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Auditory perception of the thickness of plates

Samuel Poirot,[1,a)] Antoine Bourachot,[1] Stefan Bilbao,[2] and Richard Kronland-Martinet[1]
[1]Aix Marseille Université, CNRS, PRISM, Marseille, France
[2]Acoustics and Audio Group, University of Edinburgh, Edinburgh, United Kingdom
poirot@prism.cnrs.fr, bourachot@prism.cnrs.fr, s.bilbao@ed.ac.uk, kronland@prism.cnrs.fr

Abstract: This study focuses on the auditory perception of plate thickness and investigates acoustic cues that evoke thickness in the context of sound synthesis. Three hypotheses are proposed and tested through a listening test, examining the influence of damping, nonlinear phenomena, and modal frequencies on the perceived thickness of sound sources. The stimuli are generated using the numerical resolution of the Föppl–von Kármán system. We confirm that increasing the overall damping leads to an increased perceived thickness. Additionally, the emergence of an energy cascade toward higher frequencies (characteristic of thin plates) for impacts of increasing intensity evokes a thinner object. *© 2024 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).*

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1. Introduction

Achieving intuitive control over sound synthesis is an ongoing challenge, and the ability to control sound synthesis parameters in a manner that aligns with human perception and musical expressiveness remains an area of active research and exploration.[1–4] In this context, it is important to further investigate the perceptual correlates associated with the properties of sound sources.

This study addresses the classic question, “Can we perceive the shape of an object through sound?”[5–7] In particular, it investigates which acoustic cues evoke the perception of thickness of a sound-producing object in the context of sound synthesis. Our focus is specifically on the acoustic response of thin structures, such as plates, characterized by length and width. In this context, thickness, considered as an attribute of the plate’s shape, refers to the dimension perpendicular to the surface, representing the third, smallest, dimension of the object. Many percussion instruments, including cymbals and gongs, may be approximately modeled as such thin structures.

Our approach is inspired by the ecological approach to auditory events.[8,9] Adapted from the field of visual perception,[10] it suggests the existence of invariant structures (specific patterns in the acoustic signal) that carry the relevant information to perceptually recognize sound events. Although our study focuses on the control of sound synthesis, it also provides a better understanding of how we perceive sound sources’ attributes.

Modal frequencies appear to be the primary cue enabling the recognition of an object’s shape through its impulse response. However, it has been demonstrated that this cue alone is insufficient to accurately determine an object’s shape.[11] Previous studies have shown a correlation between modal damping and perceived thickness in the context of sound synthesis.[12,13] Moreover, geometric nonlinearity is highly dependent on thickness and occurs when the displacement amplitude is at least on the order of the thickness. It is reasonable to assume that the occurrence of nonlinear phenomena will have an effect on the perceived thickness of a sounding plate.

The nonlinear behavior of thin structures, investigated in various studies,[14,15] can give rise to a range of various and often complex effects on the radiated sound. One noteworthy outcome of such nonlinear behavior is the migration of energy toward higher frequencies, which exhibits a distinctive pattern, particularly evident in the case of gongs impacted with a soft mallet. Geometric nonlinearity in structures refers to the inherent nonlinearity of the dynamics at large amplitudes of vibration and leads, in the case of plates, to chaotic behavior sometimes referred to as “wave turbulence.” Its counterpart in terms of time-frequency content is commonly referred to as the Kolmogorov–Zakharov spectrum. This phenomenon has been extensively investigated in numerous studies.[16–18]

A previous study on sounds generated by thin plates led to the conclusion that the effects of such geometric nonlinearities on the sound radiated by a plate lead to the perception of more intense impacts at a constant sound level.[19]

We propose three hypotheses that we will seek to validate through a listening test described in the following sections:

[a)]Author to whom correspondence should be addressed.

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- *hp1*: An overall increase in damping (uniform across all modes) leads to an increase in the perceived thickness of the sound source.
- *hp2*: The emergence of nonlinear phenomena for increasing impact amplitudes results in a reduction in perceived thickness.
- *hp3*: The variations in modal frequencies of a plate as a function of its thickness, as defined by Kirchhoff, lead to a coherent estimation of the perceived thickness.

