

The Memory of Water: Investigating Acoustic Imprinting through Low Frequency Resonance

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Abstract

Liquid water exhibits complex collective behavior arising from its continuously fluctuating hydrogen-bond network. Although the term “memory of water” has often been associated with controversial and scientifically unsupported claims, recent experimental and theoretical studies have demonstrated that water supports low-frequency collective dynamics that extend beyond single-molecule interactions. In this work, the concept of memory is redefined in a strictly physical sense as a transient, history-dependent response rather than permanent information storage. The study investigates whether low-frequency acoustic excitation can couple to collective hydrogen-bond dynamics in liquid water, leading to short-lived structural or dynamical persistence that may be interpreted as acoustic imprinting. By synthesizing insights from scattering experiments, ultrafast spectroscopy, and critical methodological analyses, this paper develops a conservative and physically consistent framework for examining acoustic–water interactions. The analysis highlights both the potential mechanisms through which low-frequency resonance may influence collective molecular motion and the experimental limitations that must be addressed to avoid artefacts or over-interpretation. The findings suggest that while long-term memory effects in water are not supported by established physics, transient acoustic imprinting remains a plausible and testable phenomenon within non-equilibrium liquid dynamics.

Keywords: Memory of water; Acoustic imprinting; Low-frequency resonance; Collective hydrogen-bond dynamics; Non-equilibrium liquid behavior

1. Introduction



Water is one of the most extensively studied substances in science, yet it continues to exhibit properties that challenge simple physical descriptions. Unlike many molecular liquids, water forms a dynamically evolving hydrogen-bond network that gives rise to strong intermolecular correlations, anomalous thermodynamic behavior, and complex dynamical responses. These features make water particularly sensitive to external perturbations, especially under non-equilibrium conditions.

Over the years, the phrase “memory of water” has been used in a variety of contexts, often associated with claims that water can retain information about past interactions or stimuli even after their removal. Such interpretations have largely been rejected by the scientific community due to a lack of reproducibility and incompatibility with established physical principles. However, the dismissal of permanent memory claims does not preclude the possibility that water may exhibit transient, history-dependent responses arising from its collective molecular dynamics. Clarifying this distinction is essential for advancing scientifically credible investigations in this area.

Recent experimental advances have demonstrated that liquid water supports collective motions on ultrafast timescales, involving correlated rearrangements of multiple molecules extending beyond the first solvation shell. Low-frequency vibrational and relaxational modes, in particular, are associated with large-scale fluctuations of the hydrogen-bond network. These findings suggest that external perturbations operating on comparable timescales and length scales may influence water’s dynamical behavior in non-trivial ways.

Acoustic fields represent a physically well-defined and experimentally controllable form of such perturbation. Low-frequency acoustic waves induce periodic pressure and density variations in liquids and can couple directly to collective mechanical degrees of freedom. Unlike high-frequency electromagnetic radiation, acoustic excitation interacts with water through macroscopic and mesoscopic modes, making it a promising tool for probing extended dynamical correlations. This raises the question of whether exposure to low-frequency acoustic resonance can temporarily modify the relaxation pathways or correlation lifetimes of the hydrogen-bond network.



The present study is motivated by the need to investigate this question within a strictly conservative physical framework. Rather than invoking permanent information storage, the concept of memory is redefined here as a finite-lived, history-dependent response that decays as the system returns to equilibrium. Within this interpretation, the idea of *acoustic imprinting* refers to short-term dynamical persistence induced by prior acoustic excitation.

The scope of this paper is therefore threefold. First, it aims to place the concept of memory in liquids on a rigorous physical footing by distinguishing transient dynamical effects from unsupported long-term claims. Second, it examines the role of collective hydrogen-bond dynamics as a potential mediator of low-frequency acoustic interactions in water. Finally, it outlines the experimental and methodological constraints necessary to investigate acoustic imprinting reliably, while avoiding artefacts and over-interpretation. By adopting this approach, the study seeks to bridge the gap between established liquid-state physics and carefully formulated hypotheses concerning water's response to acoustic stimulation.

2. Physical Meaning of Memory in Liquids

In physical systems, the term *memory* does not inherently imply permanent storage of information. Instead, it is commonly used to describe situations in which the present state or response of a system depends on its past history. Such behavior is well established in many areas of physics, including viscoelastic materials, glassy systems, magnetic hysteresis, and driven non-equilibrium fluids. In these contexts, memory arises from finite relaxation times, metastable configurations, or delayed responses to external perturbations, rather than from long-term structural encoding.

