# Inventing aerosols: Auguste Trillat (1861-1944) and the medical meteorology of influenza

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**SUMMARY**: 1.—Introduction. 2.—The life of Auguste Trillat 3.—The adaptation of miasma theory to Pasteurian ideas. 4.—1913: Condensation nuclei, or the missing link. 5.—Trillat and influenza. 6.—Experimental airborne transmission of influenza by microbial aerosols: Trillat's experiments in the 1930s. 7.—The physics of microbial aerosols and the legacy of this concept. 8.—Conclusion.

**ABSTRACT:** This article explores Auguste Trillat's pioneering research into the airborne transmission of influenza and the impact of meteorological factors on epidemics. A distinguished French chemist and microbiologist at the Institut Pasteur, Trillat was the first to demonstrate the airborne transmission of influenza. He applied the concept of aerosol in physics to epidemiology and updated miasma theory, which had become obsolete after Pasteur's microbiology. Initially focused on formaldehyde chemistry, Trillat became increasingly interested in the airborne transmission of infectious diseases and methods for its control. His work on antisepsis drew inspiration from historical fumigation practices that uti lized formaldehyde as an effective antiseptic. Trillat's experiments on air quality and pathogen growth in decaying environments revealed that factors such as humidity and temperature critically influenced the vitality and airborne trans mission of the pathogen. He highlighted the role of atmospheric conditions in epidemics and introduced the concept of "condensation nuclei," in which micro bes act as droplet nuclei, aiding airborne transmission under certain atmospheric conditions. This model linked the spread of influenza to specific meteorological contexts. Trillat demonstrated that recently exhaled air, rich in moisture and nu tritive gases, promoted epidemic spread. His insights significantly advanced the fields of epidemiology and medical meteorology, gaining recognition for mili tary applications post-WWI in France and post-WWII worldwide, particularly in chemical and biological warfare. His findings on airborne pathogen transmission informed strategies for both offensive and defensive measures in military set tings, underscoring the importance of air quality control to mitigate the spread of infectious agents in hazardous environments.

**KEYWORDS**: Auguste Trillat, aerosol science, influenza, formaldehyde, biological warfare.

## 1. Introduction

Over many centuries, dominant conceptions of viruses as a causative agent of disease have evolved, gradually as new knowledge has emerged. During the second half of the 19th Century the term's meaning was still very similar to its Latin etymology of *venom* or *poison* when, in his *Principles of Experimental Medicine*[1], Claude Bernard (1813-1878) conceived of viruses as "alterations of liquids under nervous influences" or as "septic liquids"[2] which could cause illness from both inside and outside of the body. At the end of the 19th century, viruses came to be understood as microbial agents that passed through a ceramic filter and could not be cultured, as bacteria could[3]. According to the germ theory of infectious diseases developed by Louis Pasteur (1822-1895) and Robert Koch (1843-1910), each infectious disease was associated with a specific micro-organism visible under the microscope, which could be grown on an appropriate nutrient medium and retained by a Chamberland filter[4]. A category of particularly small, filtering infectious agents, known as filtering viruses, passed through these filters. Since they could not be captured in the hides of infected animals, nor could they be seen through the microscope lenses of the time[5], these viruses remained an enigma in microbiology. But by the end of the 19th century, Mayer and Ivanovski (in 1892), followed by Beijerinck (in 1898), showed that the causal

1. A collection of his writing from 1858 to 1877 was posthumously published in 1947 and again in 1987 by Presses Universitaires de France (PUF) under the title: *Principes de médecine expérimentale*.
2. Claude Bernard, Léon Delhoume, and Léon Binet, *Principes de médecine expérimentale*, 2e éd, Quadrige (Paris: PUF, 1987), pp. 187-208.
3. "Filterability was, until the early 1950s, the defining criterion for identifying viruses. But this was an insufficient definition, especially because certain bacteria, such as mycoplasma, could pass through the filters that were being used. The data from research on TMV and phages drove André Lwoff (1902-1994) to propose a clear and discriminating definition of viruses in the early 1960s." (quote from virologist Henri Agut, in Henri Agut, 'Une histoire de la virologie', *médecine/sciences* 38, no. 12 (December 2022): 979-89, https://doi.org/10.1051/medsci/2022162).
4. Named after Charles-Edouard Chamberland (1851-1908), a French biologist and physicist, as well as Pasteur's assistant, who invented said filter (see Marian C. Horzinek, 'The Birth of Virology', *Antonie van Leeuwenhoek* 71, no. 1 (1 February 1997): 15-20, https://doi.org/10.1023/A:1000197505492; or on Institut Pasteur's website 'Charles Chamberland, l'inventeur d'outils de stérilisation', Institut Pasteur, 9 November 2018, https://www.pasteur.fr/fr/institut-pasteur/notre-histoire/charles-chamberland-inventeur-outils-sterilisation).
5. It was only after the second half of the 20th century and the development of electronic microscopy that nanometer-level (a billionth of a meter) observations were possible: a virus such as the flu measures approximately 100 nanometers.

agent of tobacco mosaic was a new type of infectious agent that multiplied in the cells of its host. Beijerinck named this agent *contagium vivum fluidum*. From then onwards if inoculation of a healthy animal or animal with a filtrate obtained by means of a Chamberland filter reproduced the same illness as in the organism from which it had been taken, a virus was deemed the cause. However, the true nature of these viruses and their infective mechanisms remained unknown. Experimentation therefore involved understanding how to transmit symptoms characteristic of supposedly viral diseases. In the same way, the demonstration of the airborne transmissibility of the influenza virus preceded the understanding of what the influenza agent, and a virus in general, was. It was against this backdrop of relative ignorance that Auguste Trillat (1861-1944) nevertheless demonstrated that the disease identified as influenza could be transmitted in the form of microbial aerosols.

This study explores key experimental milestones that elucidated the airborne transmission of influenza, focusing particularly on Auguste Trillat's early 20th-century demonstration, which established a critical link between the meteorology and epidemiology of the disease. We also investigate how Trillat's work was rooted in his effort to naturalize miasma theory, integrating it with the emerging scientific paradigms of his era. By tracing how Trillat's experimental practices progressively revealed the airborne properties of influenza, this article aims to offer a modest contribution to the history of virology. While acknowledging viruses as causative agents of disease, independent of human perception, we also recognize that scientific theories about them are continually subject to refinement and revision. This article draws on a wide range of sources to analyze Auguste Trillat's contributions to medical meteorology and virology. Archival materials from the Institut Pasteur, Trillat's own scientific publications, and contemporary press articles form the core of this research. Additionally, other scientific articles and books are consulted to contextualize his work within broader historical and scientific frameworks.

