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# Nebula: An Affordable Open-Source and Autonomous Olfactory Display for VR Headsets

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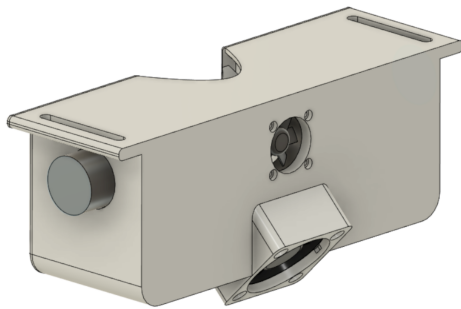


Figure 1: Olfactory display CAD model (left) and mounted on a Meta Quest 2 (right).

## ABSTRACT

The impact of olfactory cues on user experience in virtual reality is increasingly studied. However, results are still heterogeneous and existing studies difficult to replicate, mainly due to a lack of standardized olfactory displays. In that context, we present Nebula, a low-cost, open-source, olfactory display capable of diffusing scents at different diffusion rates using a nebulization process. Nebula can be used with PC VR or autonomous head-mounted displays, making it easily transportable without the need for an external computer. The device was calibrated to diffuse at three diffusion rates: no diffusion, low and high. For each level, the quantity of delivered odor was precisely characterized using a repeated weighting method. The corresponding perceived olfactory intensities were evaluated by a psychophysical experiment on sixteen participants. Results demonstrated the device capability to successfully create three significantly different perceived odor intensities (Friedman

test  $p < 10^{-6}$ , Wilcoxon tests  $p_{adj} < 10^{-3}$ ), without noticeable smell persistence and with limited noise and discomfort. For reproducibility and to stimulate further research in the area, 3D printing files, electronic hardware schemes, and firmware/software source-code are made publicly available.

## CCS CONCEPTS

• Human-centered computing → Virtual reality.

## KEYWORDS

Wearable olfactory display, Autonomous VR experiment

## ACM Reference Format:

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## 1 INTRODUCTION

The integration of multisensory cues in immersive virtual reality experiences raises a growing interest in the scientific community. Recent surveys suggest that going beyond visual stimuli, with the inclusion of auditory, olfactory or tactile cues seems to demonstrate many benefits for the experience [16], in particular on the degree of presence and immersion. Among those senses, olfaction has a great potential due to its influence on emotions, mood and memory [11]. Still, olfaction remains under-utilized in the domain of virtual reality, mostly because HMD-compatible olfactory displays are not readily available. Several authors proposed such wearable devices [7, 15, 17, 19–21]; however they are difficult or impossible to reproduce due to their complexity and/or missing information; they also may require expensive materials. This lack of inexpensive reproducible olfactory displays hinders research and makes existing studies difficult to replicate.

In this context, we propose an open source wearable olfactory display (called Nebula) that is easy to reproduce and low-cost (60 €VAT included) while still being controllable both temporally and spatially by an external program such as Unity. Its conception allows a reactive and accurate odor delivery, without noticeable noise or odor persistence. To facilitate its usability and portability, we propose a software/hardware solution to make our device work with autonomous HMD such as the Meta Quest 2, without the need for an external PC. The capability of our device to deliver smell at three different diffusion rates (no diffusion, low and high), from a same odorant, has been assessed both objectively (by a repeated weighting method) and subjectively in a psychophysical experiment on sixteen participants.

In summary, our contributions are:

- The original design and conception leading to an inexpensive device, while allowing accurate, reactive and controllable odor diffusion.
- A software/hardware solution to make the device work with autonomous headsets.
- For the three diffusion rates, an accurate characterization of (1) the delivered odor quantity, and (2) the corresponding perceived odor intensity (assessed by a psychophysical study).
- An evaluation of the reactivity, discomfort and noise induced by the device.
- The open source release of (1) the electronic hardware schemes, (2) the STL files for 3D printing, (3) all the firmware and software source code including the Unity program allowing to reproduce the conducted psychophysical study.

The paper is organized as follows. Section 2 discusses related works on portable olfactory displays. Our device, Nebula, is presented in section 3. In section 4 we present the experiment we conducted and its results. Finally, section 6 presents limitations and future works.

## 2 RELATED WORK

This section reviews existing *portable* olfactory displays designed for virtual reality experiences (either handheld or mounted on HMDs). Note that it does not cover *desktop* olfactory displays (e.g. [8, 13]).

