

ARTICLE

Sonic immersion with interactive mobile web-application

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Abstract

Over the past two decades, interactive technologies have gradually transformed audience engagement in live performance contexts. This paper explores audience interaction through a mobile web-app designed for immersive sonic experiences. The app transforms personal smartphones into a distributed speaker array and interactive controller. We examine two case studies: *Freedom Collective*, a contemporary opera where smartphones diffused pre-recorded sounds, creating a spatialized auditory field; and *Exo Signals*, an interactive sound experience at the Ubimus conference in Macau, where the audience actively shaped the soundscape by triggering audio samples and applying real-time DSP (band-pass filter) through touch interactions. We discuss the artistic and technological challenges in both cases, comparing the levels of immersion and audience engagement in passive versus active participation models.

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1. Introduction

The integration of interactive technology in live performances has significantly evolved over the past two decades, reshaping how audiences engage in concert situations.¹⁻³ This paper presents a mobile web-based application designed to create immersive sonic experiences through audience participation. The primary objective of this web-app is to transform personal smartphones into a distributed speaker array and interactive sound controller, allowing real-time interaction within a live performance setting.

Building on previous work designed for *Freedom Collective* (FC), an interactive opera where audience members' smartphones passively diffused sound throughout the performance space, we expanded the system by enabling the triggering of short sounds through buttons and real-time DSP (band-pass filter) manipulation through touchscreen gestures. This new iteration of the web-app was implemented during the Ubimus conference in Macau for the project called *Exo Signals* (ES). This transition from a passive playback model to an active audience participation system represents a significant shift in interactive live music experiences. While "immersion" is frequently invoked in interactive audio discourse, it remains an elusive and often underdefined concept. We adopt Riionheimo and Lokki's⁴ definition of immersion as a perceptual

phenomenon—the sensation of being surrounded by sound—rooted in spatial rather than purely cognitive or emotional experience. This framing is especially relevant to participatory systems like ES, where immersion arises through spatialization rather than narrative or flow. Complementing this, Nosenko⁵ expands the perspective by examining how immersive technologies (e.g. ambisonics) construct musical audio spaces—natural or artificial, online or offline—emphasizing that immersion depends not only on spatial fidelity, but also on how listeners are situated in these environments, including mobile and headphone-based contexts. Together, these views offer a framework for understanding immersion as both a spatial-perceptual quality and a presence mediated by technology. This paper explores the conceptual, artistic, and technical evolution of the project, using FC and ES as case studies. We analyze how these different modes of participation influence immersion, audience agency, and artistic intent. In addition, we examine the technical challenges encountered, including network latency, real-time synchronization, and user experience considerations, offering insights into the feasibility of web-based interactive music systems for live performances.

2. Background and related work

The increasing integration of smartphones in interactive performances has reshaped the relationship between audiences and live music. From early experiments such as *Dialtones: A Telesymphony* by Levin in 2001⁶ that transformed mobile phones into a distributed speaker system to contemporary networked performances using web-based frameworks like *SkylAR*,⁷ the field today offers more seamless and scalable audience engagement. Taylor⁸ provides an overview of how audiences have been used as speaker arrays in performance settings, demonstrating how mobile devices have increasingly become tools for spatialized sound diffusion rather than mere listening devices.

The balance between audience control and artistic intent remains a key challenge in such interactions. Studies on large-scale participatory performances like *Speakers, More Speakers!!!*⁹ emphasize the importance of well-structured affordances to prevent chaotic or distracting audience interventions. Research on networked music ensembles by Marshall and Loydell¹⁰ explores how mobile devices allow for real-time control over distributed sound diffusion, which aligns with our approach. The move from native applications to browser-based interactions presented another major shift. While early smartphone-based performances relied on custom software or dedicated apps, for example, Stanford Mobile Phone Orchestra,³ recent work has demonstrated the viability of real-time sound control through web browsers, as

seen in frameworks such as *Soundworks*.¹¹ However, as Nyckees² notes, web-based implementations still face challenges in state synchronization and modularity, which we attempt to address through direct browser-based, low-latency DSP control. Studies on audience interaction models in mobile performances further emphasize the shift from passive listening to participatory engagement. *Mobile Phone Ensembles as Classrooms*¹² highlights how mobile-based sound diffusion can create highly engaging and decentralized sonic environments, allowing large groups to contribute dynamically without technical expertise. These developments reinforce the importance of intuitive, accessible interfaces in designing interactive musical systems. By positioning our web-app within the landscape of smartphone-based audience interaction, this paper contributes to the discourse on real-time web audio performance, participatory sound control, and immersive audience experiences.