This article is organized into eight sections. In this introduction, we situate Trillat's work within the historical evolution of virology and research on airborne transmission. The second section (The Life of Auguste Trillat) provides a biographical overview of his multidisciplinary career as a chemist, inventor, and epidemiologist. The third section (The Adaptation of Miasma Theory to Pasteurian Ideas) examines how Trillat integrated elements of miasma theory with Pasteurian microbiology. In the fourth section (1913: Condensation Nuclei, or the Missing Link), we focus on his identification of condensation nuclei as a key mechanism in airborne disease transmission. The fifth section (Trillat and Influenza) explores his influenza research, particularly his contributions during and after the 1918-1919 pandemic. The sixth section (Experimental Airborne Transmission of Influenza) discusses his experiments validating microbial aerosols as vectors for airborne disease transmission. In the seventh section (The Physics of Microbial Aerosols and the Posterity of this Concept), we contextualize his work within broader scientific discourse, highlighting its connections to aerosol physics and its impact on microbiology. Finally, the Conclusion reflects on Trillat's enduring legacy, framing his contributions as significant to advancing the integration of environmental factors into epidemiological and virological theories.

## 2. The life of Auguste Trillat

Auguste Trillat was a prominent French chemist, as well as a prolific inventor and the architect of the first French biological warfare program at the beginning of the First World War[6]. At the turn of the 19th century, he carried out pioneering research on microbial aerosols[7]. Born in Isère, France, he studied in Valence and Geneva, then began a chemical engineering career in the 1880s in Switzerland and Germany, where he mainly studied formaldehyde (also known as methanal) and its applications. In 1891, he patented a formaldehyde solution under the name *formol*, along with many other innovations patented in Europe and the United States, including a process for making roquefort cheese. Following a series of positions in various industries in France in the 1890s, he rapidly rose both professionally and politically around the turn of the 19th century. In 1898 he became a lecturer at the *École de Physique et Chimie de la Ville de Paris*, and two years later, in 1900, he became a Foreign Trade Advisor[8] of the French Government. He was appointed head of the *Institut Pasteur* hygiene research department in 1905. This position deter-

6. See also Etienne Aucouturier, 'Auguste Trillat: Épidémiologie et immunologie de guerre', *Revue d'histoire des sciences* 67, no. 1 (18 July 2014): 115-50, https://doi.org/10.3917/rhs.671.0115.
7. A full chronology of the qualifications and works of Auguste Trillat is available on the website of the Institut Pasteur: "Auguste Trillat (1861-1944) Repères Chronologiques," accessed March 17, 2024, https://webext.pasteur.fr/archives/tri0.html.
8. Conseiller du Commerce Extérieur.

mined the aims of his research, which he devoted primarily to epidemiology, from this point, and for nearly 30 years until his retirement from the institute in 1934. From 1915 to 1918, during the First World War, his laboratory was designated an annex laboratory for the studies of chemical warfare, and he was appointed adviser to the Ministries of War and of the Navy on artificial clouds and the protection of light metals against corrosion. At that time, he also became the head of the biochemistry department at the *Institut Pasteur* and member of the Paris Public Health and Hygiene Council[9]. In 1922, the Ministry of War commissioned him to prepare a foundational report on the establishment of the first state biological and chemical warfare program in France. He retired in 1934, was elected a member of the French Academy of Medicine in 1937, and died in 1944 in Douar-Chott, near Carthage, Tunisia. His research in the fields of epidemiology and medical meteorology proved to be decisive in understanding how to include environmental factors of epidemics within the realm of microbiological theory.

He became more specifically interested in viruses, particularly influenza, after the unprecedented so-called "Spanish" flu pandemic of 1918-1919. His research in the fields of hygiene, bacteriology, epidemiology, and medical meteorology developed over the course of about fifty years, from the early 1890s to the late 1930s. The common denominator between that research and all his other work (from pure chemistry to chemistry applied to a wide variety of industrial sectors, to microbiology, meteorology, and the history of science and technology) is formaldehyde. He systematically researched its every possible industrial and sanitary application. In the fields of hygiene and epidemiology, he was interested in all pathogenic agents, including influenza, because he wished to understand the influence of meteorology on the trajectories of epidemics. It is contended in this paper, that it was only after a series of Trillat's and other scholars' research papers about aerosols were accepted and disseminated at an international level in the 1930s that the great influenza pandemic of 1918-19 began to be understood as an airborne illness. There was thus a noteworthy delay between the pandemic's occurrence, and it being understood in the fields of microbiology and medical meteorology.

Trillat's research, nearly forgotten in the middle of the 20th century, was rediscovered in the late 1990s. Primarily through the work of Olivier

9. Conseil d'hygiène et de salubrité de la Seine.

Lepick[10] and Patrice Binder[11]. His work also received attention in a remarkable synthesis published by Jeanne Guillemin in 2005[12]. Each of these studies focused on Trillat's major contributions to the French biological and chemical warfare programs. In 2014, Etienne Aucouturier advanced work begun by Lepick and Binder in an initial article[13] about Trillat's theories of the dynamics of epidemics, which was based on archival research at the *Institut Pasteur* in Paris. In 2017, Aucouturier also devoted an entire chapter to Trillat in a study on France's biological warfare program[14] (translated and published in English in 2020).

The possibility of airborne transmission of viral infectious diseases now seems obvious, particularly after the Covid-19 pandemic, during which we had to protect ourselves against infectious aerosols using respiratory masks to limit the spread of the virus. This mode of transmission, now precisely documented scientifically[15], was not apparent at the beginning of the 20th century when miasma theory continued to influence the popular and scientific imagination of disease transmission. Despite the famous controversy in this era between Pouchet and Pasteur on the issue of spontaneous generation —in which Pasteur's pathogenic model was vindicated, it was still commonly believed that diseases were produced in, if not by, polluted or supposedly rotten air. If Trillat did not seek to rehabilitate the theory of spontaneous generation, he nevertheless sought to partially save miasma theory, at the heart of which he believed there to be a relevant intuition as to which atmospheric conditions fostered the spread of epidemics.