To our knowledge, one of the first wearable olfactory device for VR was proposed more than 20 years ago by Dinh et al. [9]. Participants were wearing a small oxygen mask connected to a canister of coffee grounds and a small pump. Several years later, Yamada et al. [21] proposed two prototypes: the first one was based on gas phase odors and used air pumps generating airflow passing through cotton infiltrated with perfume material; the second one was intended to be less cumbersome and used liquid phase odor by injecting droplets directly near the user's nose. Both prototypes were well characterized with respect to the diffused odor intensities and reactivity. More recently, several lighter devices have been proposed based on varying technologies. Ranasinghe et al. [19] proposed a multisensory VR device integrating olfaction, thermoception and wind. Different technologies were compared for the olfactory stimulation; based on the results, they developed a prototype based on air pumps, capable of diffusing four odorants. Tsai et al. [20] considered ultrasonic atomizer, as we do, and were able to deliver three levels of intensity (for one single odorant). The use of other technologies for diffusing scents can be found in the literature. For instance, Kato and Nakamoto [15] and Nakamoto et al. [17] developed devices that rely on a surface acoustic wave (SAW) atomizer combined with an FPGA. The proposed devices are well characterized in terms of odor delivery quantity and a special effort has been done to reduce smell persistence. Another type of technologies employed can be found in the work of Brooks et al., stimulating the trigeminal nerve. In particular, they took advantage of a temperature illusion to create warm and cool sensations by mixing olfactory stimulants with trigeminal stimulants (capsaicin and eucalyptol) [5] and also employed the trigeminal nerve to create a stereo smell experience using electrical stimulations [6]. While the portable devices presented above diffuse a single odorant at a time, recent work from Bahremand et al. [3] proposed a new device called *The Smell Engine*, capable of dynamically mixing several odorants in their vapor phase, along with a framework to operate it in Unity. de Paiva Guimarães et al. [7] proposed a low-cost olfactory display, battery operated, integrated into a Google Cardboard. The diffusion is based on an ultrasonic atomizer. Niedenthal et al. [18] used similar technology to develop a hand-held device, attached to a VR controller. Finally, Dobbstein et al. [10] and Amores and Maes [1] proposed wearable olfactory devices not integrated with VR but worn around the neck; they both rely on the atomization of liquid phase odorants.

The devices presented above considered a variety of technologies and demonstrated various effects of olfaction on the user experience; however, most of them are difficult or impossible to reproduce due to their complexity and/or missing details from the relevant publications. Some of them also rely on expensive (or not easily accessible) components. Finally, most of those devices were used in further experiments (e.g., to evaluate the interaction between olfaction and other sensory cues) without properly characterizing the stability and repeatability of odor quantity delivery, or induced discomfort, which makes the results hard to reproduce. Lack of reproducibility, in particular for researchers unfamiliar with electronics, slows down progress in the field. To cope with this issue, we propose a low-cost open-source device, integrated with VR and accurately characterized in terms of delivered odorant quantity

which can be easily replicated by olfactory experts wishing to assess the impact of the olfactory cues without investing too much time and effort in building an *ad-hoc* device for their experiments. We also evaluate our device in a user study regarding the perceived olfactory intensities, comfort and noise and release the software allowing to reproduce the study.

Note that a few commercial devices have been launched on the market: VAQSO<sup>1</sup> and Olorama<sup>2</sup> propose headset-integrated olfactory devices, however, prices remain high (resp. 3000\$ USD and 2249 €)

### 3 PROPOSED OLFACTORY DISPLAY

#### 3.1 System requirements

Nebula is intended to become a standard, reproducible display with the objective to stimulate research in immersive olfactory experience. As such, we oriented the conception of the device in such a way to be accurate, controllable and compatible with most of VR headsets whether they use an external computer like the Varjo XR3, HTC Vive or are autonomous like the Meta Quest 2. We list below the requirements that guided the design of our device:

- The device must be able to diffuse a given odorant at, at least, 3 different levels: no diffusion, weak and strong diffusion.
- The device must be easily reproducible, this includes low-cost 3D printing, the use of hardware easily accessible on the market, and simple to use and easily modifiable software.
- The cost of the device must be below 100 €.
- The device must be compatible and able to be mounted on a maximum of headsets, including autonomous headsets.
- Refilling the device with an odorant must be simple and fast.
- The diffusion of odors must be reactive, this includes the latency at the beginning of the diffusion and the reduction of persistence in the short term.
- The device should be able to diffuse simultaneously two different odors.

