease of procurement, a smartphone can play a role as an instance of vibrating. Another rationale for provisioning it stems from its ability to be integrated with the `PlaySEM SER`, as performed by Jalal et al. [39]. This choice, however, does not hinder the use of other devices listed in Table 1. A remark to finish this topic is that the `PlaySEM SER` should be set up accordingly to the chosen protocols.

5.4 Assembling a 360° VR mulsemedia system

A trendy mulsemedia environment involves 360° VR media where the user is free to explore the environment. As it happens, unwieldy devices are unbidden guests to create sensory effects. Therefore, wearable devices are especially recommended in this scenario. Owing to the fact that most wearables devices are still in their very early stage of maturity, it becomes a challenge to find and integrate suitable devices to VR headsets. Thus, DIY seems to be a feasible solution [81].

This suggested environment comprises fewer devices than the regular mulsemedia system because the lighting device is the own VR headset. However, it requires a bit more of hands-on to build your own devices. As shown in Figure 2, there is a `VR Headset` whereby a smartphone is attached running a `360° App`, capable of reproducing local `AV Content` and `SEM`. This smartphone is linked to `Headphone`, to reproduce high-quality audio, and to the internet through a `Wi-Fi Router` so as to communicate with the `Mulsemedia Renderer`. As this is a crucial system's component, it is worth recapitulating its purpose in Section 5.1.3. It runs a portable computer in the user's environment and send commands to the devices after processing the received `SEM` from the `360° App`.

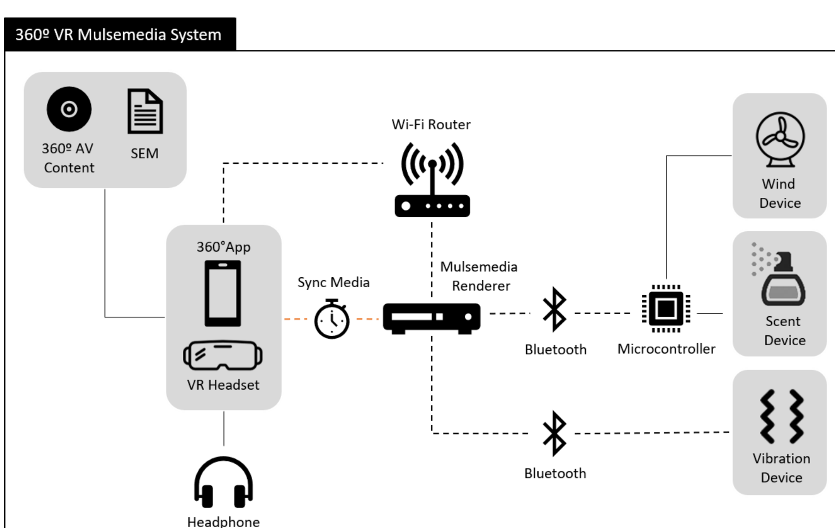

Fig. 2. 360° VR mulsemedia system's design blueprint suggestion.

A Wind Device, a Scent Device, and a Vibration Device are linked to the Mulsemedia Renderer via wireless connections. The first two are connected via wire to a Microcontroller, responsible for handling the devices, which in turn, is linked to the Mulsemedia Renderer through Bluetooth. The Vibration Device is connected to the Mulsemedia Renderer directly via Bluetooth.

The list of components required to engineer the 360° VR mulsemedia system and their current estimated price are described in Table 5.

Table 5. 360° VR mulsemedia system's setup suggestion.

Type of component	**Component**	**Ver.**	**Goal**	**Cost (≈)**
360° App	Unity3D 360° App	N/A	Play 360° AV content, read SEM data, and convey it to the mulsemedia renderer.	£0.00
VR Headset	Samsung VR Gear	2016+	Deliver 360° AV content along with the 360° App.	£70.00
360° AV Content and SEM	Whatever 360° video annotated with MPEG-V SEM	N/A	Provide the system with 360° AV Content and SEM (wind, smell, and vibration effects).	£0.00
Headphone	Logitech Gaming Headset	G231	Play high-quality audio.	£30.00
Wi-Fi Router	TP-LINK Archer C50	V3	Connect the multimedia application to the mulsemedia renderer and devices.	£35.00
Mulsemedia Renderer	PlaySEM SER	2.0.0	Receive SEM, convert it to hardware commands, synchronize media, and handle devices.	£0.00
Microcontroller	DFRobot Bluno Nano	DFR0296	Receive commands from the mulsemedia renderer and activate physical devices accordingly.	£25.00
Wind Device	Portable Fan Cooler	50mm DC5V 0.2A	Blow airflow to create wind effects in sync with the mulsemedia renderer.	£10.00
Scent Device	Mini Dupont Brushless Cooling Fan	30mm DC5V 0.2A	Emit scents direct to the user's node from mesh scent bags in sync with the mulsemedia renderer.	£7.00
Vibration Device	Android Smartphone	6.0+	Vibrate the smartphone fastened to the user's torso or limbs in sync with the mulsemedia renderer.	£100.00