The sound synthesis of geometrically nonlinear structures, including gongs and cymbals, is an actively explored domain,[20–22] marked by advancements that enable the generation of highly realistic auditory stimuli for reasonable computing times.[23] The stimuli for our study are generated through the time domain numerical resolution of the Föppl–von Kármán system.[24] Employing this approach offers several advantages compared to the use of recorded sounds, notably, enabling the creation of a substantial dataset of well-calibrated, realistic sounds while affording precise control over experimental conditions.

2. Synthesis of the stimuli

The stimuli were synthesised through direct numerical solution of the dynamic analogue of the Föppl–von Kármán system,[25,26] a widely used model of the nonlinear dynamics of thin plates at moderate amplitudes. The Föppl–von Kármán system, accompanied by terms emulating frequency-dependent loss and a pointwise forcing term, can be presented in a compact form,[27]

$$\partial_t^2 u* = -\frac{D}{\rho H}\Delta\Delta u + \frac{1}{\rho H}\mathcal{L}(\phi, u) - 2\sigma_0\partial_t u + 2\sigma_1\partial_t\Delta u + \frac{1}{\rho H}\delta\left(x - \frac{L_x}{2}, y - \frac{L_y}{2}\right) f_{exc}(t), \tag{1a}$$

$$\Delta\Delta\phi = -\frac{EH}{2}\mathcal{L}(u, u). \tag{1b}$$

Here, $u(x, y, t)$ is the transverse plate deflection, and $\phi(x, y, t)$ is often referred to as the Airy stress function. Both are defined for $t \geq 0$ and for spatial coordinates (x, y) defined over the rectangular region $(x, y) \in [0, L_x] \times [0, L_y]$. ∂_t represents partial differentiation with respect to time t, and Δ is the two-dimensional Laplacian operator, defined by

$$\Delta = \partial_x^2 + \partial_y^2, \tag{2}$$

where ∂_x and ∂_y represent partial differentiation with respect to x and y. $\Delta\Delta$ is the biharmonic operator. In Cartesian coordinates, the nonlinear operator $\mathcal{L}(\cdot, \cdot)$ is defined, for any two arbitrary functions $\zeta(x, y, t)$ and $\eta(x, y, t)$, by

$$\mathcal{L}(\zeta, \eta) = \partial_x^2\zeta\partial_y^2\eta + \partial_y^2\zeta\partial_x^2\eta - 2\partial_x\partial_y\zeta\partial_x\partial_y\eta. \tag{3}$$

The boundary conditions[28] are set to be of simply supported type over all edges,

$$u = \partial_x^2 u = 0, \quad \phi = \partial_x\phi = 0, \quad \text{for} \quad x = 0, L_x, \tag{4a}$$

$$u = \partial_y^2 u = 0, \quad \phi = \partial_y\phi = 0, \quad \text{for} \quad y = 0, L_y. \tag{4b}$$

This decision was made because these conditions are straightforward to implement and imply a simple expression of modal deformations.

The plate is defined by the following parameters: linear dimensions L_x and L_y, in m; ρ, the material density, in $\text{kg} \cdot \text{m}^{-3}$; H, the plate thickness, in m; E, Young's modulus, in Pa; and the flexural rigidity D, defined as

$$D = \frac{EH^3}{12(1 - \nu^2)}, \tag{5}$$

where ν is Poisson's ratio for the plate material. σ_0 in s^{-1} and σ_1 in $\text{m}^2 \cdot \text{s}^{-1}$ are damping coefficients, allowing for a simple model of frequency-dependent decay—see Chaigne and Lambourg[29] for a much more refined model of damping in a thin plate. This simple model enables independent control over the overall damping with σ_0 and frequency-dependent damping with σ_1. While this characteristic facilitates a straightforward implementation, it deviates from real-world complexity.