#### 3.2 Diffusion principle

Existing olfactory displays (wearable or not) basically consider two classes of methods for delivering odors. The first consists of diffusing the scent in a *gas* phase[4, 9, 10, 21]. It has the advantage of being controllable in a precise way and detectable by sensors of volatile organic compounds[8]. The second class of methods considers a *liquid* phase, for which the odor is carried by micro-droplets of water suspended in the air, forming a scented mist. According to the requirements listed above, we selected the diffusion using a liquid phase because hardware is more accessible and less expensive than the gas phase alternative. Such a *liquid* phase diffusion can be realized with different technologies[2, 12], the easiest to find on the market comes from the technology used in domestic essential oil diffusers: ultrasonic atomizers allowing for a cold diffusion of scented mist. We thus selected this technology, which is both inexpensive as widely available on the market, and easy to use.

The ultrasonic atomizer is a small metallic surface with micro-perforations ( $\sim 80\mu\text{m}$ ). When powered, the oscillation of the surface

will diffuse a mist composed of small droplets of water[12] carrying the odorant. In our case, the liquid is held by a cotton stick located inside the reservoir (see 2), in direct contact with the atomizer, as usually conducted in previous studies[1, 18, 20]. As the mist is being inhaled directly by the user, we nebulize a water based odor material allowing for an easier dilution, and to minimize (1) solvents toxicity over long expositions and (2) smell persistence in the device.

#### 3.3 Design

Figures 1, 2 and 3 illustrate the design of our device. The mist produced by the atomizer is guided to the nose by a small fan (5V DC 25x25x6mm). This fan is always active and forces a constant air flow to be able to smell the odor more rapidly after its diffusion and mitigates the pressure drop when enabling the extraction fan. The extraction fan (5V DC 40x40x10mm) is responsible for expelling the remaining odor material when the diffusion is over. This one is running only for two seconds when the diffusion stops. Evacuating the remaining scent prevents short-term persistence in the system, helping making the olfactory display and the perception of the smell more reactive in the VR scene. The design of our device allows to have two atomizers, cotton sticks and reservoir tanks and thus to diffuse two odors simultaneously. Finally, both reservoirs are easily accessible from the outside of the device without the need for disassembly for an easy refill between each experiment.

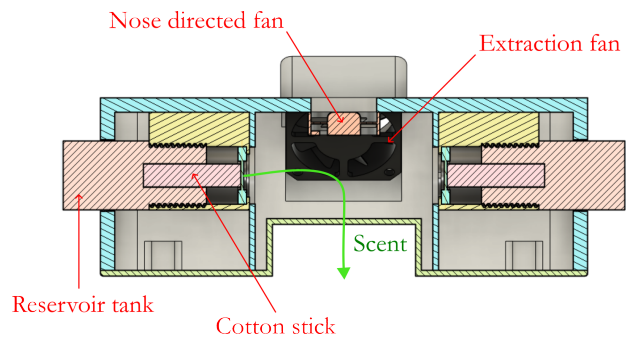


Figure 2: Section of the olfactory display CAD model.

#### 3.4 Control

Each atomizer is powered by a pulse width modulated signal: increasing the duty cycle results in an increased rate of diffusion[12][20]. This modulation, handled by the micro-controller of the olfactory display (Arduino Nano Every), allows to reach several olfactory intensities. Figure 4) illustrates this modulation, with the three diffusion rate : low, high and no diffusion. After the end of each diffusion, the extraction fan runs for 2 seconds in order to extract the remaining odorant and thus improve the reactivity of the device. This control principle demonstrated good results in our experiment described in section 4.3.4.

<sup>1</sup><https://vaqso.com/>

<sup>2</sup><https://www.olorama.com/professional-scent-generator>



**Figure 3: Internal view of our device. Note that we consider only the diffusion of one single odor in this paper (using the left part of the device) ; however, the design allows the diffusion of two odors simultaneously by equipping the right part of the device.**

### 3.5 Autonomous capabilities and Unity integration

As stated above, one important requirement we had was to be able to use our device on an autonomous headset, without the need for an external PC. This makes it ideal for experiments in museums, schools, and other places without the need to carry cumbersome hardware. Controlling Nebula with an autonomous headset like the Meta Quest 2 comes with its own challenges. Such HMDs running on an Android operating system requires extra work to setup a communication with an external micro-controller from Unity. Additionally, to make our Unity plugin easy to use, we wanted to make sure that one could create a scene using Nebula that could be built both for Android and/or Windows without any extra work needed to make it compatible with the targeted HMD.