To assemble this 360° VR mulsemedia environment, the initial steps are similar to the regular mulsemedia system's setup except that instead of using a multimedia application, one requires a Unity3D 360° App that runs on a smartphone that can be attached to the Samsung VR Gear. First, the PlaySEM SER should be downloaded and installed following its *readme* instructions. Next, it is necessary to create a Unity3D 360° App which will read 360° content, SEM data, and transmit the latter to the PlaySEM SER. There is a simulation mode in which the integration of both can be tested without using real physical devices. They must be connected to the TP-LINK Archer C50 router.

Thereafter, a Portable Fan Cooler device for producing wind shall be connected to the DFRobot Bluno Nano and subsequently integrated to the PlaySEM SER following the same strategy of the regular mulsemedia system's wind device. Although the use of multiple fans would allow the creation of positional wind effects, this is optional in this guideline so as not to increase the project's complexity at this point. As DFRobot Bluno Nano is compatible with Arduino, the same code written for the regular mulsemedia system can be used. The difference is that the communication between the PlaySEM SER and DFRobot Bluno Nano is established via Bluetooth Low Energy which is not supported natively by Arduino microcontrollers, unless a complementary module is attached to it. Furthermore, DFRobot Bluno Nano is more compact and therefore more appropriate to go wireless. Power supply for DFRobot Bluno Nano must be provided by a portable battery, e. g. a powerbank, so that the user can wear the device. On this matter, covers for the wind fans and the battery might be desired. A suggestion of covers can be inspired by the work of Ranasinghe et al. [81]. As well as the regular mulsemedia wind device, schematics to develop an Arduino-based 5V fan for controlling intensity through PWM (Pulse Width Modulation) are largely encountered on the Internet. At this stage, there may be a need to acquire some electronic components to succeed in doing it.

Then, the same process used to create the wind device, using `DFRobot Bluno Nano` though, can be performed to create a scent device. What differs is that it is suggested the use of a smaller fan such as the `Mini Dupont Brush-less Cooling Fan` combined with either some mesh bags filled with scent crystals provided by Exhalia or oil essence and cotton. A mesh bag with some scent needs to be placed at a short distance of the fan so that it blows the scent towards the user's nose. Moreover, it should be attached to the `Samsung VR Gear` so as to follow the user's head movement to provide a more accurate sense of scents. It would differ from the olfactory DIY displays available in Table 3 in the sense that not only the duration of scents could be programmed, but also the intensity. It should be noted that creativity is strongly required to design a cover that fits the purpose here. This process might require a cycle of creating and testing the device until a reasonable version is reached. A suggestion to annotate sensory effects in 360° VR mulsemedia environments is described in [15]. Combined with an adaptation in MPEG-V, it would allow an unprecedented viewport-aware interoperability between real and virtual world in 360° environments.

Last but not least, the process to deliver vibration effects to the user is exactly the same as that of the regular mulsemedia system and can be followed in the past section.

5.5 Assessment and QoE in mulsemedia environments

Though this work is about technical aspects of mulsemedia systems, one might also be interested in assessing QoE in mulsemedia environments. Undoubtedly, this would excite the curiosity of researchers who are concerned with understanding the perception of sensory effects by humans and the influence of human factors in these sort of systems, among other pertinent subjects. Investigating QoE involves capturing users' level of satisfaction or boredom whilst engaged in an application or service in computers. In fact, this is not all plain sailing because QoE ranges from technical aspects (e.g. devices, content format, and network) to psychosocial factors (e.g. environment, content valence, arousal, expectation, and current emotional state). QoE has been assessed by either performing subjective surveys [60, 109, 118, 119] or objective evaluations [26, 42]. Additionally, technical recommendations have been used together such as ITU-R-BT.500-13[27] (Methodology for the subjective assessment of the quality of television pictures), ITU-T-P.910[28] (Subjective video quality assessment methods for multimedia applications), ITU-T-P.913[29] (Methods for the subjective assessment of video quality, audio quality and audiovisual quality of Internet video and distribution quality television in any environment), and ISO 8589:2007[30] (Sensory analysis - general guidance for the design of test rooms).