Finally, the excitation is characterized by a two-dimensional Dirac delta function δ, selecting an excitation location at the plate center or at $x = L_x/2$, $y = L_y/2$. We chose to excite the plate at its center, as it seems to be the most natural point to impact a plate. This results in the absence of numerous modes that remain unexcited due to having a nodal point of vibration at the center of the plate. $f_{exc}(t)$ is an externally supplied excitation force, in N, intended to approximate a striking interaction. For the stimuli, we chose the form of five successive finite duration Hann windows or raised cosine pulses (as proposed by various authors[27,30]) of duration T (in s) and increasing amplitude nA (in N), defined as follows:

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$$f_{\mathrm{exc}}(t) = \sum_{n=1}^{5} n f(t-n), \quad \text{where} \quad f(t) = \begin{cases} A\sin^2(\pi t/T), & 0 \le t \le T, \\ 0 & \text{else.} \end{cases} \tag{6}$$

We have employed here a sequence of five impacts of increasing amplitude to facilitate participants' comprehension of the evolving acoustic responses of the plate with increasing excitation amplitude. The parameter A is the amplitude of the first impact in N.

Furthermore, it is worth noting that in a physical model describing the interaction between a mallet and a plate, which is inherently nonlinear, the contact duration of the interaction varies inversely with the striking velocity. This relationship leads to a perceptual effect of increased brightness as the striking velocity rises. In our study, to focus specifically on the influence of geometric nonlinearity within the plate and to avoid introducing additional cues related to impact strength, we hold the parameter T constant. For typical plate strikes in percussion instruments, the strike duration T is on the order of 1–4 ms.

A finite difference time domain scheme simulating the system (1a) and (1b) is detailed elsewhere.[23] It operates as a recursion over a spatial grid (ranging between 16×20 and 32×40 grid points) discretizing the dependent variables u and ϕ. To test our hypotheses in the experiment, we need to vary the overall damping, the appearance of non-linear phenomena, and the modal frequencies independently. The overall damping can be controlled simply by the parameter σ_0. We use the amplitude parameter A to control the appearance of nonlinear phenomena and the surface parameter S ($S = L_x \times L_y$) to modify the modal frequencies of the plate. We refrain from using the thickness H to modify the modal frequencies, as it exerts a significant influence on the emergence of non-linear phenomena. The modal angular frequencies of a simply supported plate in the linear case (following the Kirchhoff model) are expressed as shown below,[31] and it should be noted that increasing the thickness by a certain factor has the same effect on the frequencies as decreasing the surface area by the same factor (while keeping the aspect ratio $\beta = L_x/L_y$ constant),

$$\omega_{lm} = \pi^2 \sqrt{\frac{D}{\rho H}}\left(\frac{l^2}{L_x^2} + \frac{m^2}{L_y^2}\right) = \frac{H}{S}\pi^2\sqrt{\frac{E}{12\rho(1-\nu^2))}}\left(\frac{l^2}{\beta} + \beta m^2\right), \quad l, m = 1, \ldots, \infty. \tag{7}$$

Stimuli are normalized in amplitude and are available online.[32] The values of the various parameters used for synthesis are listed in Table 1, excluding σ_0, A, and S, which are variable as they are used as factors in the listening test.

3. Perceptual evaluation

3.1 Experimental design

The experiment is a full factorial design. We study the influence of three factors on the perceived thickness of a plate. The jth level of the factor ζ is indicated by ζ_j. The three factors ($\mathcal{A}$, $\mathcal{D}$, $\mathcal{F}$) are as described below:

- $\mathcal{A}$ (three levels) changes the excitation amplitude A in the synthesis model, which affects the strength of nonlinear phenomena.
- $\mathcal{D}$ (four levels) changes the global damping coefficient σ0.
- $\mathcal{F}$ (four levels) changes the modal frequencies via the surface parameter S in the physical model.

A total of 48 ($3 \times 4 \times 4$) stimulus conditions are thus employed. The values of the control parameters for the different factor levels are shown in Table 2.

The value of displacement normalized by thickness $[\max(u)/H]$, providing an indicator quantifying the importance of the nonlinear effects, ranges from 0.038 to 0.045 for $\mathcal{A}_1$, from 1.24 to 1.51 for $\mathcal{A}_2$, and from 2.32 to 2.88 for $\mathcal{A}_3$.

Table 1. Parameter set for the plate model.