For simple liquids in thermal equilibrium, molecular motions are typically assumed to be Markovian, meaning that correlations decay rapidly and the system has no long-lasting dependence on prior states. However, this assumption becomes less accurate when strong intermolecular interactions or collective degrees of freedom are present. Liquid water is a notable example, as its hydrogen-bond network introduces cooperative effects that can sustain correlations over extended spatial and temporal scales compared to ordinary molecular liquids.



From a theoretical perspective, memory in liquids can be framed in terms of time-correlation functions and relaxation dynamics. If a perturbation alters these correlations in a measurable way, and the altered response persists for a finite duration after the perturbation is removed, the system may be said to exhibit memory in a physical sense. Importantly, such memory is transient and decays as the system relaxes back toward equilibrium, in accordance with the second law of thermodynamics.

In water, hydrogen bonds are continuously breaking and reforming on femtosecond to picosecond timescales, yet these processes are not purely random. Experimental and computational studies have shown that hydrogen-bond rearrangements often involve coordinated motion of multiple molecules, indicating the presence of collective relaxation pathways. These collective processes provide a natural mechanism through which water may retain short-lived dynamical signatures of prior excitation without undergoing permanent structural change.

It is therefore essential to distinguish between memory as transient dynamical persistence and claims of long-term information storage, which lack experimental support and contradict established physical principles. The former is compatible with modern liquid-state theory, while the latter is not. By adopting this distinction, the concept of memory can be meaningfully applied to liquids such as water without invoking non-physical interpretations.

Within this framework, memory is best understood as a history-dependent response function rather than as a static property. External perturbations—such as mechanical, thermal, or acoustic excitation—may temporarily bias the distribution of molecular configurations or influence relaxation pathways. The persistence of these effects is governed by intrinsic relaxation timescales and dissipative processes within the liquid.

In the present study, this physically grounded interpretation of memory provides the conceptual foundation for examining acoustic imprinting in water. Rather than suggesting permanent encoding, the focus is on whether low-frequency acoustic stimulation can induce measurable, short-lived modifications in collective dynamics. This approach ensures consistency with statistical mechanics while allowing for experimentally testable hypotheses regarding non-equilibrium behavior in liquid water.



3. Hydrogen-Bond Network and Collective Dynamics

The distinctive properties of liquid water arise primarily from its extended hydrogen-bond network, which links individual molecules into a dynamically evolving, three-dimensional structure. Unlike covalent bonds, hydrogen bonds in water are weak and transient; however, their collective organization produces strong intermolecular correlations that significantly influence water's structural and dynamical behavior. As a result, water cannot be accurately described as a collection of independent molecules but must instead be treated as a correlated many-body system.

Early structural studies established that each water molecule participates, on average, in a tetrahedral hydrogen-bond arrangement. While this local coordination is continuously disrupted by thermal motion, experimental evidence from scattering techniques has shown that statistically well-defined short-range order persists in the liquid state. These measurements provide reliable information about average intermolecular distances and coordination numbers, forming the structural baseline for understanding water's behavior.

More recent advances in ultrafast spectroscopy and molecular dynamics simulations have revealed that hydrogen-bond rearrangements in water are not purely local or random events. Instead, they often involve coordinated motion among multiple molecules, extending beyond the first solvation shell. Such collective rearrangements occur on femtosecond to picosecond timescales and are associated with low-frequency vibrational and relaxational modes of the hydrogen-bond network. These modes reflect large-scale fluctuations in molecular orientation and density rather than isolated bond breaking.

Of particular importance are low-frequency collective dynamics, which correspond to motions involving groups of hydrogen-bonded molecules moving in a correlated manner. These dynamics are distinct from high-frequency intramolecular vibrations and are more sensitive to external mechanical perturbations. The presence of such collective modes indicates that the hydrogen-bond network can respond coherently over nanometer length scales, providing a physical mechanism for extended correlations in liquid water.

From a theoretical perspective, the collective nature of hydrogen-bond dynamics implies that perturbations applied to one part of the network can influence neighboring regions through



correlated motion. This does not imply long-term structural stability, but it does suggest that transient dynamical states can propagate through the liquid before dissipating. The lifetime of these states is governed by relaxation processes intrinsic to the hydrogen-bond network, ensuring that equilibrium is ultimately restored.

The existence of collective hydrogen-bond dynamics is particularly relevant when considering water's response to low-frequency excitation. Since these modes operate on timescales comparable to acoustic perturbations, they provide a plausible channel through which mechanical energy may couple to the liquid at a mesoscopic level. This coupling forms the physical basis for exploring whether external stimuli, such as acoustic fields, can temporarily influence the organization or relaxation pathways of the hydrogen-bond network.