We propose an hardware/software solution for this requirement, that we tested on the Meta Quest 2, as shown in figure 1. The headset supplies 5V through its USB-C port to the Arduino (using a 15cm USB-C to Micro-USB cable) and communicates with the olfactory display using a UART protocol. We chose USB as the most viable solution for communicating with the olfactory display as it is more stable than Bluetooth or Wifi in environments saturated with electromagnetic signals, requires little to no configuration on the headset and no extra battery. We establish a communication between the Arduino and the autonomous HMD running the Unity program through a Java plugin (an Android Archive Library embedded in our Unity plugin) which uses native serial features of Android, and communicate with it using the Java Native Interface (JNI). The architecture is represented in figure 5. To make the compilation work both for Android and Windows targets, our Unity scripts include conditional compilation, excluding and/or including parts of it when needed or not supported by the platform selected. This way, no extra work is required from the user to use our Unity package. To validate its proper functioning, the same scene was tested successfully on the following setups: Android (Meta Quest 2), Windows standalone build and inside the Unity Editor. Furthermore, we added a GUI (only visible on the computer) to control Nebula manually. The commands sent using the GUI take precedence over the commands sent by the scene's scripts. Using the GUI allows to

manually activate/deactivate Nebula by overriding scripted triggers, setup a minimum and maximum duty cycle (influencing scripted triggers and manual activation) and get a visual feedback about the current diffusion, in real-time.

Consequently, Nebula coupled to a Meta Quest 2 can be used in a wide range of environments, especially where VR can't be used easily as setup are usually bulky and needs a lot of preparation. The Meta Quest 2 is cheap, easy to use and fast to set up. Moreover, this version allows for complete freedom of movement, which is useful for experiments on the scale of one or more rooms.

### 3.6 Assets provided

All resources required to reproduce and use Nebula are made publicly available on our GitHub repository<sup>3</sup> and provided as supplementary materials for the reviewers. This includes (1) STL files with recommendations for 3D printing, (2) a list containing the references of the hardware components, (3) the wiring diagram for soldering the components on the Arduino, (4) the firmware to flash on the Arduino and the software to control it with Unity, and (5) two Unity scenes: the one used for conducting the user study described in Section 4.3, and a sample scene (a kitchen with a graspable orange) illustrating a use case of our device. Raw results of the user study are also provided.

## 4 EXPERIMENTS

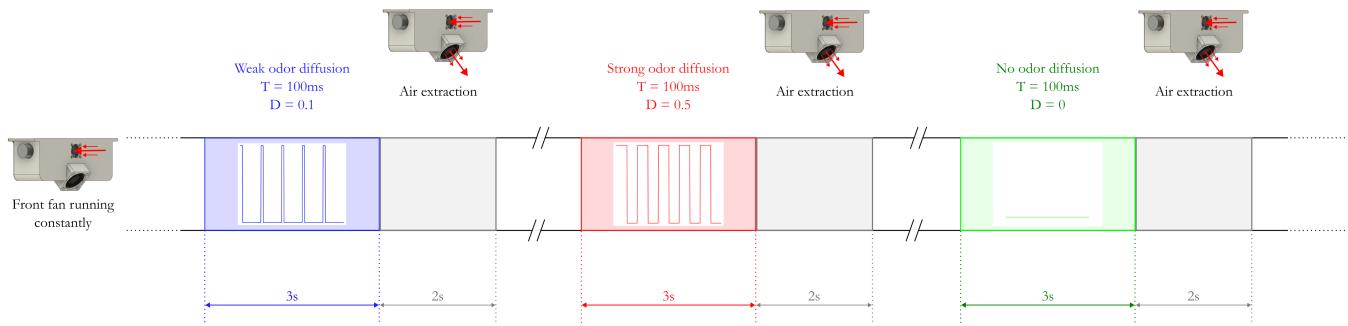
In this section we first characterize objectively the control and the accuracy of the odor diffusion in terms of stability and repeatability of odor quantity delivery (see section 4.2). We then evaluate, in a user study, the capability to successfully create significantly different perceived odor intensities (see section 4.3). The experimental setup (selected odorant and diffusion levels) is first described in section 4.1.