Parameter	Role	Value
A	Excitation amplitude	Variable (N)
σ_0	Global damping coefficient	Variable (s^{-1})
S	Surface area	Variable (m^2)
β	Aspect ratio	1.2
H	Thickness	0.5 mm
E	Young's modulus	200 GPa
ν	Poisson's ratio	0.3
ρ	Density	$7850\,kg \cdot m^{-3}$
T	Excitation duration	2 ms
σ_1	Frequency-dependent damping coefficient	$4 \times 10^{-4}\,m^2 \cdot s^{-1}$

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Table 2. Levels for factors $\mathcal{A}$, $\mathcal{D}$, and $\mathcal{F}$.

Factor $\mathcal{A}$	
Level	Value for A
$\mathcal{A}_1$	0.05 N
$\mathcal{A}_2$	2 N
$\mathcal{A}_3$	5 N
Factor $\mathcal{D}$	
Level	Value for σ_0
$\mathcal{D}_1$	1.5 s^{-1}
$\mathcal{D}_2$	3 s^{-1}
$\mathcal{D}_3$	4.5 s^{-1}
$\mathcal{D}_4$	6 s^{-1}
Factor $\mathcal{F}$	
Level	Value for S
$\mathcal{F}_1$	0.1 m^2
$\mathcal{F}_2$	0.05 m^2
$\mathcal{F}_3$	0.033 m^2
$\mathcal{F}_4$	0.025 m^2

3.2 Participants

Sixteen participants (nine male, seven female) took part in the experiment. Eight work in audio-related fields (as a researcher or technician). The age range was from 22 to 47 years old (with a mean age of 28 years). None reported any hearing problems.

3.3 Procedure

After a short training phase during which participants listened to four reference stimuli ($\mathcal{A}_1\mathcal{D}_1\mathcal{F}_1$; $\mathcal{A}_3\mathcal{D}_1\mathcal{F}_1$; $\mathcal{A}_1\mathcal{D}_4\mathcal{F}_1$; $\mathcal{A}_1\mathcal{D}_1\mathcal{F}_4$), they were asked to evaluate the thickness of the impacted plate producing the sound ($\mathcal{H}$) by moving a slider ranging from "very thin" to "very thick" for the 48 stimuli presented in a random order. The data collected range from 0 ("very thin") to 100 ("very thick"). The total duration of the listening test was between 9 and 18 min per participant (and 11 min on average).

3.4 Results

We conducted a repeated-measures analysis of variance (ANOVA) to study the influence of the factors on the responses (evaluated thickness $\mathcal{H}$). An overview of the results is provided in Table 3.

Only factors $\mathcal{A}$ and $\mathcal{D}$ induce a significant variation of the perceived thickness. We can reconsider the hypotheses stated in the Introduction:

Table 3. Statistics of the repeated-measures ANOVA analysis. DoF, degree of freedom; MS, mean square. Boldface values highlight significant variations resulting from the factor ($p < 0.05$).

Effect	DoF	MS	F	p-value
$\mathcal{A}$	2	25 381	23.26	**<0.001**
$\mathcal{D}$	3	31 138	18.50	**<0.001**
$\mathcal{F}$	3	620	0.29	0.836
$\mathcal{A} \times \mathcal{D}$	6	369	1.28	0.277
$\mathcal{A} \times \mathcal{F}$	6	690	1.58	0.162
$\mathcal{D} \times \mathcal{F}$	9	194	0.58	0.813
$\mathcal{A} \times \mathcal{D} \times \mathcal{F}$	18	480	1.80	**0.026**