10. Olivier Lepick, 'Le Programme Français De Guerre Biologique: 1919-1945', *Guerres Mondiales et Conflits Contemporains*, no. 185 (1997): 29-54.
11. Patrice Binder and Olivier Lepick, *Les Armes Biologiques* (Presses Universitaires de France - PUF, 2001), p. 47.
12. Jeanne Guillemin, *Biological Weapons: From the Invention of State-Sponsored Programs to Contemporary Bioterrorism* (New York: Columbia University Press, 2005), pp. 24-29.
13. Aucouturier, 'Auguste Trillat'.
14. Etienne Aucouturier, *Biological Warfare* (Editions Matériologiques, 2020), pp. 61-72.
15. For example, in these works modeling the dispersion of Sars-Cov-2 droplets on public transit created by investigators from the French Alternative Energies and Atomic Energy Commission (CEA, France): Patrick Armand and Jérémie Tâche, '3D Modelling and Simulation of the Dispersion of Droplets and Drops Carrying the SARS-CoV-2 Virus in a Railway Transport Coach', *Scientific Reports* 12, no. 1 (7 March 2022): 4025, https://doi.org/10.1038/s41598-022-08067-6.

## 3. The adaptation of miasma theory to Pasteurian ideas

In his book *Inventing Temperature*, historian and philosopher of science Hasok Chang introduced a definition of history and philosophy of science as a "complementary science"[16], with the purpose of the "continuation of science by other means", a paraphrase of General von Clausewitz's characterization of the relationship between politics and war. Auguste Trillat, who was not only an engineer, chemist, and microbiologist, but also a historian of science, seems emblematic of this understanding of history of science. To support his intuition that miasma theory should not be completely abandoned, he looked not only to experimental work but also history for the means our ancestors might have used to try to defend themselves against major epidemics, despite their ignorance of underlying causes and determinants. In 1905, the year when he began working at the *Institut Pasteur*, he started cataloguing all the uses of fumigation that had been made during past plague epidemics and assessing the relevance of the process for disinfecting the air, based on his knowledge of the antiseptic properties of formaldehyde[17].

A few years later, and after much experimentation, Trillat, who had by that time worked on air quality and how to infect and disinfect it for nearly twenty years, publicly discussed, in a more theoretical respect, the importance of not discarding elements originating from miasma theory from modern epidemiology. During a conference held at the University of Geneva on July 20th, 1912, he reported on his historical research on fumigation techniques, after having previously published it in the *Archives des sciences physiques et naturelles* under the title *Sur la théorie miasmatique et les idées du jour*[18]. This process, formerly used against epidemics, had particularly drawn his attention because it was closely linked to his substance of choice, formaldehyde:

> I was able to demonstrate that the Ancients, without knowing the effects of formaldehyde, nevertheless observed its effects through its deodorizing

16. Hasok Chang, 'Complementary Science-History and Philosophy of Science as a Continuation of Science by Other Means', in *Inventing Temperature: Measurement and Scientific Progress*, ed. Hasok Chang (Oxford University Press, 2004), https://doi.org/10.1093/0195171276.003.0006.
17. Auguste Trillat, 'Etude historique sur l'utilisation des feux et des fumées comme moyen de défense contre la peste.', *Annales de l'Institut Pasteur: journal de microbiologie* Novembre, no. 11 (1905): 734-52.
18. Auguste Trillat, 'Sur La Théorie Miasmatique et Les Idées Du Jour', *Archives Des Sciences Physiques et Naturelles* 33 (1912): 500-523.

> properties. They often placed themselves in very favourable conditions for disinfection by choosing substances to burn and methods of combustion that produced formaldehyde vapors[19].

He showed that in many societies, from the time of Hippocrates to the beginnings of hygienics in the 19th century, "fires and fumes"[20] were produced with the aim of disinfecting the air. Trillat worked to support his historically derived thesis experimentally, by evaluating, on the basis of numerous practices described in historical texts, to what degree these fumigation practices would have been able to produce enough formaldehyde vapours such that they would have had a truly destructive effect upon the microorganisms supposedly present in the air in the contexts described during past epidemics.

The widespread use of juniper berries in the fumigation preparations detailed and examined by Trillat aligns with his thesis because they are "one of the substances whose incomplete combustion yields the highest levels of polymerized formaldehyde"[21], the substance akin to *formol*, patented by Trillat in 1892. Through testing the combustion of various mentioned substances, Trillat demonstrated that "the ancient physicians unknowingly created a potent antiseptic... formaldehyde!" He also listed various deodorization methods and devices, such as "perfume burners"[22] found at the British Museum in London, which he regarded as unintentional disinfection devices. Even now, do we not often strike a match —the satisfying and traditional deodorizer— to freshen our bathrooms or other spaces? In this speech given at the University of Geneva, Trillat gave numerous examples of similar practices in his day, which we now regard as outdated:

> Everyone is familiar with the practice of burning sugar on a heated shovel or burning juniper seeds in the rooms of the sick or dead, to remove unpleasant odors. It is still common practice among well-diggers to light braziers in wells, to correct the exhalations of the earth; it is recommended, for example, in certain regions, to introduce lit wood faggots into wells, which are then left to burn out[23].

19. Institut Pasteur, 'Notice Sur Les Titres et Travaux Scientifiques de M. A. Trillat', 1921, Institut Pasteur, pp. 18-19.
20. Trillat, 'Sur La Théorie Miasmatique et Les Idées Du Jour', p. 505.
21. Trillat, p. 510.
22. Trillat, p. 512.
23. Trillat, p. 512.

The aim of this historical and experimental study was to show that his contemporary work on medical meteorology and air disinfection with formaldehyde was connected with millenary practices: but it was also to challenge the idea that the age-old miasma theory, according to which the rotting of the air itself was the cause of epidemics, was unfounded.