### 4.1 Odorant description and diffusion levels

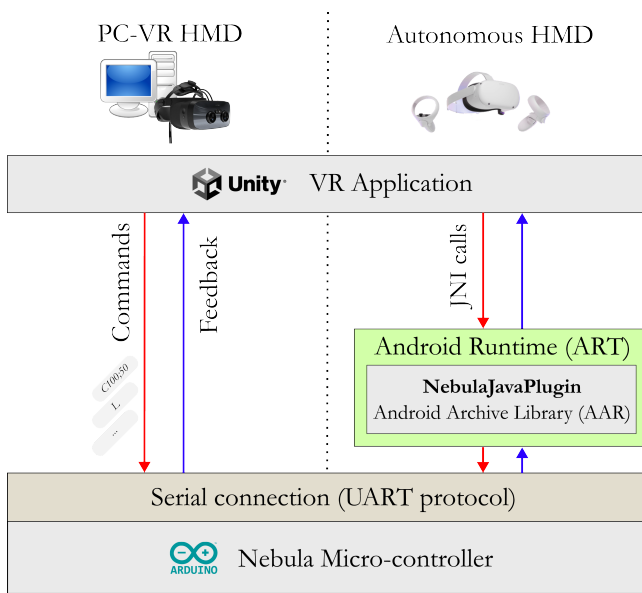
The odorant used is a pre-mixed orange water-based compound ("Nuage Orange" from *Laboratoires Camylle* in France). It is composed of natural essential oils of orange solubilized in water using PEG-40 castor oil and emulsified using PEG-7 glyceryl cocoate. The compound was then diluted using 5ml of water-based odor material for 20ml of water in order to reach a desired concentration of 25 %, the same dilution was used throughout the experimentation. The cotton was saturated before each participation with this solution.

To test the controllability of Nebula, we have set three distinct diffusion levels. Although Nebula is theoretically capable of diffusing at any levels, we have chosen to set three levels to facilitate our technical validation process. The first level, for the "clean" condition, corresponds to an absence of diffusion. For this level, the PWM signal's duty cycle is set to 0% and the period to 100ms, no odorous product is diffused. The second level, for the "low" condition, corresponds to a weak diffusion, the odor is not very aggressive while remaining sufficiently intense to be perceptible. For this level, the PWM signal's duty cycle is set to 10% and the period to 100ms. The third level, for the "high" condition, corresponds to a strong diffusion, the odor is slightly below the threshold where it would appear aggressive for the nose. For this level, the duty cycle of the

<sup>3</sup><https://github.com/Plateforme-VR-ENISE/Nebula-Core>



**Figure 4: Timeline of 3 different intensities and their associated pulse-width modulated (PWM) signal used to power the atomizer, with T the period and D the duty cycle.**

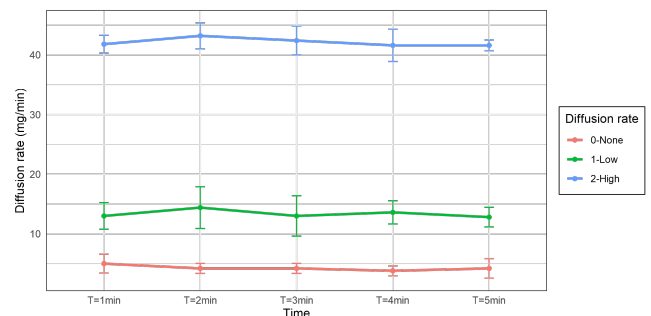


**Figure 5: Software architecture used to communicate commands to Nebula with both PC-VR and autonomous HMDs.**

PWM signal is set to 50% and the period to 100ms. The "weak" and "strong" odor ratings were determined subjectively in our laboratory and during one of our outdoor interventions in a museum, during which we collected user feedback when varying the PWM signal duty cycle.

## 4.2 Objective characterization

Classical methods for odor concentration measurement (e.g., to characterize olfactometers) consider Photo Ionization Detector (PID). However, these sensors are not meant for droplet mist, but for gas phases. Instead, as in [12], we performed a repeated weight measurement. On a precision balance ( $d = 0.1$  mg,  $e = 1$  mg) we placed a petri dish filled with the solution described in section 4.1. A cotton ball is placed in it, saturated with the solution. The experiment consists in placing the atomizer in contact with this cotton and atomizing with the configurations stated previously.



**Figure 6: Diffusion rate (mg/min) of the solution in function of time. 5 independent measurements are used to evaluate the diffusion rate every minute. The red curve corresponds to the natural evaporation of the solution (no diffusion).**

For each configuration, we diffused continuously for 5 minutes, taking a measurement every minute, and repeated this process 5 times for each configuration. The experiment is performed at  $20^{\circ}$  Celsius in a large space to avoid any condensation of the diffused product. The mass-differences thus calculated (25 values in total for each diffusion rate) allow us to determine the quantity of product diffused per minute. A set of measurements without any diffusion was also carried out to take into account the natural evaporation rate of the solution. The calculated diffusion rate are given below:

- Evaporation rate (95% CI): [3.79; 4.77] mg/min (is mitigated inside the closed device)
- Low diffusion rate condition (95% CI): [12.32; 14.39] mg/min (without evaporation correction), [8.04; 10.12] mg/min (with evaporation correction)
- High diffusion rate condition (95% CI): [41.30; 42.94] mg/min (without evaporation correction), [37.02; 38.66] mg/min (with evaporation correction)

Figure 6 also illustrates the calculated mass-differences per minute for each condition. Those results demonstrate a remarkably stable diffusion throughout the experience, for both the low and high diffusion rate condition. Note that the evaporation rate is probably lower in our device; results from the next section does not demonstrate a significant smell persistence when no diffusion occur.