3. Web-app development

Our web-based application was designed for immersive, smartphone-mediated sonic diffusion for the opera FC and later expanded for the ES performance. The goal was to develop an accessible, cross-platform tool that allows audiences to participate in performances using only a standard web browser, eliminating the need for installations or specialized software. The initial implementation, used in FC, focused on passive audience engagement, where smartphones functioned as a diffused speaker array. This approach leveraged the inherent latency and spatial distribution of mobile networks to create dynamic sound diffusion effects in theatrical settings. Through ten performances across three German theatres, this version of the web-app was rigorously tested, allowing for fine-tuning of synchronization, server load management, and playback consistency (stage design in Figure 1). Similar models



Figure 1. Stage design for the opera Freedom Collective. Copyright© Sascha Kreklau.

of large-scale audience diffusion have been explored in projects such as *Poème Numérique*,¹³ which investigated the artistic and logistical challenges of smartphone-based sound spatialization.

Building upon this foundation, ES introduced active audience participation, marking a significant shift in the mode of interaction. In this iteration, users were no longer limited to passive sound diffusion only but could also trigger short sounds and manipulate DSP parameters (band-pass filter) through touchscreen gestures. These additional modes align with research on interactive mobile sound design and telematic performance by researchers such as Xambo and Goudarzi,¹⁴ who discuss the impact of audience-triggered sound events and touch-based musical controls. Implementing these new functionalities required new interaction models, real-time data processing, and optimization for responsiveness, to keep it running smoothly on regular web browsers. Subsequent paragraphs detail the progressive evolution of the interaction modules, examining technical implementation and challenges at each developmental stage.

3.1. Interaction modules

The web-app was initially designed for FC with three modules, all of which relied on smartphones functioning as passive speaker arrays (Figure 2).

The first module was designed like a dating app, introducing the opera characters while playing shaker-like background noise in different registers, creating a dense mass of sound. The second module was designed as a chat app, where chat-like notification sounds popped up at different times from different cell phones. The third module displayed a video of the final scene, allowing the audience to switch between five different camera angles by tapping on the screen. However, no audio interaction was possible – instead, eight pre-rendered voices were randomly assigned to each smartphone, generating a dense granular texture.

For ES, unlike FC, we did not have visual guidelines or a designer on our team. Consequently, we opted for a simplified, user-friendly graphical interface. We introduced two new interactive modules while retaining a passive diffusion module as one of the three available modes (Figure 3).

The hover module retained the structural concept of the third module from FC but introduced several modifications. The number of voices was reduced from 8 to 6, new sonic content was introduced, and instead of random assignment, the audience could manually switch between voices by hovering over six displayed bubbles.

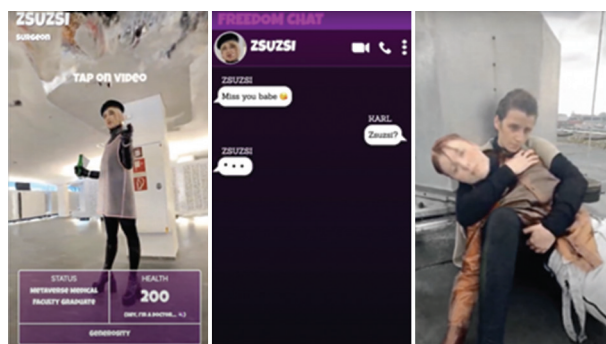


Figure 2. Different interaction modules from Freedom Collective. Copyright© Rosa Wernecke.

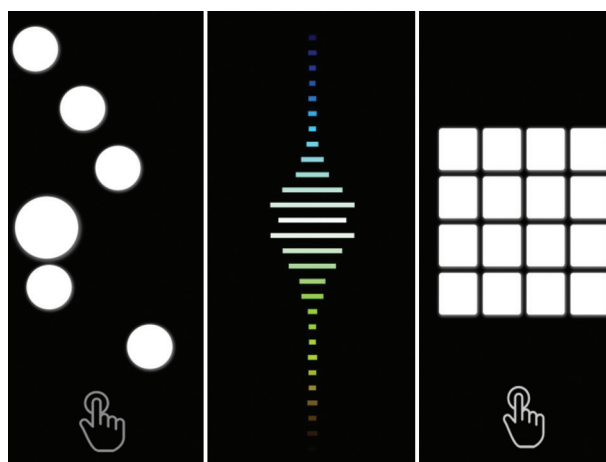


Figure 3. Different interaction modules from Exo Signals. Copyright© Maurice Oeser.