In experimentally studying the nutritive qualities of air, depending on whether it contained the products of putrefaction, on a variety of known pathogens ("diphtheria, typhoid and plague"[24]), and rigorously comparing the effects of "contaminated" versus "control"[25] air, Trillat was able to conclude in that microorganisms cultured in putrefying atmospheres grew about three times as fast as in control air[26]. By repeating this experimental method in the study of the link between vitality of microbes in the air and a great diversity of putrefying matter ("Animal products, plant products, marsh mud, topsoil, sewage water, breath gases, etc."[27]), Trillat was able to conclude that there were environments favourable to the development of pathogenic microorganisms, but that the presence of putrid gases was not a sufficient condition to "make the atmosphere more favourable to the preservation of microbes"[28]. This synthesis, which Trillat called for and achieved in epidemiology, between age-old empirical knowledge and modern biology, was later brilliantly summed up in an article published by Louis Pasteur's grandson in the *Revue des deux mondes*, in 1938:

> Before Pasteur, contagion was explained in terms of noxious gases, volatile substances emanating from patients and corpses, and miasma. Pasteur demonstrated the role of microbes and immediately transformed all notions of epidemiology; instead of invoking a mysterious process, we finally grasped the mechanism of contagion. Today, with the theories of M. Trillat, we are back to the concept of the atmosphere as an agent of contagion, but an agent of contagion because a vector of microbial germs[29].

This idea lies at the heart of Trillat's original conception of microbial aerosols and was the basis of his meteorological conception of epidemio-

24. Trillat, p. 517.
25. Trillat, p. 517.
26. Trillat, 'Sur La Théorie Miasmatique et Les Idées Du Jour', p. 517.
27. Trillat, p. 517.
28. Trillat, p. 517.
29. Joseph Louis Pasteur Vallery-Radot, 'Questions Médicales: Météorologie Et Médecine', *Revue Des Deux Mondes (1829-1971)* 44, no. 3 (1938): 658-73.

logy, which he continually strived to support experimentally, by naturalizing miasma theory. In his belief, specific physicochemical atmospheric factors (primarily pressure, temperature, and humidity) served as reliable predictors of epidemic trajectories. Air, which he believed could contain "nutritious gases"[30], acted as an airborne nutrient medium and provided a "favourable environment"[31] for the development of pathogenic microorganisms, and he was now able to prove this experimentally[32].

## 4. 1913: Condensation nuclei, or the missing link

The year 1913 was marked, in Trillat's own words, by an "important stage"[33] in his epidemiological research. He had been working on applications of formaldehyde in epidemiology since around 1906, and made the discovery that "microbes suspended in the air act as condensation nuclei of humidity and can form microbial droplets of which they occupy the centre"[34]. He was acquainted with the research of Carl Flügge on salivary droplets[35] and their contagiousness, which he claimed had "already been reported by French authors and later by Flügge"[36]. In his work and publications, he regularly makes claims of anteriority or authorship of certain discoveries, or defensive remarks about foreign scientific work, particularly of German origin[37]. This is particularly true of synthetic resins, derived from casein formaldehyde, which he developed as early as 1896 and which "Bakeland studied in greater depth to make plastics known as 'Bakelites'"[38]. His least cordial remarks are

30. "Gaz aliments" in French, in Institut Pasteur, 'Notice Sur Les Titres et Travaux de M. A. Trillat' (Imprimerie Barnéoud, 1933), Institut Pasteur.
31. Institut Pasteur.
32. For a more detailed perspective on Trillat's experiments with air infection and disinfection, see also Aucouturier, 'Auguste Trillat'.
33. Institut Pasteur, 'Notice Sur Les Titres et Travaux Scientifiques de M. A. Trillat'.
34. Institut Pasteur.
35. Carl Flügge, 'Ueber Luftinfection', *Zeitschrift für Hygiene und Infektionskrankheiten* 25, no. 1 (1 February 1897): 179-224, https://doi.org/10.1007/BF02220473.
36. Institut Pasteur, 'Notice Sur Les Titres et Travaux de M. A. Trillat'.
37. This Franco-German competition seems to have become widespread between the Pasteurians and German researchers and industrialists, mirroring the original rivalry between Pasteur and Koch (see: Agnes Ullman, 'Pasteur-Koch: Distinctive Ways of Thinking about Infectious Diseases', *American Society for Microbiology* 2, no. 8 (2007): 383-87).
38. Institut Pasteur, 'Notice Complémentaire Sur Les Titres et Travaux de M. Trillat. Sciences Appliquées à l'industrie' (Imprimerie Barnéoud, Laval, 1924), Institut Pasteur.

directed at his colleagues in German industry, with whom he collaborated for nearly fifteen years at the beginning of his career in the last decades of the nineteenth century, and whose intellectual honesty and integrity he questions in several passages:

> This is illustrated by the fact that in some German monographs, my name is not mentioned in relation to the names of the Casein formaldehyde I developed, the word Formol and the word Urotropin. This is because the Germans called Galalith what I had called Casein formaldehyde, Formalin what I had called Formol and Urotropin what I had called Formin. [...] These examples show the systematic way in which the Germans monopolise the precedence of our inventions[39].

By the early 1900s his studies in medical meteorology were proving pivotal in the area of airborne transmission. However, the limited international dissemination of his work in the 1920s can largely be attributed to scientific, industrial, political, and military competition —particularly concerning the development of biological and chemical weapons[40]— in the aftermath of World War I.

In a brief lecture delivered before the Académie Nationale de Médecine at the close of 1914, just over three months before the outbreak of World War I, Trillat introduced the concept of "condensation nuclei", which he regarded as central to a "novel theory"[41]. What was new about this theory was that it proposed a deterministic model of the role of the environment of pathogenic microorganisms as a vector for epidemics. In line with the synthesis that Trillat called for between miasma theory and Pastorian microbiology, these "condensation nuclei" provided the missing link: "in short, the relationships between the transmission of epidemics by airborne germs and meteorological phenomena derive from the property of germs to function as condensation nuclei"[42] Over the ensuing decade, Trillat refined this model and subjected it to experimental testing. He systematically substantiated it, using a variety of animals and infectious agents, across diverse circumstances and contexts.

39. Institut Pasteur.
40. Aucouturier, *Biological Warfare,* pp. 61-72.
41. Auguste Trillat, 'Relations entre les phénomènes météorologiques et les épidémies transmissibles par l'air', *Bulletin de l'Académie nationale de médecine*, no. 36 (1914): 262-64.
42. Trillat.