In summary, the hydrogen-bond network in liquid water supports collective dynamical behavior that extends beyond individual molecular interactions. These collective dynamics are transient, spatially extended, and inherently dissipative, making them consistent with thermodynamic principles. Understanding this framework is essential for evaluating any claims of history-dependent response in water and provides the necessary foundation for examining acoustic imprinting within a scientifically credible context.

4. Interaction of Acoustic Fields with Water

Acoustic fields represent a well-defined mechanical perturbation capable of interacting with liquids through pressure, density, and velocity fluctuations. When an acoustic wave propagates through water, it induces periodic compressions and rarefactions, leading to oscillatory variations in local pressure and density. These variations can influence intermolecular distances and collective molecular motion, particularly in systems where intermolecular interactions are strong and highly correlated.

In liquid water, the presence of an extended hydrogen-bond network makes the response to acoustic excitation more complex than in simple liquids. Hydrogen bonds are sensitive to changes in intermolecular separation and orientation, both of which can be modulated by pressure fluctuations associated with sound waves. As a result, acoustic fields have the potential to perturb not only individual molecular motions but also collective degrees of freedom involving multiple hydrogen-bonded molecules.



From a mechanistic standpoint, the interaction between acoustic fields and water can be understood at multiple length and time scales. At the macroscopic level, sound propagation is described by classical hydrodynamics, where acoustic waves transport mechanical energy through the medium. At the mesoscopic level, these waves couple to density fluctuations and collective relaxation modes of the liquid. At the microscopic level, periodic pressure modulation can transiently influence hydrogen-bond lengths, angles, and rearrangement pathways.

Low-frequency acoustic excitation is of particular interest because its characteristic timescales overlap with those associated with large-scale collective dynamics in water. Unlike high-frequency electromagnetic radiation, which primarily excites intramolecular vibrations or electronic transitions, low-frequency acoustic waves couple directly to translational and orientational motions of molecular assemblies. This makes them a plausible candidate for selectively interacting with collective hydrogen-bond modes rather than isolated molecular degrees of freedom.

Previous experimental studies in liquids have shown that acoustic fields can influence relaxation processes, enhance molecular mobility, and modify fluctuation spectra under certain conditions. In water, such effects are often subtle and strongly dependent on experimental parameters, including frequency, amplitude, temperature, and dissolved gas content. Importantly, many reported acoustic effects are transient and reversible, disappearing once the external excitation is removed, which is consistent with a non-equilibrium dynamical response rather than permanent structural change.

Theoretical treatments of acoustic–liquid interactions suggest that resonance effects may arise when the frequency of the applied acoustic field overlaps with intrinsic collective modes of the system. In water, low-frequency modes associated with hydrogen-bond network fluctuations provide a potential channel for such resonant coupling. Under these conditions, acoustic excitation may temporarily bias the distribution of molecular configurations or alter relaxation pathways, leading to short-lived persistence of modified dynamical behavior.

However, it is essential to distinguish genuine acoustic–molecular coupling from secondary effects such as bulk heating, cavitation, or artefacts introduced by experimental boundaries.



Theoretical models predict that any physically meaningful acoustic influence on water's structure or dynamics must remain constrained by dissipation and entropy production, ensuring that equilibrium is ultimately restored.

In the context of the present study, the interaction of acoustic fields with water is viewed as a mechanism for inducing transient collective perturbations rather than long-term modifications. This perspective provides a physically consistent foundation for exploring acoustic imprinting, where prior exposure to low-frequency resonance may influence short-time dynamical responses without implying permanent memory or violation of thermodynamic principles.

5. Acoustic Imprinting: Hypothesis and Constraints

The concept of *acoustic imprinting* proposed in this study is formulated as a testable physical hypothesis, not as an assertion of permanent structural modification or information storage in water. The central hypothesis is that exposure to low-frequency acoustic resonance can transiently influence the collective dynamical behavior of liquid water, such that the system exhibits a short-lived, history-dependent response after the acoustic stimulus is removed.

In this framework, acoustic imprinting refers specifically to temporary modifications in relaxation pathways, correlation lifetimes, or collective hydrogen-bond dynamics, rather than to static rearrangements or long-term memory effects. The hypothesis is grounded in the existence of low-frequency collective modes in water, which involve correlated motion of multiple hydrogen-bonded molecules and operate on timescales comparable to acoustic excitation. If an external acoustic field couples to these modes, it may bias the system toward particular dynamical states for a finite duration.