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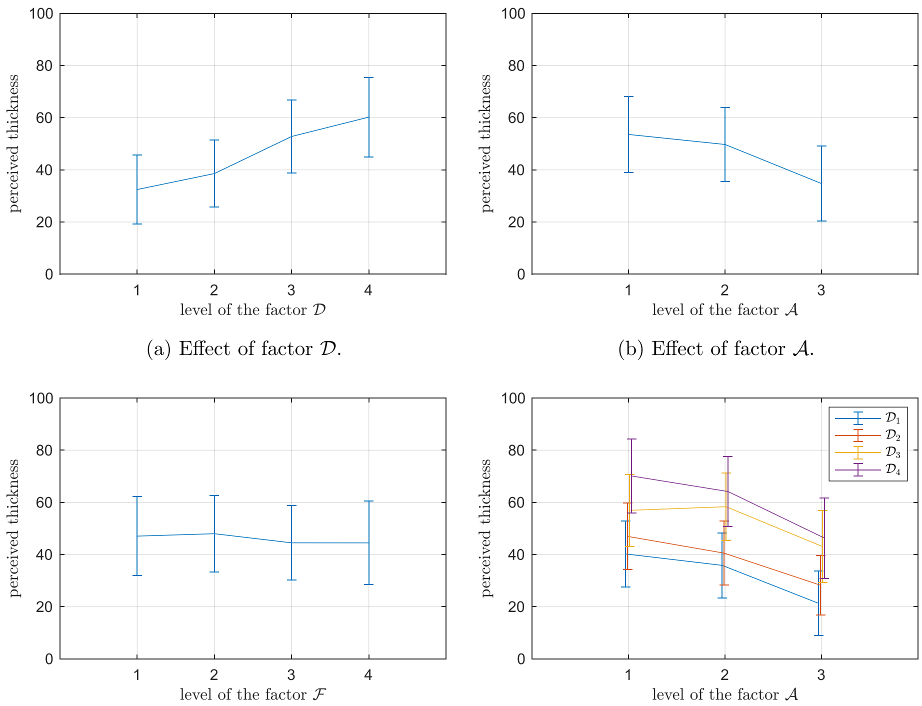

(a) Effect of factor $\mathcal{D}$.

(b) Effect of factor $\mathcal{A}$.

(c) Effect of factor $\mathcal{F}$.

(d) Combined effects of factors $\mathcal{A}$ and $\mathcal{D}$.

Fig. 1. Effect of the factors on the perceived thickness. Least square means are shown. Vertical bars denote ± standard deviations.

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- *hp1*: An increase in overall damping leads to a significant increase in perceived thickness [$p < 0.001$; see Fig. 1(a)].
- *hp2*: The occurrence of nonlinear phenomena results in a significant decrease in perceived thickness [$p < 0.001$; see Fig. 1(b)].
- *hp3*: Modal frequency variations do not lead to a significant variation in perceived thickness [$p = 0.863$; see Fig. 1(c)].

It is also noteworthy that the two significant factors do not exhibit a significant interaction [$p = 0.277$; see Fig. 1(d)].

Finally, the three-way interaction $\mathcal{A} \times \mathcal{D} \times \mathcal{F}$ yields a significant effect ($p = 0.026$). Specifically, participants exhibited slightly divergent responses for conditions $\mathcal{A}_1\mathcal{D}_3\mathcal{F}_3$ and $\mathcal{A}_1\mathcal{D}_3\mathcal{F}_4$, with average results lower than those for conditions $\mathcal{A}_2\mathcal{D}_3\mathcal{F}_3$ and $\mathcal{A}_2\mathcal{D}_3\mathcal{F}_4$ (respectively). This effect, visible on the curve corresponding to $\mathcal{D}_3$ [Fig. 1(d)], is attributed to a subset of participants who proposed notably low responses for these conditions. Interestingly, none of these participants concurrently exhibited markedly diminished response for both scenarios ($\mathcal{A}_1\mathcal{D}_3\mathcal{F}_3$ and $\mathcal{A}_1\mathcal{D}_3\mathcal{F}_4$). Moreover, these participants reported contrasting responses for analogous auditory stimuli, rendering the identification of a discernible pattern in these outcomes challenging.