As a side result, we measured that a cotton stick with a 8mm diameter and a length of 36mm like the one we use in our olfactory display absorbed approximately 2.1g of liquid. This means that one refill could handle a non-stop high diffusion rate for approximately 45min. In reality, the cotton stick needs to be wet enough for the atomizer to diffuse the solution correctly. However, it is unlikely that an experiment will require continuous high-level diffusion for 45 minutes. As an example, the experiment described in the next section lasts approximately 20 minutes and no drop in intensity was observed. Thus we can reasonably say that a refill would last long enough for a classic experiment.

### 4.3 User study

We conducted a psychophysical experiment to investigate whether our olfactory display was capable of diffusing scent at three significantly different perceived intensities. We also investigate the perceived discomfort and noise induced by the olfactory display, as well as the perceived change in immersion.

**4.3.1 Participants.** Sixteen healthy volunteers, 9 females and 7 males who ranged in age from 20–45 years (mean  $\pm$  S.D. 28.69  $\pm$  7.87 years) participated. Ages did not differ significantly between the two sexes (two-tailed t-test  $p > 0.76$ ). After reading and understanding the instructions of the experiment, all participants gave their informed consent to participate. 7 participants reported that they have used a VR head-mounted display before.

**4.3.2 VR setup.** Our setup is composed of a Meta Quest 2 head-mounted display with the olfactory display strapped on it. To simplify the monitoring process, we ran the experiment on a PC with Unity and streamed it on the Meta Quest 2 using Air Link.

**4.3.3 Experimental design.** During the experiment, participants are sitting, wearing the VR headset with the mounted olfactory device and grasping two Meta Quest 2 controllers. They are presented with a neutral virtual environment (VE) and experience a sequence of odor diffusion at different intensities ; for each olfactory stimulation they are asked (1) to press the trigger when they detect an odor and (2) to rate the perceived intensity (using ray pointers).

At the beginning, instructions were displayed on a neutral screen in the VE, and participants performed two test trials with no odor delivery to familiarize with the task. As detailed in Sections 4.1 and 4.2, the three olfactory conditions are (1) a clean condition, consisting in diffusing clean air without any odor, (2) a low diffusion rate, and (3) a high diffusion rate. The inter-stimulus interval was set at 33 seconds: 30 seconds of questionnaire followed by 3 seconds of a neutral screen (a grey cross on a blue background, as illustrated in the supplementary material) before diffusing the next scent (with a countdown). The olfactory stimuli duration was fixed to 3 seconds. Trials were pseudo-randomly presented, so that two "clean" conditions never followed each other and the "low" and "high" conditions were not repeated more than twice in a row. Each condition was presented 6 times, the generated sequence of diffusion is the following: [2, 1, 0, 2, 0, 2, 1, 0, 1, 0, 2, 1, 2, 0, 2, 1, 0, 1], with 0, 1 and 2 corresponding respectively to the "clean", "low" and "high" condition. The order of trials was the same for all participants. For each trial, participants were asked to press a button as soon as they detected an odor, and to rate the intensity of the stimulus they

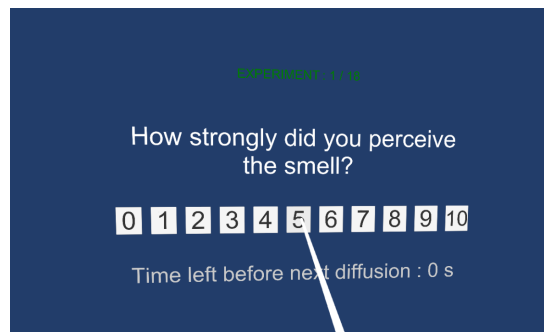


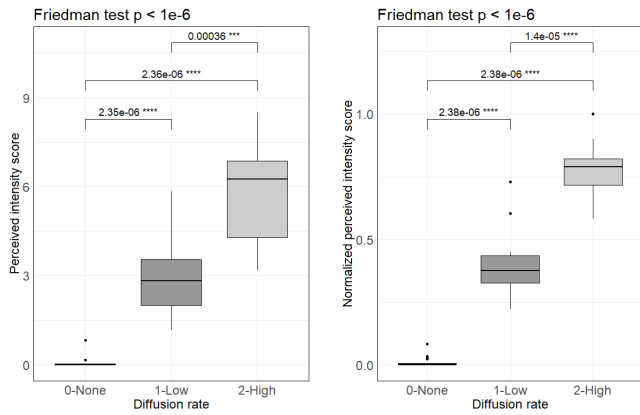
Figure 7: Screenshot of the rating panel of our psychophysical experiment.