He also demonstrated, through a series of measurements, that the scenario in which air is most likely to serve as a disease vector is that of "recently exhaled air, which forms an environment highly conducive to epidemic propagation due to its moisture content, the vesicular nature of this moisture, the emission of nutritious gases, and the continuous seeding occurring therein"[43]. This work on condensation nuclei earned him peer recognition and established a strong link between meteorology and epidemiology. The impact of climatic factors (such as humidity, temperature and pressure) on morbidity and mortality from flu is still considered to be relevant and decisive to this day[44]. Knowledge of the airborne transmission of viruses was also decisive in the fight against the Covid-19 pandemic, in that among other prophylactic measures it made it clear that it was important to wear masks and ventilate rooms to limit the transmission of the virus through exhaled air, something that was still not self-evident in 2019, at the onset of the pandemic[45].

## 5. Trillat and influenza

After the war, it appears that to Trillat and the medical community of his era, the focal point of epidemiological inquiry was not the recent Spanish influenza pandemic (1918-1919), but rather the earlier so-called Russian influenza outbreak of 1889-1890. This epidemic was extensively documented in France by "M. Masson, Hygiene Inspector in Paris at the time", and in Central Europe by "Russian scientists [who] meticulously recorded all accompanying factors"[46]. During a lecture at the *Académie Nationale de*

43. Auguste Trillat, 'Influence Des Agents Météorologiques Sur La Propagation Des Épidémies. Établissement Des Diagrammes', *Bulletin de l'Académie Nationale de Médecine*, no. 17 (1921): 509-12.
44. For more, see this longitudinal study by Robert E. Davis, Colleen E. Rossier, and Kyle B. Enfield, 'The Impact of Weather on Influenza and Pneumonia Mortality in New York City, 1975-2002: A Retrospective Study', *PLOS ONE* 7, no. 3 (28 March 2012): e34091, https://doi.org/10.1371/journal.pone.0034091.
45. Lidia Morawska and Donald K Milton, 'It Is Time to Address Airborne Transmission of Coronavirus Disease 2019 (COVID-19)', *Clinical Infectious Diseases* 71, no. 9 (1 November 2020): 2311-13, https://doi.org/10.1093/cid/ciaa939.or room scale.
46. Auguste Trillat, 'Influence Des Agents Extérieurs Sur La Marche Des Épidémies Transmissibles Par l'air et Par l'eau. Cas de La Grippe et de La Fièvre Typhoïde', *Bulletin de l'Académie Nationale de Médecine*, no. 24 (1930): 698-701.

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*Médecine* in spring 1921, Trillat supported his condensation nuclei theory using this epidemic as an example[47]. He specified that “when we say that the air spreads disease, we mean that the air can carry these germs via the moisture it contains in vesicular form”[48]. On comparing the mortality graph and meteorological data, each of which is well documented “both in France and abroad”, he observed an almost perfect concordance between the relative humidity of the atmosphere and mortality: the higher the relative humidity, the higher the mortality. He regretted that previous comparisons only considered absolute humidity during the epidemic, which didn’t align with mortality rates. He also noted a reverse correlation with temperature: “its lowering increases the rate of relative humidity and consequently the vesicular state of humidity”[49].

Trillat had just witnessed, in France, at the end of the First World War, the great so-called Spanish influenza pandemic between 1918 and 1919. Why does he seem to have neglected the scientific study of the environmental causes of this disease, when he was widely quoted in the press at the time and regarded in France as a specialist in the field? A number of factors documented elsewhere justify this apparent omission. Firstly, the Spanish flu pandemic was too recent, and its international scale made it impossible to use epidemiological data reliably within such a short timeframe[50]. The near-simultaneity of the war and the pandemic also contributed to the natural phenomenon being overshadowed by the political phenomenon, with the latter having a greater impact on public opinion: influenza was one more piece of bad news in wartime, and the press seems to have censored itself massively on the subject[51]. A conspiratorial atmosphere in French public opinion as to the geographical origin of the pandemic at the end of the war and whether or not it was intentional, may also have determined this choice. According to Pierre Darmon, citing the archives of the *Préfecture de police de Paris*:

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47. Trillat, ‘Influence Des Agents Météorologiques Sur La Propagation Des Épidémies. Établissement Des Diagrammes’, p. 699.
48. Trillat, p. 699.
49. Trillat, p. 699.
50. Trillat, ‘Influence Des Agents Météorologiques Sur La Propagation Des Épidémies. Établissement Des Diagrammes’, p. 699.
51. Freddy Vinet, *La Grande Grippe: 1918, La Pire Épidémie Du Siècle: Histoire de La Grippe Espagnole*, Collection Chroniques (Paris: Vendémiaire, 2018).

> According to the rumour circulating, military medical officers believe that the Spanish flu epidemic was caused by the consumption of canned food from Spain, into which bacilli had been introduced. It is also said that many canning factories are in German hands. It is also claimed that oranges were similarly inoculated[52].

This last quote is also evocative of the lack of knowledge about the nature of the causal agent of influenza and the controversial nature of the origin of the pandemic[53]. To the extent that the disease's existence itself was brought into question[54]. There was talk of Pfeiffer's bacillus[55], but also of pneumococcus, streptococcus and the so-called Annamites' disease[56].

As a result, Trillat seems to have been unwilling or unable to study the 1918-1919 pandemic scientifically, as he was unable to access reliable epidemiological data, and he may also have been mobilised or too busy with his secret projects for the Navy or concerning biological and chemical warfare. However, his name was consistently featured in French newspapers from the onset of the epidemic, underscoring his scientific renown in France and the widespread acceptance of his condensation nuclei theory. He was well known throughout the national and regional press from the 1890s, largely as a result of his inventions of disinfection devices using formaldehyde vaporisation.

While he couldn't conduct scientific research on the Spanish flu pandemic at the time, he didn't stay entirely silent during the outbreak. In October 1918, he appeared before the *Académie de Médecine* to give his advice on how to protect oneself against the disease, drawing on his work on exhaled air. This advice was subsequently widely reported in the press:

> Alongside isolation and disinfection, it would be wise to contemplate removing respiratory droplets from patient rooms and crowded spaces. This

52. Pierre Darmon, 'Une tragédie dans la tragédie: la grippe espagnole en France (avril 1918-avril 1919)', *Annales de démographie historique* 2000, no. 2 (2001): 153-75, https://doi.org/10.3406/adh.2001.1982.
53. Anne Rasmussen, 'Dans l'urgence et le secret. Conflits et consensus autour de la grippe espagnole, 1918-1919', *Mil neuf cent. Revue d'histoire intellectuelle* 25, no. 1 (2007): 171-90, https://doi.org/10.3917/mnc.025.0171.
54. Frédéric Vagneron, 'La grippe existe-t-elle?', *Revue d'anthropologie des connaissances* 15, no. 3 (1 September 2021), https://doi.org/10.4000/rac.24324.
55. A bacterium now known as *Hæmophilus influenzae*, earlier named after the German biologist and doctor Richard Pfeiffer (1858-1945).
56. Darmon, 'Une tragédie dans la tragédie'.