Users' QoE assessment is undoubtedly time and effort demanding. However, there has been some guidance in the literature, notably the works of Rainer and Timmerer [78] and Murray et al. [57]. In a nutshell, Rainer and Timmerer [78] provide the following steps in order to carry out subjective evaluations:

(1) Introduction - it describes the experiment to the user including how to rate the experience;
(2) Pre-questionnaire - it is used to collect demographics;

[27] Recommendation ITU-R-BT.500-13 available at: https://www.itu.int/rec/R-REC-BT.500-13-201201-I/en
[28] Recommendation ITU-T-P.910 available at: https://www.itu.int/rec/T-REC-P.910-200804-I/en
[29] Recommendation ITU-T-P.913 available at: https://www.itu.int/rec/T-REC-P.913-201603-I/en
[30] ISO 8589:2007 - Sensory analysis - available at: https://www.iso.org/standard/36385.html

(3) Main evaluation - it includes training users and gather their perceptions;
(4) Post-questionnaire - to know whether users have participated in similar subjective evaluations.

A detailed and stepwise tutorial/guide, but focused on olfactory-based mulsemedia experiences, is presented by Murray et al. [57]. Their work includes a comprehensive study of approaches for QoE evaluation including aspects such as methods, environment, types of scents, length of the experiment, quantity and balance of participants. Two important recommendations that they provide in mulsemedia assessment encompass "performing assessment in controlled and known conditions with minimum distraction" and "reducing physical condition and psychological factor effects on human judgement." The authors also include thorough proposals for participants trial and training, physical environment and experimental design, and methods.

With regard to objective evaluations in mulsemedia experiences, the work of Egan et al. [26] combined heart rate and electrodermal activity monitoring to subjective questions. They correlated the results and found out that high values of these objective metrics were associated with physiological arousal. Keighrey et al. [42] also showed the potential and benefits of using these objective metrics as indicators of user QoE for immersive experiences in AR applications. Thereby, physiological devices can be useful in effective state monitoring and are a valid way to gather sometimes concealed data about the experience. Complementary to subjective assessments, these objective evaluations have the potential to bring revealing insights.

In relation to the type of assessment for both regular and 360° VR mulsemedia systems, it will depend mostly on the research question and hardly on the way the environment is built. In objective assessments though, the employed equipment should be adapted accordingly. For instance, an eye-tracker for monitoring eye gaze on screens should be different for VR goggles.

5.5.1 Mulsemedia Datasets. Evaluating QoE in mulsemedia environments is not a straightforward task. A great deal of time must be employed to arrange the environment for the experience, which involves not only setting up the devices, but also the creation of mulsemedia content. Taking into account that other researchers might be interested in shortcutting this time, Waltl et al. [110] made available an extensible mulsemedia dataset[31] to be used in different setups. They gathered 76 video clips with different lengths from varied genres including action, documentary, sport, news, and commercials, and annotated them with MPEG-V to provide wind and vibration effects.

Another noticeable mulsemedia dataset is reported by Murray et al. [58]. With the aim of making research reproducible and allowing researchers to follow unpaved ways on the same data, the authors collected and made available a mulsemedia dataset[32]. A total of 6 video clips of 90-seconds length were annotated with olfactory effects. The genres included cookery shows, news, and documentary associated with the following categories of smell: burnt, flowery, foul, resinous, spicy, and fruity. The data was written in text format separated by commas. Information about the test environment, as well as employed research methods, are also described in the work.

5.6 Considerations on how to build a mulsemedia environment

After providing guidelines for building your own mulsemedia environment, it is worth mentioning that there are other possibilities to reach the same results by adapting the blueprints suggested in Sections 5.3 and 5.4 to support different applications and devices taking into account also distinct ways of communication. Owing to the fact that we advised the PlaySEM SER as a mulsemedia renderer (Section 5.1.3), software and hardware using standards and protocols such as MPEG-V, UPnP, WebSocket, CoAP, MQTT, Bluetooth, Wi-Fi, and Serial communication, can be directly

[31] Sensory Experience Lab's dataset available at http://selab.itec.aau.at/software-and-services/dataset
[32] Murray's dataset available at http://www.niallmurray.info/Research/appendix

accommodated via configuration without changing its code. For applications protocols or devices that do not work with them, extensions can be created. For instance, to add support to a new device, a class extension to drive it (mapping generic command structures to specific ones) can be written without modifying other constituents. This is possible thanks to design patterns applied to the PlaySEM SER [87]. Naturally, other mulsemedia renderers could also be considered.

From Section 5.2, it is noticeable that the availability of resources, cost, need, among others, should be taken into account when constructing a mulsemedia DIY environment. Furthermore, personal aspects such as preferences and safety related to developers and users should not be forgotten.

As gustatory devices are in early stages of development, we did not include them in the proposed mulsemedia environments. The jury is still out on this subject because it is hard for a single machine to chemically produce different flavors and deliver them to the users. Although one could have the same argument for scent devices, the sense of taste entails more features such as hardness, viscosity, chewiness, geometry, temperature, and among others, so that a person could have a food experience. Then, there is standardization or the lack thereof. For instance, MPEG-V does not support taste.