perceived on a scale from 0 (imperceptible odor) to 10 (extremely strong odor). The rating panel is illustrated in Figure 7. They were informed that they were expected to respond as fast as possible. Follow-up questionnaires were given to the participants after the end of the VR experiment, containing the following questions: (Q1) Are you familiar with virtual reality? (Q2) How would you rate your comfort during the experiment? (Q3) Did the smell cause you discomfort? (Q4) How much do you think smells can change your immersion in virtual reality? (Q5) How do you rate the noise of the olfactory display? (Q6) Do you have any comments?

**4.3.4 Results.** Participants' intensity ratings for each repetition are collected. Since each participant used a different range of values (e.g., some participants systematically rated between 0 and 5 while others rated between 0 and 8), the raw ratings of each participant are normalized by his maximum rating across all stimuli. We thus obtain normalized intensity scores between 0 and 1.

**Perceived odor intensity.** A statistical analysis was conducted on both the normalized and raw data. For each diffusion rate, the 6 scores given by each participant are averaged. A non-parametric repeated-measures Friedman analysis is performed, followed by a *post hoc* Wilcoxon test to assert that the distributions of the intensity scores are significantly different. Results are significant (Bonferroni adjusted  $p_{adj} < 10^{-3}$  for both the normalized and raw data), boxplots are shown in figure 8. Those results clearly demonstrate the ability of our device to create three different perceived olfactory intensities, including no perceptible odor when no odor is diffused.

**Reaction time.** For each participant, we averaged the duration between the start of the diffusion and the trigger pull. The average was calculated separately for the low and high diffusion rate conditions. Obtained values are resp. 1866 ms ( $\pm$  348 ms) and 1615 ( $\pm$  308 ms) for the low and high conditions. Those values are significantly different ( $p < 0.005$ , cf. figure 9), meaning that participant were faster to detect the higher diffusion. Those values are in line with response times reported by the recent study of Iseki and Nakamoto [14] who evaluated the temporal response of several olfactory displays, including a wearable one [17]. Note that, the response time is mostly due to the cognitive reaction time of the individuals before



(a) Raw intensity score for each diffusion rate. (b) Normalized intensity score for each diffusion rate.

Figure 8: Boxplots of rated intensity scores depending on the diffusion rate. Friedman ( $p < 10^{-6}$ ) and pairwise Wilcoxon tests (Bonferroni adjusted  $p_{adj} < 10^{-3}$ ) are significant.

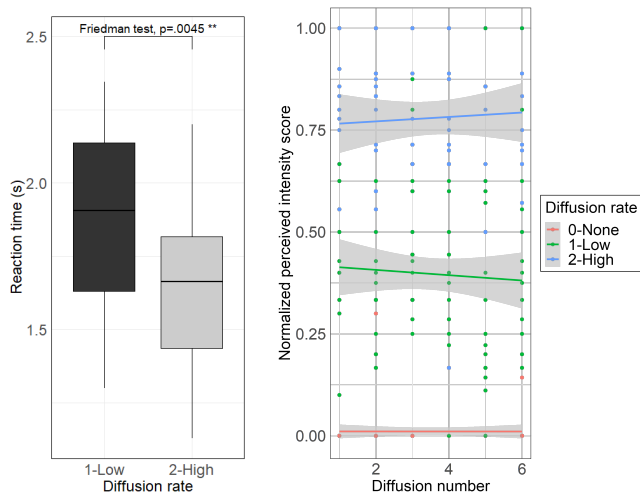


Figure 9: Reaction time for each diffusion rate. Friedman test is significant ( $p < 0.005$ ). Figure 10: Linear regression of the normalized odor intensity scores in function of the diffusion number (increases with time). No significant correlation is found.

detecting the smell and pressing the trigger, the propagation time of the mist from the atomizer to the nose is negligible.

*Smell persistence across time.* One of the main issues with wearable olfactory devices is that odorants may remain in the device after the diffusion and create a smell persistence that impairs the further experience. The large extraction fan that we introduced in our device specifically targets this issue.