> may be achieved either by appropriate ventilation, or by the use of cooling surfaces as I have already suggested, or by exhaust devices. The complete removal of moisture from clothing by exposure to the sun or a source of heat is also advisable. Finally, I would point out that the old practices of fumigation and deodorization, still commonly used by the general public, are not to be discarded, because in the absence of absolute disinfection, they are able to saturate nutritious gases and to hinder microbial growth by their more or less antiseptic emanations[57].

In October 1918, the newspaper *L'Œuvre* quoted him extensively on the influenza epidemic:

> Influenza is transmitted by exhaled air, which is not only a transient microbial carrier but also, by virtue of its humidity and gaseous elements, an airborne culture medium in which, if circumstances are favourable, the multiplication of microbes is instantaneous. Mr Trillat of the *Institut Pasteur*, pursuing his series of experimental investigations into the mechanism of contagion of airborne diseases, explains how his theory can be applied to the current influenza epidemic. Mr Trillat has studied the properties of these microbial droplets; in a propitious atmosphere, in their nascent state, microbes act as condensation nuclei for moisture, forming droplets that evade gravity [...] Mr Trillat recommends rapid and continuous evacuation of the moisture produced by breathing[58].

Meanwhile, the daily Algiers newspaper *Les nouvelles* of 5 December 1918 indicated, quoting Trillat, "what you need to know about influenza and how it spreads":

> When we speak, cough or sneeze, we project moist droplets, a microbial cloud, from a distance varying from 0.50 centimetres to a metre or more, which, under certain atmospheric conditions, can spread not only into the room, but also into neighbouring rooms. We carry these germs with us in the felting of our clothes, hair and beard[59].

In the second phase of the pandemic, on March 18, 1919, the newspaper *Le Matin* featured an article under the heading "L'air, bouillon de culture",

57. Auguste Trillat, 'Rôle de l'air Expiré Dans La Transmission Des Épidémies', *Bulletin de l'Académie Nationale de Médecine* 80, no. 26 (1918): 369-72.
58. Anonyme, 'L'épidémie de Grippe', *L'oeuvre*, March 1918, p. 3.
59. Anonyme, 'La Grippe', *Les Nouvelles*, December 1918, p. 2.

preceding a section on a purportedly mysterious flu complication (sudden hair loss). Here, one could find an exposition of his condensation nuclei theory: these "air particles evaluated for their capacity to condense moisture and create fog"[60]. A week later, *Le Figaro* (and other national and regional newspapers such as *L'Est-Éclair*) also featured an article advertising a pharmaceutical antiseptic against influenza (*Aniodol*), using Trillat's authority as a selling point:

> There is every reason to fear [...] that influenza will become endemic in the future, according to the experiments of Mr. Trillat, who has shown that atmospheric air flowing over decaying organic matter is charged with noxious particles that promote the revival of the germs it contains and carry the disease far and wide[61].

While Trillat didn't focus on the Spanish flu epidemic as it unfolded, he continued to serve as a point of reference for the press and the public regarding public health issues during the challenging post-World War I years. The pandemic must subsequently have encouraged the dissemination of his epidemiological work, as well as prompting him to continue his work on influenza.

## 6. Experimental airborne transmission of influenza by microbial aerosols: Trillat's experiments in the 1930s

Trillat's research on experimental airborne disease transmission received frequent mention in French scientific literature from the conclusion of World War I until the early 1930s, particularly in contexts where a correlation between meteorological conditions and epidemic patterns was delineated. Similarly to his French colleagues, Trillat received scant acknowledgment outside France, save for sporadic mentions of his studies in the 1920 edition of the *American Meteorological Society's Monthly Weather Review*, also

60. Anonyme, 'La Grippe Espagnole. L'épidémie Semble Périodique. Va-t-Elle Recommencer En Avril? On Envisage Cette Hypothèse.', *Le Matin*, March 1919, p. 2.
61. Dr B. de Cordebugle, 'La Grippe. Doit-on La Considérer Comme Une Maladie Périodique?', *Le Figaro*, March 1919, p. 4.

brought before the *Académie des Sciences* in that same year[62,63]. In France and Switzerland, his work seems to have been more widely recognized at the time, but he was probably somewhat marginalized in the scientific community for wanting to save miasma theory, which could be seen as retrograde, as can be read between the lines of this excerpt from an article in the *Bulletin de la Murithienne* (the bulletin of the Valais Society of Natural Sciences): "According to Trillat's research, it would appear that humidity plays a role as an agent in the propagation of infectious diseases and epidemics. This author revives in a scientific form the ancient miasma theory which, before the Pastorian discoveries, explained the origin of infectious diseases"[64]. This relative invisibility ended with the publication in 1938 of a series of articles on microbial aerosols, four years after his retirement and six years before his passing in Douar-Chott in 1944.