Another critical shortcoming in mulsemedia standardization is related to the lack of mechanisms to annotate individual viewport in 360° environments, which also hits the current version of MPEG-V. This would be especially useful to increase the level of immersion in the way that users could feel stronger or weaker intensities based on what is surrounding them and where they are gazing at whislt consuming 360° content. For example, the smell of a rose behind users could be delivered with low intensity. However, if they turned their heads into the direction of that flower, the smell could be stronger. These mechanisms would also allow the creation of 3D wind effect. As as result, users could feel positional wind effects coming from different directions and with appropriate intensities. Therefore, there is an open field for investigation in this area.

6 CONCLUSION AND FUTURE DIRECTIONS

The proliferation of mulsemedia devices focuses on displaying media elements that stimulate one (or a combination) of the senses of hearing, seeing, smelling, touching, and tasting [31]. Recently, there have been an explosion of DIY and commercial off-the-shelf, which makes it difficult to select a setup appropriately. In this paper, we explored various characteristics associated with the devices namely form-factor (desktop, laptop, hand-held, and wearable), current availability, and provided tips on how to build a mulsemedia environment.

This review showed that there are a number of haptic technologies which exist as wearable, handheld, desktop and haptic chair with a fair number being commercially available. Compared to other mulsemedia devices, the haptic technologies are successful in that various haptic effects can be generated by automatically transforming audio input. However, most of the devices do not provide SDKs which would enable further integration for building a multisensorial environment as well as being drivers behind mulsemedia DIY efforts.

Gustatory and olfactory displays are less understood than their haptic counterpart and the existence of such displays is generally insignificant compared to conventional audio-visual displays. While many commercial technologies which aim to engage olfaction failed, an increasing number are commercially available as desktop devices in the market; the task of integrating these devices is not effortless, though. The literature also shows that most of the DIY olfactory devices are wearable and that gustatory initiatives are generally DIY.

A paltry few mulsemedia systems are also designed to engage more than one sense and do provide their own SDKs for further integration. Some devices combine more than one kind of sense. However, most display systems target just one of the additional senses beyond vision and audition.

There is also a concern that existing multimedia systems do not support multiple-sensorial effects and lack standardization. In addition, there are issues concerning synchronization between content and sensory effects rendering, processing, and masking effects. Thus, we proposed an approach for building a mulsemedia environment (focusing on engaging multiple senses either by integrating mono-sensory or bi-sensory devices, or using devices incorporating multisensory functionality).

We have identified various existing solutions to deliver and render mulsemedia. However, most of them were not designed to be reused, which creates some barriers either when a new set of devices needs to be integrated into a new system or multimedia applications need support to deliver sensory effects. Therefore, we claim that a seamless solution would be one that decouples multimedia applications from mulsemedia renderers, thereby, raising the need for mulsemedia middleware. Regarding the devices, we also emphasized the potential of the art of DIY for customizing and building new mulsemedia environments. Accordingly, we provided the blueprints and prototypes for assembling both regular as well as 360° VR mulsemedia systems.

In general, our review of the literature showed that most multisensory devices available on the market as well as in the research area cannot yet be compared in terms of scale and market share to their conventional audio-visual counterparts, which makes it a barrier for researchers without engineering skills who want to design novel digital multisensory interactions. Thus, it is hoped that our findings and the proposed guide for custom building a mulsemedia environment will encourage researchers to investigate new approaches which enhance the usability of mulsemedia devices and systems so as to seamlessly integrate more sensory effects and provide an increased sense of reality and immersion to users.

In spite of the evident progresses of developing proper hardware and software, there are still many remaining issues. For example, future work could focus on integrating mulsemedia devices into the conventional desktop/laptop environment, much akin to how speakers, mice, and cameras already are, that is, plug and play. Furthermore, standardization appears as a hitherto unsolved issue. Whilst the MPEG-V standard has devoted considerable effort and resources to enable the annotation of audiovisual content with sensory effects, it does not yet consider taste and viewport annotation in 360° environments. Moreover, device manufacturers have also neglected standardization initiatives and further work and research could be done toward this end. Another little-traced path is related to the sense of taste. We draw attention to the need to develop gustatory displays that take into account not only the tongue, but also the whole gustatory system that comprises vision, smell, and trigeminal nerve stimulation. Cross-cultural factors that also affect the sense of taste such as education, knowledge, social class, context, cost, experiences, beliefs, among others, makes this task even harder. Therefore, studies on the dimensions of cross-cultural aspects should be explored in mulsemedia environments. All our worthy future pursuits.

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