3.5 Discussion

We have confirmed through this experiment that an overall increase in damping in a sound synthesis context induces the perception of a thicker object (*hp1*). In the physical realm, the relationship between thickness and damping is complex, and an increase in thickness does not necessarily result in increased losses. In the case of metallic plates, the two main mechanisms affecting damping are thermoelasticity and radiation (the effect of air on the plate). Thermoelasticity is predominantly influent at low frequencies, and its effect decreases as the thickness increases. The radiation from thin plates induces a more complex behavior: The damping effect at frequencies below a critical frequency is negligible, but flexural waves with frequencies below this critical frequency are not (or minimally) radiated. Around the critical frequency and beyond, the waves become more damped and are radiated. An increase in thickness leads to a reduction in the critical frequency and an overall decrease in damping.[29] In summary, increasing the thickness of a thin plate results in an overall decrease in damping, except around the new critical frequency value, where damping may increase, and the frequency components below the critical frequency are not radiated, corresponding to evanescent waves (thus, requiring close proximity to the plate to detect them). In the more marginal case of the acoustic black hole effect, a localized reduction in thickness can even result in a drastic increase in damping.[33] Thus, it is rather surprising that damping is considered by participants as a key indicator to evaluate the thickness of a plate. On the other hand, thick and resonant objects (poorly damped) are rarely encountered in the everyday environment of the average person. Additionally, massive and resonant objects (such as thick metal plates) are often very heavy and require support, preventing them from freely resonating. This could explain this perceptual expectation. Additional tests involving a model that accounts for these damping mechanisms or recorded sounds could be considered in future studies to assess whether this effect persists with the same significance in a more realistic context. It is also worth noting that damping is a key indicator for material recognition,[34,35] and it would be interesting to observe participants' responses if they were to simultaneously evaluate their perception of both material and thickness.

Regarding the occurrence of nonlinear phenomena (*hp2*), the perceptual expectation aligns with physical reality. Indeed, it is easier to produce a cascade toward higher frequencies (requiring less forceful strikes) if the object is thinner. These parameters can be used in the design of synthesis algorithms to control the evocation of sound source attributes. The absence of interaction between these two factors may seem somewhat unexpected, given that damping typically exerts a significant influence on the occurrence of nonlinear phenomena.[36] Nevertheless, this outcome enables their independent and simultaneous utilization in controlling sound synthesis processes.

In contrast, modal frequencies are not an indicator influencing decision-making in the proposed experiment (*hp3*). This suggests that we are not able to establish a clear connection between the thickness of an object and its modal frequencies when listening to the emitted sound. This result may seem surprising, as modal frequencies are one of the primary indicators present in physical reality. This finding aligns with experiments showing that we are generally not very adept at perceiving the shape of an object solely based on the sound it produces upon impact.[37]

To further analyze the data, distinct strategies emerged among participants. An evident and consistent increase in perceived thickness for increasing modal frequencies occurred for three participants (two of whom work in acoustics). This suggests that modal frequencies serve as a significant cue for certain individuals who probably approach the task analytically, drawing on their physics knowledge. Conversely, two participants (one working in acoustics) showed a clear decrease in perceived thickness as the factor $\mathcal{F}$ level increased. Informal discussions revealed a possible explanation: Some participants found the task difficult and expressed a preference for assessing length or width, finding it more intuitive. It is plausible that these two participants associated the idea of a smaller object with a thinner one and vice versa. For the rest, no discernible correlation was observed, leading to the probable conclusion that factor $\mathcal{F}$ does not serve as an indicator for these participants and that the link between modal frequencies and thickness is not intuitive for the majority of people.

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4. Conclusion and perspectives

In conclusion, this paper explores the perception of thickness in sound sources and investigates the acoustic cues that evoke thickness in the context of sound synthesis. The goal is toward the development of algorithms that enable users to manipulate sound characteristics intuitively. A listening test has been described here that examines the influence of damping, nonlinear phenomena, and modal frequencies on the perceived thickness of sound sources. Stimuli are generated using the numerical resolution of the Föppl–von Kármán system.

The results of the listening test reveal important findings. Increasing the overall damping leads to a perceived increase in thickness, supporting the hypothesis that damping affects the perception of thickness in sound sources. The emergence of energy cascading toward higher frequencies, characteristic of thin plates, for impacts of increasing intensity evokes a thinner object, supporting another hypothesis related to nonlinear phenomena. Conversely, variations in modal frequencies do not modify the evocation of the thickness, which may appear surprising given the relationship between thickness and modal frequencies of plates. This leaves us with the likely conclusion that the link between resonance frequencies and plate thickness is not intuitive for most people.

Author Declarations

Conflict of Interest

The authors have no conflicts to disclose.

Ethics Approval

This study received approval from the Ethical Committee of Aix-Marseille University, and informed consent was obtained from all participants.

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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