From 1913, Trillat would persistently publish papers reinforcing his condensation nuclei model, buttressing his amalgamation of miasma theory and contemporary microbiology. This model had been confirmed by numerous experimental studies, when, in the early 1930s, Wilson Smith, Christopher Andrewes, George Dunkin and Patrick Laidlaw published their confirmation of the 1926 hypothesis that influenza was caused by a filtering virus[65] and not by a bacillus or another bacteria: building on the work of Richard Shope, Charles Stuart-Harris and Thomas Francis Jr, they "showed that inoculation of a ferret[66] with filtrates of nasopharyngeal secretions from men suffering from influenza causes the animal to develop a disease that is contagious to the ferret and even to man"[67]. René Dujarric de la Rivière, who had already pointed out as early as 1918 that influenza was probably due to a filtering

62. Auguste Trillat, 'The Influence of the Variation of the Barometric Pressure on the Microbial Droplets in Suspension in the Atmosphere', *Monthly Weather Review* 48, no. 5 (1920): 284-284, https://doi.org/10.1175/1520-0493(1920)48<284c:TIOTVO>2.0.CO;2.
63. Auguste Trillat, 'The Influence of Infinitesimal Traces of Nutritive Substance in the Humidity of the Air upon Contagion', *Monthly Weather Review* 48, no. 9 (1 September 1920): 508-508, https://doi.org/10.1175/1520-0493(1920)48<508:TIOITO>2.0.CO;2.
64. Marcel Bornand, 'L'influence Des Phénomènes Atmosphériques Sur l'organisme', *Bulletin de La Murithienne*, no. 50 (1932): 84-101.
65. Wilson Smith, C. H. Andrewes, and P. P. Laidlaw, 'A Virus Obtained from Influenza Patients', *The Lancet* 222, no. 5732 (8 July 1933): 66-68, https://doi.org/10.1016/S0140-6736(00)78541-2.
66. Ferrets are perfect animal subjects for the study of influenza affecting humans because it is easily transmitted to them.
67. René Dujarric de la Rivière and Jean Chevé, 'Le virus grippal du furet, Étude de sources françaises du virus grippal', *Annales de l'Institut Pasteur* 59 (1937): 445-456.

virus[68] (by inoculating himself with filtrates from "four of the most serious cases of influenza"[69]), and Jean Chevé also pursued and verified this work by injecting the virus into ferrets[70] in France in 1937. These experiments and others firmly established the viral aetiology of influenza, challenging the generally accepted idea that it was caused by Pfeiffer's bacillus or some other bacteria. Subsequently, Trillat embarked on illustrating that this filtering virus could also be transmitted via air, aligning with his condensation nuclei framework.

In 1938, alongside Arthur Beauvillain, Trillat showcased the airborne transmission of human influenza to ferrets through the pulmonary and ocular pathways, employing an influenza virus preparation akin to that utilized by Dujarric de la Rivière and Chevé the year prior[71]. In their article entitled *Essai de transmission aérienne de la grippe au furet par voie pulmonaire ou oculaire*, they documented experiments in which ferrets were exposed to varying concentrations and durations of influenza virus sprayed emulsions[72]. They also pointed out that "one of them has already shown that certain diseases can be transmitted to animals by inhalation of air containing microbial germs in infinitesimal proportions, in the form of nebulized microbial droplets"[73]. Trillat was referring to his own work on airborne transmission, which predated that of the English and American authors cited: his experiments on airborne transmission of paratyphoid bacillus to mice in 1921 and of cholera to hens in 1931. Trillat and Beauvillain also reported having "found in these trials that contagion occurred with doses of the same order of magnitude as the lethal doses indicated by the authors [Dujarric de la Rivière and Chevé] when administered by injection"[74].

This is the major contribution of Trillat's research: to show that the effects of airborne transmission, which is a passive or natural way of transmitting the disease, are comparable to its experimental artificial transmission by

68. René Dujarric de la Rivière, "La Grippe Est-Elle Une Maladie à Virus Filtrant?" *Comptes Rendus de l'Académie Des Sciences*, October 28, 1918, 606-7.
69. Dujarric de la Rivière, p. 606.
70. Dujarric de la Rivière and Chevé, 'Le virus grippal du furet, Étude de sources françaises du virus grippal', pp. 445-456.
71. Auguste Trillat and Arthur Beauvillain, 'Essai de Transmission Aérienne de La Grippe Au Furet Par Voie Pulmonaire Ou Oculaire', *Compt. Rend. Acad. d. Sc.* 205 (1938): 104-107.
72. Trillat and Beauvillain, p. 105.
73. Trillat and Beauvillain, p. 102.
74. Trillat and Beauvillain, p. 106.

injection. This was also confirmed by the results of ocular transmission. These experiments, on a globally studied infectious agent, firmly established the relevance of Trillat's concept of microbial aerosols: air had been experimentally rehabilitated internationally as a vector of infectious disease.

So it was not lost on Trillat to suggest, at the end of this publication with Beauvillain, that creating aerosols of antiseptics, something he had been striving to achieve for over forty years, could reciprocally be a means of combating influenza:

> [...] comparative experiments carried out under 40-liter bell jars on ferrets have demonstrated that the influenza virus suspended in the air is extraordinarily sensitive to the presence of certain nebulized antiseptics which, at a dose of 1/20000000 calculated roughly by volume, are sufficient not only to infertilize the air, but to kill the virus"[75].

This last excerpt recalls the idea, derived from miasma theory, of air as a seeding medium, able to act as a fertilizer for the cultivation of microbes, as well as the idea of a complementarity between chemistry and biology in the field of hygiene: sterilizing contagious air was as much a sanitary issue as a military one. Trillat and Beauvillain alluded to prospective research in this domain in their 1938 publication, likely thwarted by the eruption of the Second World War the subsequent year.

## 7. The physics of microbial aerosols and the legacy of this concept

Trillat's investigations into airborne disease dissemination during the 1930s, and his introduction of what he termed "microbial aerosols"[76] into the aetiology of infectious diseases across multiple publications, ultimately garnered him acknowledgment, albeit tardily, as a pivotal figure among international scientists advancing comprehension of airborne disease transmission. Commencing in the 1940s, Trillat's inquiries into microbial aerosols featured prominently in leading publications[77] on the topic, garnering attention from

75. Trillat and Beauvillain, p. 107.
76. Auguste Trillat, 'Les aérosols microbiens: applications', *Bulletin de l'Académie nationale de médecine*, no. 2 (1938): 64-74.
77. This continued until the mid 1960s. For example, see: Ronald Hare, 'The Transmission of Respiratory Infections', *Proceedings of the Royal Society of Medicine* 57, no. 3 (1 March 1964): 221-30, https://doi.org/10.1177/003591576405700329.

military circles at the onset of World War II, as evidenced by Sir Christopher Howard Andrewes' 1940 article on air decontamination in air-raid shelters: "Bacteria can be killed in the air by means of persistent mists of very fine particles produced by nebulising certain antiseptic solutions with atomisers of special design. Trillat (1938), who introduced them, called such mists 'aerosols'"[78]. In 1944, an article on airborne infections published by the US Navy also presented him as the inventor of this concept (in his 1938 article on *Les aérosols microbiens*[79]):

> The term aerosol was coined by Trillat in 1938 to designate all microscopic particles suspended in air. Because of their heterogeneity Trillat speaks of these particles as constituting solid and liquid aerosols or live and dead aerosols; fumes and mists are examples of dead aerosols, while suspensions of bacteria and fungi in air are live ones. In English and in American usage the term aerosol refers to non-living substances which can be suspended in the air, the particles being sufficiently small to remain suspended for long periods. In England and America the term infectious nuclei designates small aggregates of pathogenic bacteria or viruses dispersed in air[80].