The filter module featured a broadband noise-like sound as playback on all devices. Audience members could manipulate the center frequency of a band-pass filter by sliding their fingers on the screen. This interaction required fine-tuned DSP processing, offering users a dynamic and expressive tool to shape sound in real time.

The trigger module was displayed as a 4×4 grid of touch buttons, each assigned a very short sound sample (< 1 s). This module enabled real-time triggering, allowing participants to actively shape the rhythmic pulsations within the sonic landscape. The pre-designed sounds were derived from FC's chat module, maintaining sonic cohesion through a consistent palette of 16 mobile messaging sounds.

The structured affordances of these modules align with research on performative engagement and gamification in interactive sound environments by Koszolkó and Studley,¹⁵ where clear interaction pathways encourage participation while maintaining artistic coherence. The trigger module, for example, adopted a grid-based interface reminiscent of interactive game mechanics, allowing audience members

to engage playfully with the sound while still operating within defined compositional parameters. During inactive periods, a countdown system displayed a timer (e.g., Next interaction possibility in: 00:01:43), ensuring that audience focus alternated between interaction and pure listening. This approach preserved artistic integrity, while allowing the audience to focus on the live performance.

3.2. Technical implementation

The web-app was built as a fully browser-native system, eliminating the need for dedicated applications while ensuring cross-platform accessibility. The underlying architecture required careful consideration of synchronization, real-time audio processing, and interactive response times.

Client-side implementation focused on accessibility and stability. The interface was designed as a progressive web app, allowing seamless performance across smartphones and tablets. The Web Audio API handled real-time DSP processing for the filter module, ensuring smooth gesture-controlled band-pass filtering, while the trigger module leveraged preloaded audio buffers to prevent latency issues when users activated sounds. The usage of the Web Audio API - instead of the more standard HTML audio - allows for more complex, real-time DSP processing for the cost of a more technical advanced setup, which could impact the result on certain devices. On iOS¹⁶, for example, the WebAudio API is muted while the ringer is put into silent mode. Server-side processing was crucial in maintaining stability across devices. A centralized server controlled interaction windows, synchronizing on-screen countdowns across all connected devices (Figure 4). In the passive module, a scheduled playback system managed sound diffusion across audience devices, ensuring time-aligned execution. While latency was embraced as an aesthetic feature in FC, it needed to be minimized for real-time modules in ES. Research on web-based distributed music systems by Matuszewski¹⁷ highlights similar challenges in real-time synchronization and network-based performance environments, emphasizing the need for lightweight, low-latency communication protocols in browser-based music systems.

This technological framework enabled a scalable, robust, and flexible system, allowing audience members to seamlessly engage with performances in real time. The *Soundworks*¹¹ framework provides a key reference in this domain, offering insights into browser-based real-time collaborative audio performance.

3.3. Challenges and refinements

Throughout its development, the web-app underwent multiple refinements to address technical limitations

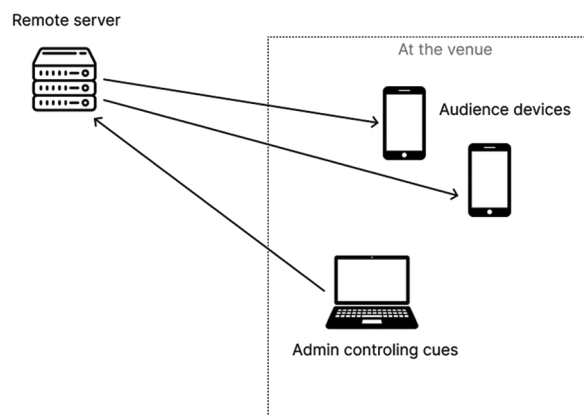


Figure 4. Network overview of the Freedom Collective web-app. Copyright© Maurice Oeser.

and artistic constraints. Several key challenges emerged, including the lack of perfect synchronicity, balancing innovation with artistic integrity, connectivity issues, and cross-device compatibility.