To evaluate the olfactory persistence of our device, we performed, for each condition (no diffusion, low and high), a correlation test between the intensity scores given by the participants and the

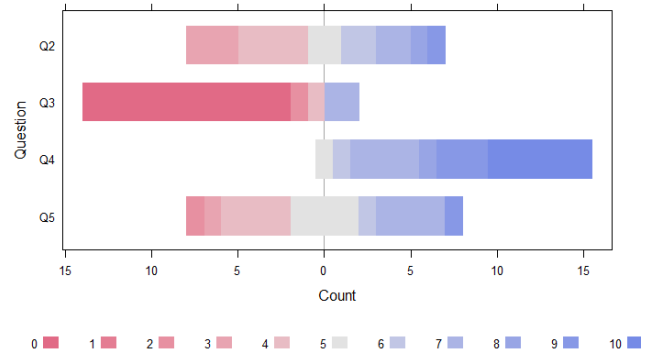


Figure 11: Questionnaire results, scale labels vary depending on the question: (Q2) How would you rate your comfort during the experiment? *Not comfortable at all / Very comfortable* (Q3) Did the smell cause you discomfort? *Not at all / Completely* (Q4) How much do you think smells can change your immersion in virtual reality? *Not at all / Very much* (Q5) How do you rate the noise of the olfactory display? *Silent / Very noisy*.

diffusion number corresponding to the index of the repetition of the condition (ranging from 1 to 6). We applied a Kendall rank correlation test as our data did not present a normal distribution. No significant correlation ( $p > 0.5$ ) between the odor intensity scores and the diffusion number was detected. The score values and associated linear regression plotted in figure 10 tend to confirm the absence of perceived smell persistence across time whatever the diffusion condition.

*Questionnaires.* Follow-up questionnaires were used to evaluate the overall discomfort introduced by our olfactory display. Results are presented in figure 11. Results of (Q3) show no discomfort due to the smell intensity, both for the low and high diffusion rate. The noise coming from the fans has been perceived by several participants (Q5), in particular the extraction fan, but with an overall neutral rating of noisiness. In practice, this slight noise from our extraction system becomes unnoticeable if the immersive experience has ambient sound or music. The overall comfort of wearing the device evaluated by (Q2) still shows a margin of progress. In fact, 6 participants reported a slight discomfort due to the weight of the device (~250g). This issue wasn't pointed out when testing the device on a headset like the Varjo XR-3. The main reason of this problem is due to the fixation system of the Meta Quest 2 that uses a strap around the head. As such, no solid support at the back of the head prevents the headset from sliding and pressing the olfactory display on the lower part of the face. To mitigate this issue, one can replace the Meta Quest 2 straps with a solid mounting system (eg. Elite Strap by Kiwi). Our future work will include reducing the mass of the olfactory display as well as its size to improve its ergonomics. Finally most participants felt that olfactory cues have a great potential for improving immersion (Q4).



## 5 LIMITATIONS

Nebula uses an open-loop diffusion to release the scent. We assume that the diffusion profile does not differ too significantly from the results shown in 6. We believe that ultrasonic atomizers controlled via pulse-width modulated signal remain a good compromise between ease of use, accuracy and wide availability. While the variability of the diffusion rate is low enough to have three clearly distinct diffusion rates, Nebula is not meant to be as precise as other devices available in the literature that propose a finer level of granularity (eg. [3, 17]). To achieve a finer granularity, the use of a closed-loop regulation can be used. This method on a liquid phase diffusion (mist) is particularly challenging as widely available sensors such as photoionization detectors are not suitable for non-gaseous phases. Additionally, natural evaporation occurs in the reservoir tanks. As a consequence, Nebula performance is not guaranteed after more than 45min, as shown in section 4.2.

## 6 CONCLUSION AND FUTURE WORK

In this paper we present Nebula, a low-cost (60 €VAT included) olfactory display compatible with most HMDs (e.g., HTC Vive Pro, Meta Quest 2, Varjo XR3) and capable of diffusing scents at different diffusion rates. We conducted an in-depth objective characterization and subjective evaluation of our device, in terms of delivered odor quantity, perceived odor intensity, and perceived discomfort, noise and smell persistence. All hardware schemes and specifications, 3D printing files and software are released in open-source for reproducibility and to stimulate further research on multi-sensory immersive experiences. As stated in the experiment section, the comfort of our device can still be improved, in particular when used with the Meta Quest 2, for which the mounting system is just composed of a strap. The main avenue for future work concerns the use and calibration of two odors simultaneously that could also be used to control odor directionality. While we limited the present study to the diffusion of one single odorant, our device was designed for two and is thus ready for the exploration of this new avenue.

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