While Trillat may indeed be credited as the progenitor of this concept in epidemiology, or more specifically, medical meteorology, he conceded in the same 1938 article that the term's initial emergence stemmed from physics, not from his own endeavours:

> When physicists use the term aerosol, they refer to any collection of microscopic particles suspended in the air, irrespective of their nature, by analogy with liquid colloidal suspensions, because they resemble, albeit in a distant way, some of the properties of the latter. [...] I have been able to verify by numerous tests that some of the results obtained by these physicists apply to the microbial aerosols I am about to discuss. [...] In the absence of a more precise definition, I will call "microbial aerosols" the dispersion of microbial particles in the air [...][81].

The physicists to whom he refers, albeit without direct citation, are two German peers, meteorologists, and physicists August Schmauss (1877-1954)

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78. C.H. Andrewes, 'Control of Air-Borne Infection in Air-Raid Shelters and Elsewhere', *The Lancet* 236, no. 6121 (December 1940): 770-74, https://doi.org/10.1016/S0140-6736(00)92121-4.
79. Trillat, 'Les aérosols microbiens: applications'.
80. U.S. Navy Bureau of Medicine and Surgery, 'Air-Borne Infections: A Review', *War Medicine* 4 (July 1943): 1-30.
81. Trillat, 'Les aérosols microbiens: applications', p. 64.

and Albert Wigand (1882-1832), who authored a treatise on the atmosphere as a colloidal system (*Die Atmosphäre als Kolloid*[82]) in 1929, where the term *aerosol* first emerges[83]. Trillat posited that living microbial aerosols adhered to the same physical laws as inert aerosols, including the dry or aqueous particulates prevalent in the atmosphere[84]. However, as he pointed out in *Les aérosols microbiens*, transferring this notion of physics to the field of epidemiology entailed taking additional elements into account:

> Microbial aerosols are quite different from the mineral, organic or electrical sediment-based aerosols discussed above. This is because an important factor comes into play here: life. These are living particles rather than dead ones, and this biological character imparts properties to a microbial aerosol that are not always consistent with the properties of aerosols in general[85].

According to Trillat, this transfer had to take account not only of movements in the surrounding air, but above all of variations in the size of the pathogen, which were decisive in assessing its physical behaviour, and were modified by the age of the pathogen's culture, temperature, hygrometry, atmospheric pressure (itself influencing temperature) and air ionization. Above all, since a dead or biologically non-functional particle is not contagious, understanding the physical mechanisms of aerosol dispersion was not enough to understand its epidemiological or medical dimension:

> The influence exerted by the presence of infinitesimal proportions of gaseous substances is almost nil on aerosols in general: but in the case of a microbial aerosol, it plays a major role. This is because we are now dealing with living rather than inert particles, and Stokes' law no longer applies[86].

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82. The term refers to a state of subdivision, implying that the molecules or polymolecular particles dispersed in a medium have in at least one direction a dimension roughly between 1 nm and 1 µm, or that in a system, discontinuities are found at distances of that order (Source: PAC, 1972, *31*, 577. (*Manual of Symbols and Terminology for Physicochemical Quantities and Units, Appendix II: Definitions, Terminology and Symbols in Colloid and Surface Chemistry*) on page 605 [https://goldbook.iupac.org/terms/view/C01172]).
83. August Schmauss and Albert Wigand, *Die Atmosphäre als Kolloid* (Wiesbaden: Sammlung Vieweg, 1929), https://doi.org/10.1007/978-3-322-98656-6.
84. This was mainly Stokes' formula, which makes it possible to describe the drop speed of droplets in the air by evaluating air particles' drag force.
85. Trillat, 'Les aérosols microbiens: applications', p. 66.
86. Trillat, 'Les aérosols microbiens: applications', p. 70.

Although he generally considered that airborne contagion depended on laws of physics, Trillat concluded that the assessment of the presence of favourable factors in the air ("nutritious gases") or unfavourable factors ("antiseptics") remained decisive in measuring the airborne transmission of a disease, in that these factors determined, in his view, whether the biological functions of pathogens were maintained in the air.

## 8. Conclusion

Trillat played a pivotal role in formulating the concept of microbial aerosols, thereby integrating environmental variables into our comprehension of epidemics, and solidifying the connection between meteorology and epidemiology. Through a substantial corpus of experimental investigations, marginally supported by historical research, Trillat effectively naturalized and incorporated miasma theory into the discourse on epidemic causation. Trillat's research on condensation nuclei and microbial aerosols garnered delayed yet noteworthy acclaim, especially for its elucidation of the epidemiology of human influenza. In doing so, he made pivotal contributions to establishing the groundwork for contemporary comprehension of the airborne dissemination of infectious diseases. Auguste Trillat passed away in relative obscurity in 1944, amid the tumult of the Second World War, his international scientific recognition attained only in the twilight years of his career, during retirement. Nonetheless, his contributions had already left a significant mark on both the French public and military. Following the Second World War, Professor Michel Macheboeuf, Director of the *Institut Pasteur's* Biological Chemistry Department and a notable civilian member of the Medical Commission for Defense against Modern Warfare[87] (1947), paid Trillat a posthumous tribute[88]. Trillat's investigations into microbial aerosols exerted a lasting impact on discussions surrounding modern warfare and aerosol science, a domain crucial in its implications for biological and chemical warfare.

87. The *Commission médicale de défense contre la guerre moderne*, a civilian and military commission that worked to restore France's biological, chemical and nuclear warfare programs, in the post-WWII era.
88. Michel Machebœuf, 'M. A. Trillat (1861-1944)', *Annales de l'Institut Pasteur* 73, no. 7 (1947): 622-23.

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