

# Generation and Real-Time Detection of High-Fidelity Odour Plumes

*Amirreza Gholivand<sup>1</sup>, Anantha Padmanabhan<sup>1</sup>, Florian Paul Schmidt<sup>2</sup>, Tobias Ackels<sup>1</sup>*

<sup>1</sup> *University of Bonn, Faculty of Medicine, Sensory Dynamics and Behaviour Laboratory, Institute of Experimental Epileptology and Cognition Research, Venusberg-Campus 1, 53127 Bonn, Germany,*

<sup>2</sup> *Bielefeld University, Faculty of Biology, Biological Cybernetics, Universitätsstr. 25, 33615 Bielefeld, Germany*

*tobias.ackels@ukbonn.de*

## Summary:

Understanding how animals navigate their environment requires experimental tools capable of generating plumes and detecting odour fluctuations. We present a unified framework comprising the temporal Odour Delivery Device (tODD) and the detection method with compact passive chemical sensors coupled with WaveNet-based signal recovery architecture. The delivery system achieves rapid onset latencies and decay times to precisely reproduce naturalistic plumes. In combination with the sensor system, this creates a high-dynamics framework suitable for use in behaving animals.

**Keywords:** Signal reconstruction, Odour delivery, Deep learning model, MOX, Sensor dynamic

## Background, Motivation and Objective

Olfactory navigation is crucial for survival-related behaviours in animals. In natural environments, odours are transported in turbulent plumes, generating highly intermittent and rapidly fluctuating signals rather than smooth gradients. These fluctuations contain rich temporal information about the structure and origin of odour sources. Reproducing these naturalistic stimuli in a controlled lab environment remains a significant challenge. Capturing their real-time dynamics in freely behaving animals adds further complexity. Unlike visual or auditory systems, chemical stimuli are constrained by fluid dynamics, requiring vaporization, transport, and clearance that introduce temporal delays and concentration variability [1-3]. Standard olfactometers often lack the millisecond precision required to reproduce the rapid "whiff" and "blank" sequences of turbulent plumes, typically relying on slow onset/offset dynamics or steady state concentrations [2]. Furthermore, recording these dynamics in combination with behaving animals presents a parallel bottleneck. While Photoionisation Detectors (PID) offer high sensitivity, their size and active suction mechanisms distort local flow streams, making them unsuitable for head-mounted applications [4]. Conversely, miniature Metal Oxide Chemical Sensors (MOX) are compact but suffer from slow response times that filter out the high-frequency fluctuations that might aid navigation. To bridge this gap between

stimulus generation and sensory recording, a unified system capable of both delivering and resolving fast temporal odour dynamics is required.

To overcome these dual limitations, we present a comprehensive framework comprising the temporal Odour Delivery Device (tODD) and a compact detection strategy combined with a robust signal processing pipeline based on the WaveNet architecture.

## Description of the New Method or System Odour Delivery Device

To overcome these limitations, we developed tODD, designed specifically to replicate the fast temporal dynamics of natural odour plumes. Figure 1 shows the assembled setup and a schematic of the device. This allows the precise and reproducible generation of fast odour dynamics, thereby providing a tool to capture the complex structure of natural odour plumes (Fig. 1d).

## Sensing and Reconstruction

To overcome the constraints of conventional detection techniques, we utilize a miniature Micro Chemical Sensor (MiCS). Its compact size and low weight make it ideal for head-mounted implantation on freely behaving mice. Crucially, as a passive sensor, MiCS does not distort local plume structures or flow streamlines. However, MiCS inherently suffers from slower response dynamics compared to reference detectors. To address this latency, we established a WaveNet-based deep learning

architecture. This model learns the non-linear mapping between raw, low-bandwidth MiCS responses and high-fidelity PID references. By effectively deconvolving sensor inertia, our method restores the temporal resolution lost to hardware constraints, creating a virtual "high-dynamics" sensor. Together, tODD and the WaveNet decoder form a closed-loop experimental platform that synchronizes high-precision stimulus delivery with real-time, high-fidelity plume reconstruction.

## Results

Characterization of tODD using 100 ms square pulses revealed an average onset latency of  $5.6 \pm 0.1$  ms, a rise time of  $8.5 \pm 0.6$  ms, and a decay time of  $43 \pm 3.7$  ms for Ethyl Butyrate at a concentration of 10% (Fig. 1c). These metrics demonstrate the system's capability of fast odour pulse generation, satisfying the requirement for naturalistic plume reproduction. To verify the high-fidelity generation of complex stimuli, we compared device output against empirical plume recordings for two distinct odorants: Ethyl Butyrate and Limonene. As shown in Fig. 1d, tODD reliably reproduced rapid concentration fluctuations. The coefficient of variation across five repeated trials remained below 6%, confirming robust stimulus stability essential for behavioural studies.