A key constraint of this hypothesis is that any imprinting effect must be transient and dissipative. According to statistical mechanics and thermodynamics, liquid water at ambient conditions cannot sustain permanent structural order without continuous energy input. Therefore, any acoustic-induced modification must decay as the system relaxes back to equilibrium, with the relaxation timescale determined by intrinsic molecular interactions and dissipative processes. This ensures full consistency with the second law of thermodynamics.



Another important constraint is that acoustic imprinting must be distinguishable from secondary or artefactual effects. Phenomena such as bulk heating, cavitation, changes in dissolved gas concentration, or container-induced resonances can produce apparent changes in water's properties without reflecting genuine molecular-level dynamics. The hypothesis therefore requires that imprinting effects, if present, arise from direct coupling between the acoustic field and collective molecular motion, rather than from macroscopic or experimental artefacts.

The hypothesis also explicitly excludes claims of long-term or permanent memory in water. There is no expectation that acoustic excitation leads to stable encoding of information, persistent structural rearrangement, or violation of equilibrium behavior once the external perturbation is removed. Instead, the proposed imprinting is analogous to short-term memory in physical systems, where prior excitation influences subsequent response only within a limited temporal window.

Finally, the hypothesis is constrained by experimental observability. Any claim of acoustic imprinting must be supported by reproducible, time-resolved measurements that demonstrate a clear dependence on prior acoustic exposure and that decay predictably with time. Without such evidence, interpretations must remain conservative.

By explicitly defining both the scope and the limitations of acoustic imprinting, this hypothesis provides a scientifically credible basis for investigation. It allows exploration of non-equilibrium collective dynamics in water while maintaining strict adherence to established physical principles and avoiding unsupported extrapolations.

6. Critical Perspective and Experimental Pitfalls

Investigations into anomalous or history-dependent behavior in water require exceptional experimental caution, as the system is highly sensitive to external conditions and measurement artefacts. Many claims regarding unusual properties of water have failed not because the underlying questions were uninteresting, but because experimental limitations and uncontrolled variables were not adequately addressed. A critical perspective is therefore essential when examining the possibility of acoustic imprinting.



One major source of experimental artefacts arises from thermal effects. Acoustic excitation, particularly at higher amplitudes, can lead to localized or bulk heating of the liquid. Even small temperature variations can significantly alter hydrogen-bond dynamics, viscosity, and relaxation times in water. Without precise thermal control and monitoring, observed changes may be incorrectly attributed to acoustic imprinting rather than simple temperature-driven effects.

Another important consideration is the role of dissolved gases and nanobubbles. Acoustic fields can nucleate, redistribute, or oscillate gas bubbles within water, especially under low-frequency excitation. These bubbles can influence optical, acoustic, and electrical measurements, producing signals that mimic changes in bulk water properties. Failure to control or characterize gas content can therefore lead to misleading interpretations of acoustic–water interactions.

Cavitation and nonlinear acoustic effects represent additional challenges. At sufficiently high acoustic intensities, transient cavitation events may occur, generating localized pressure spikes and microjets that strongly perturb the liquid. While such effects are well documented in sonochemistry, they are incompatible with the gentle, collective dynamical perturbations proposed in the acoustic imprinting hypothesis. Experiments must therefore operate well below cavitation thresholds and verify linear acoustic response regimes.

Container effects and boundary conditions also play a critical role. Resonances associated with experimental vessels, transducers, or interfaces can introduce frequency-dependent artefacts that are unrelated to intrinsic properties of water. Careful experimental design, including variation of container geometry and materials, is necessary to distinguish genuine bulk effects from boundary-induced phenomena.

From a methodological standpoint, reproducibility and time-resolved measurements are essential. Any claim of acoustic imprinting must demonstrate a clear dependence on prior acoustic exposure and show predictable decay behavior consistent with relaxation toward equilibrium. Single-measurement observations or qualitative trends without statistical validation are insufficient to support meaningful conclusions.



Finally, interpretative restraint is crucial. Even when reproducible effects are observed, they must be framed within the limits imposed by thermodynamics and liquid-state physics. Over-extrapolation from subtle, short-lived phenomena to claims of long-term memory or information storage undermines scientific credibility and obscures legitimate physical insights.

In summary, the study of acoustic effects in water demands rigorous experimental controls, careful separation of primary and secondary effects, and conservative interpretation of results. By explicitly acknowledging these limitations and pitfalls, the present work aims to establish a robust foundation for investigating acoustic imprinting while avoiding the methodological weaknesses that have historically plagued research in this area.

7. Future Experimental Directions

To evaluate the hypothesis of acoustic imprinting in water within a physically rigorous framework, future investigations must employ carefully designed experiments and simulations that can isolate collective dynamical effects from secondary artefacts. The following directions outline feasible and scientifically grounded approaches for advancing this line of research.