One of the primary challenges was synchronization. In early iterations of the web-app, a timestamp-based system was implemented to align playback timing across devices, ensuring greater coherence in real-time interactions. Despite these efforts, perfect synchronicity remained difficult to achieve, particularly due to inconsistent network speeds among audience members. Similar concerns have been explored in research on mobile-device-based sound diffusion, where real-time synchronization across a distributed system remains a critical challenge, e.g. *Fields* by Shaw *et al.*¹⁸ Rather than attempting to eliminate these flaws entirely, we instead embraced them as aesthetic elements, exploring musical situations where asynchronous playback could become an artistic advantage, such as grain fields and noisy background soundscapes.

Balancing technological innovation with artistic integrity was another key consideration. While interactive audience participation expanded the performative framework, unrestricted engagement risked shifting focus away from the structured musical composition, particularly in an operatic setting. To maintain balance, interaction windows were restricted, ensuring that participatory moments alternated with periods of focused listening.

Furthermore, relying on web-based technology meant that variable Wi-Fi and mobile data speeds could disrupt participation. This issue is particularly relevant in closed theatre halls, where thick walls obstruct regular signals, forcing reliance on venue-provided Wi-Fi, which is often not strong enough to support large audience members simultaneously. This was less problematic for ES, as the

performance took place on the top floor of a large university space, where mobile signal was strong. However, private networks often restrict certain functionalities or throttle bandwidth, which occasionally slows down transmission. To mitigate this, the trigger and filter modules were optimized to function with minimal data exchange, reducing dependency on continuous high-speed internet access. In addition, audio file quality was reduced from WAV to MP3, decreasing bandwidth consumption while maintaining sufficient fidelity for live performance. Similar challenges in network-reliant immersive environments have been explored in usability studies, such as Chang,¹⁹ which highlights how adaptive data transmission strategies are necessary for maintaining stable user interactions in dynamic web-based sound environments.

The final challenge was cross-device compatibility. Given that performances relied on audience smartphones, there was significant variability in hardware capabilities, browser performance, and operating systems. Early trials revealed inconsistencies in sound triggering and DSP response times between iOS and Android devices, but testing across all possible configurations would have been impractical. Implementing progressive enhancement techniques and simplifying the design addressed many of these disparities, ensuring a stable experience across platforms and most smartphone models. These refinements ensured that the final iteration of the web-app was robust, flexible, and responsive, while preserving artistic integrity and performative coherence.

4. Audience feedback

Audience response was collected for FC during its performances at several theatres in Germany.²⁰ Due to privacy regulations, a general audience survey was not permitted; instead, feedback was gathered from invited participants and colleagues ($n = 21$), which severely limited the number of participants for the pilot study. Quantitative ratings averaged 3.62/5 for overall experience, 4.14/5 for ease of use, and 3.43/5 for perceived enhancement of engagement. While 38% reported no technical issues, others cited connection glitches (related to browser refresh or load times) and occasional audio or visual dropouts—likely influenced by the scale of the audience (200 participants on average), and the variability of available networks. Qualitative responses reflected a spectrum of opinions: while many found the interaction novel and enjoyable, others perceived it as distracting or lacking in synchrony.

Suggestions included the desire for more interactive content, clearer integration into the performance, and smoother delivery. These findings directly informed the design of ES, with a particular focus on improving

synchronization, minimizing interface complexity, and enhancing content structure for live interaction.

ES premiered as a one-off site-specific performance during the Ubimus Conference at the University of Saint Joseph in Macau. Unlike the large and demographically diverse audiences in Germany (ranging from teenagers to senior citizens), the Macao audience was smaller (approx. 25 people) and more cohesive, composed primarily of researchers in ubiquitous music and related fields, as well as students from the university's music program. While no formal survey was conducted, informal conversations following the performance indicated high levels of interest and positive engagement, particularly with the concept of audience-controlled sonic input. Crucially, the event took place in a technically stable environment—a university media lab configured as a concert hall—where no connectivity issues were reported. The performance also garnered attention from “Teledifusão de Macau” News, which featured the project in a national television report, highlighting the novelty of mobile interaction in live music contexts. While this feedback is anecdotal, its specificity and consistency, along with the applied learning from earlier performances, reinforce the iterative improvement of the project's interactive design.