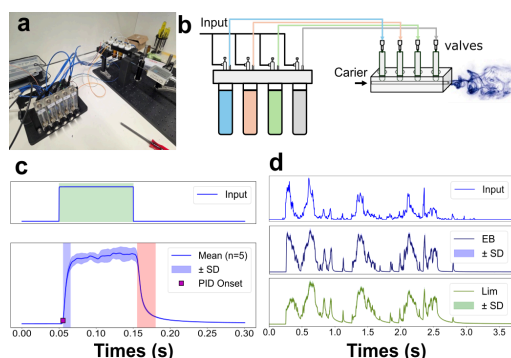


**Fig. 1. Temporal Odour Delivery Device.** (a) Photo of the assembled setup, (b) schematic design of the tODD, where pressurized air is guided through odour bottles towards high speed valves to generate odour plumes. (c) 100 ms pulse command (top panel) with corresponding tODD odour output (bottom panel). The blue area represents the 90% rise time and the red area represents the 10% decay of the signal. (d) Exemplary plumes. Input signal (top) and reproduced odour signals using Ethyl Butyrate (EB; middle) and Limonene (Lim; bottom). Solid line: average of 5 different repeats, shaded area: SD. All plots are normalized.

Finally, we evaluated the deep learning model's ability to recover high-frequency dynamics from MiCS recorded signals. The model successfully reconstructed transient features with a correlation coefficient of  $R^2 = 0.92 \pm 0.05$  against PID ground truth, effectively resolving "whiff"

events that were otherwise smoothed out by the raw sensor data (Fig. 2c). The detection system was systematically evaluated across varying odorant concentrations and distances within the test arena. Results demonstrate that the sensor array reliably captures low odorant concentrations at distal recording positions (Fig. 2b), highlighting the system's sensitivity and spatial range. This integrated detection platform enables real-time odorant concentration monitoring, with potential applications in olfactory navigation paradigms and behavioural studies. Furthermore, the incorporation of a deep learning model in principle could facilitate source discrimination, allowing the decomposition and identification of individual odour sources within complex, mixed-signal environments.

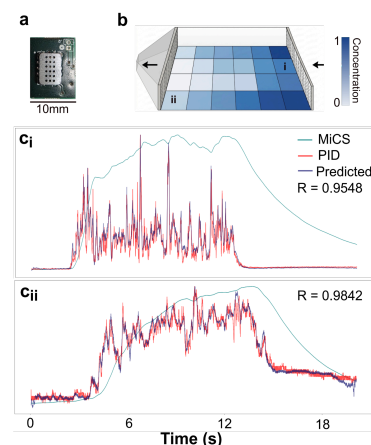


**Fig. 2. MiCS** (a) Photo of the MiCS mounted on a PCB. (b) Schematic representation of the experimental arena partitioned into 24 spatial grids, illustrating the distribution of odorant concentration across grid positions. (c) Comparative traces of PID (red) and MiCS (teal) signals recorded at two arena positions (i) and (ii); see Fig. 2b, alongside the model-predicted signal (blue).

## References

- [1] C. Doyle, J. Wang, E. Galliano, C. Guillaume, A low-cost and open-source olfactometer to precisely deliver single odours and odour mixtures, (2026) 2025.09.11.675563. <https://doi.org/10.1101/2025.09.11.675563>.
- [2] T. Ackels, A. Erskine, D. Dasgupta, A.C. Marin, T.P.A. Warner, S. Tootoonian, I. Fukunaga, J.J. Harris, A.T. Schaefer, Fast odour dynamics are encoded in the olfactory system and guide behaviour, *Nature* 593 (2021) 558–563. <https://doi.org/10.1038/s41586-021-03514-2>.
- [3] S. Gorur-Shandilya, C. Martelli, M. Demir, T. Emonet, Controlling and measuring dynamic odorant stimuli in the laboratory, *J Exp Biol* 222 (2019) jeb207787. <https://doi.org/10.1242/jeb.207787>.
- [4] A.C. True, J.P. Crimaldi, Distortion of passive scalar structure during suction-based plume sampling, *Sensors and Actuators B: Chemical* 367 (2022) 132018. <https://doi.org/10.1016/j.snb.2022.132018>.