One promising experimental strategy involves time-resolved pump–probe measurements, where low-frequency acoustic excitation acts as the pump and an independent spectroscopic technique probes the system’s response. For example, acoustic stimulation could be applied for a controlled duration, followed by time-dependent measurements of relaxation dynamics using optical, infrared, or terahertz probes. By varying the delay between acoustic excitation and measurement, it would be possible to determine whether prior exposure alters correlation lifetimes or relaxation pathways, and to quantify the decay timescales of any observed effects.

Another important direction is the use of frequency-dependent acoustic excitation. Systematic variation of acoustic frequency and amplitude may help identify resonance-like behavior associated with intrinsic collective modes of the hydrogen-bond network. Observing a selective response within a narrow frequency window would provide stronger evidence for



genuine coupling between acoustic fields and collective molecular dynamics, as opposed to non-specific thermal or mechanical effects.

Controlled experiments examining the influence of environmental parameters are also essential. Temperature, dissolved gas concentration, ionic strength, and confinement geometry can all influence hydrogen-bond dynamics and acoustic propagation. Performing measurements under carefully controlled and systematically varied conditions would help distinguish intrinsic properties of water from extrinsic experimental influences. Comparative studies using isotopically substituted water or weakly interacting liquids may further clarify which effects are unique to hydrogen-bonded systems.

From a theoretical standpoint, molecular dynamics simulations offer a valuable complementary approach. Simulations incorporating externally applied, time-dependent pressure or density oscillations can be used to model the effect of acoustic fields at the molecular level. By analyzing time-correlation functions, relaxation spectra, and collective motion before and after simulated acoustic excitation, it is possible to test whether transient imprinting effects emerge within realistic physical constraints. Such simulations can also guide experimental design by identifying relevant timescales and frequency ranges.

Extensions of this work may explore confined or interfacial water systems, where collective dynamics and relaxation behavior can differ significantly from bulk water. While the present study focuses on bulk liquid behavior, confinement may amplify or suppress certain dynamical modes, offering additional insight into how structural correlations influence history-dependent responses.

Overall, progress in this area will require close integration of experiment and theory, with an emphasis on reproducibility, time-resolution, and conservative interpretation. By adopting such approaches, future studies can determine whether acoustic imprinting represents a measurable manifestation of transient collective dynamics in water, or whether observed effects can be fully accounted for by known relaxation processes.

8. Conclusion



This study has examined the concept of the “memory of water” through a strictly physical and conservative lens, focusing on the possibility of *acoustic imprinting* arising from low-frequency resonance. By reframing memory as a transient, history-dependent response rather than permanent information storage, the work aligns the discussion with established principles of liquid-state physics and thermodynamics.

The analysis highlights that liquid water is characterized by a dynamically evolving hydrogen-bond network that supports collective molecular motions extending beyond individual interactions. Experimental and theoretical studies reviewed in this work demonstrate that these collective dynamics operate on timescales and length scales compatible with low-frequency mechanical perturbations. Within this context, acoustic fields emerge as a physically meaningful means of interacting with water’s collective degrees of freedom.

The central hypothesis proposed is that low-frequency acoustic excitation may transiently influence relaxation pathways or correlation lifetimes within the hydrogen-bond network, leading to short-lived dynamical persistence that can be interpreted as acoustic imprinting. Importantly, such effects are constrained to be reversible, dissipative, and finite in duration, ensuring consistency with equilibrium statistical mechanics. Claims of long-term or permanent memory in water are not supported within this framework.

A critical assessment of experimental pitfalls underscores the need for rigorous controls, time-resolved measurements, and cautious interpretation. Factors such as thermal effects, dissolved gases, cavitation, and boundary-induced artefacts can easily confound observations if not properly addressed. Recognizing these limitations is essential for distinguishing genuine collective dynamics from experimental artefacts.

Looking forward, the study identifies several promising avenues for future research, including time-resolved pump–probe experiments, frequency-dependent acoustic studies, and molecular dynamics simulations incorporating externally applied perturbations. Such approaches can provide quantitative insight into whether transient acoustic imprinting is observable and how it relates to intrinsic collective modes in water.



In conclusion, while the notion of permanent memory in water remains incompatible with established physics, the exploration of transient, history-dependent responses induced by low-frequency acoustic excitation represents a scientifically plausible and experimentally testable direction. By maintaining a clear boundary between verified physical behavior and speculative interpretation, this work contributes a balanced framework for advancing research on non-equilibrium collective dynamics in liquid water.

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