5. Discussion on interactive immersion in web-based performance

The evolution of the web-app from FC to ES reflects a broader shift in interactive performance design, where the audience moves beyond passive reception to active participation. In FC, smartphones functioned as diffused speaker arrays, reinforcing spatial immersion while maintaining a strictly composer-controlled sonic environment. This also created a necessity to have engaging visuals to compensate for the lack of interaction. The transition to ES introduced more sonic interaction, eliminating the need for flashy visual interface and allowing audience members to shape the sonic outcome directly.

While these technological advancements expanded the scope of participation, their impact on audience engagement varied depending on the performance context, audience demographics and their familiarity with interactive systems. These factors became particularly evident in how audiences engaged with the performances in different settings. FC was staged in formal theatrical venues across Germany, where audience members were not necessarily familiar with interactive technology and varied in age and digital proficiency. A short survey conducted after these performances revealed that while many found the smartphone-based sound diffusion immersive, some were unsure of its necessity or hesitant to use personal

devices in a theatrical setting (audience interacting in Figure 5).

In contrast, the audience for ES at the Ubimus conference in Macau primarily consisted of researchers and students with backgrounds in audio technology or music, already inclined toward exploring new interaction paradigms. While both FC and ES included a brief introduction explaining interaction possibilities, observations and post-performance discussions indicated that participants in Macau were more receptive to the structured “distractions” provided by the interactive elements and were more engaged in the process.

The spatial and technological constraints of each performance further shaped audience interaction. FC designed for large theatrical spaces, where latency and spatial diffusion were intentionally embraced as artistic elements. In contrast, ES took place in a smaller venue, with the audience seated in a circle around violinist Roberto Alonso and surrounded by a 23-speaker setup (Figure 6). Both projects incorporated structured interaction windows, ensuring that moments of focused listening alternated with active participation. Research on smartphone use in opera performances, such as *Crafting Trajectories of Smart Phone Use at the Opera*,²¹ highlights how digital interaction within staged works must be carefully integrated to guide audience attention without detracting from the performance. The interactive structure in ES aligns with this approach, demonstrating how mobile-based engagement can be choreographed to enhance immersion rather than create distraction. This approach proved effective in balancing user engagement with musical integrity, echoing concerns raised in usability studies such as *An Investigation of Usability* by Chang,¹⁹ which highlights how excessive complexity or unrestricted interaction can hinder rather than enhance audience immersion.

Another important factor was the level of technological friction. In FC, with audiences ranging from 100 to 250 people, a chamber orchestra, amplified singers, electronics, lighting, video projections, and other multimedia elements, limited time and resources made it difficult to address playback inconsistencies. Several participants reported issues such as missing sound or video playback. In ES, however, all participants were able to access and use the web-app without apparent connectivity issues, likely due to their higher digital literacy and the controlled environment. This contrast suggests that while web-based interactive music systems can be widely applicable, their effectiveness depends on audience familiarity with interactive technology and is directly influenced by the scale of participation. Similar insights are found in



Figure 5. Two audience members interacting with the *Freedom Collective* web-app during the performance. Copyright© Benjamin Weber.



Figure 6. Roberto Alonso pauses his violin performance to invite audience interaction via smartphones, with Davor Vincze handling electronics in the background. Copyright© Davor Vincze.

Mobile Phone Ensembles as Classrooms by Essl,¹² which demonstrates how structured guidance and simplified interfaces significantly improve engagement in mobile-based musical experiences.

While ES marked a significant step forward in audience interaction, it remained constrained by design limitations. The three interaction modules—hover, filter, and trigger—offered distinct ways to shape the soundscape, but the interaction possibilities were intentionally kept minimal to prevent overwhelming users. Research on interactive mobile music systems, such as *SkylAR* by Ciciliani,⁷ suggests that offering diverse interaction types without excessive cognitive load enhances audience engagement. Heim²² explores how contemporary performances increasingly blur the boundaries between performer and spectator, shifting the audience’s role from passive observer to active participant. This shift aligns with our findings in ES, where interaction was deliberately structured to enhance immersion without disrupting the artistic framework. Future iterations of the web-app could introduce additional DSP effects, such as reverb, delay, or pitch

modulation, broadening the scope of sonic interactions while maintaining simplicity. Expanding options to allow audience members to record sounds for integration into the repository or incorporating machine learning could further enhance agency, enabling the system to adapt dynamically to audience behavior.

Overall, these two case studies demonstrate how different performance contexts, audience demographics, and interaction frameworks influence the effectiveness of web-based interactive music systems. While FC prioritized large-scale diffusion and artistic control, ES fostered a more intimate and participatory model, engaging audiences through structured but flexible interaction modules. These findings contribute to broader discussions on real-time audience participation, networked music systems, and the evolving role of smartphones as creative tools in immersive performance environments.

6. Conclusion

The development of this web-app and its implementation in FC and ES demonstrate how mobile-based audience interaction can expand immersive performance environments. By transitioning from passive sound diffusion in FC to active audience participation in ES, the project explored the creative potential and limitations of web-based interactive sound systems. While both approaches offered unique modes of engagement, their effectiveness was shaped by technical constraints, audience demographics, and performance settings. The FC model, designed for large-scale operatic settings, leveraged network latency and spatial diffusion as compositional tools but faced challenges in usability and audience familiarity with digital interaction. ES, by contrast, was more intimate, fostering direct audience engagement through structured participation, enhanced by the audience's pre-existing technical literacy and the controlled performance setting.

These findings underscore the importance of balancing technological innovation with usability and artistic intent. The comparative analysis of FC and ES highlights how structured interaction frameworks, clear affordances, and appropriate technological scaling can enhance audience immersion. Research in mobile sound performance, such as *Performing Audiences* by Xambó and Roma,²³ suggests that participatory experiences are most effective when they align with the artistic and technical realities of a given performance. Similarly, insights from *An Investigation of Usability in Immersive Environments*¹⁹ reinforce the idea that immersive interfaces must carefully manage complexity to avoid disrupting engagement.

Future iterations of this web-app could further expand on these findings by integrating adaptive interaction

models that dynamically respond to audience behavior. Expanding the range of DSP effects, incorporating audience-generated sounds, or using machine learning for predictive interaction could offer new avenues for participatory sound design. In addition, the *We're in This Together* project (presented at New Interfaces for Musical Expression 2025) enabled the refinement of these interactive models in a new performance context, further testing the balance between structured participation and open-ended sonic agency. As digital performance environments continue to evolve, web-based platforms hold significant potential for redefining audience engagement, offering new tools for collaborative, immersive, and interactive musical experiences.

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Conflict of interest

The authors declare they have no competing interests.

Author contributions

Conceptualization: All authors

Data curation: Davor Vincze

Formal analysis: Davor Vincze

Investigation: Davor Vincze

Methodology: Davor Vincze

Software: Maurice Oeser

Visualization: All authors

Writing – original draft: Davor Vincze

Writing – review & editing: All authors

Ethics approval and consent to participate

This study involved an anonymous survey of 21

adult participants who attended performances of FC. Participants were acquaintances and colleagues of the authors and received a link to the survey, which included a clear statement of purpose, voluntary participation, data anonymity, and usage. No personal or identifiable information was collected.

Formal approval from a Research Ethics Committee or Institutional Review Board (IRB) was not obtained, as the survey was non-invasive, posed minimal risk, and was conducted independently of a university-led research protocol. Participants provided informed implied consent by choosing to proceed with the survey after reading the information and consent statement at the beginning of the form.

The study adhered to standard ethical principles for research involving human participants, including respect for autonomy, voluntary participation, and secure data handling.

Consent for publication

No identifiable personal data, images, or direct quotes from participants were collected or used in this study. The survey responses were fully anonymous, and participants were informed at the outset that their data might be used for academic research and publication in anonymized, non-identifiable form. Consent for publication was therefore obtained implicitly, as participants chose to proceed with the survey after reading this information. Given the absence of any identifying information and the non-sensitive nature of the questions, formal written or verbal consent for publication was not deemed necessary. For the three pictures used in the paper, consent was obtained from all three visual artist photographers.

Availability of data

This study includes a statistical summary of responses to a short audience survey, as presented in the paper's Audience Feedback section. The individual response data are not publicly available due to privacy considerations, but are securely stored by the main author. These data can be made available for inspection upon reasonable request, particularly for purposes of verifying the analysis or methodology.

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