4D

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München, 2026
Open Publishing LMU

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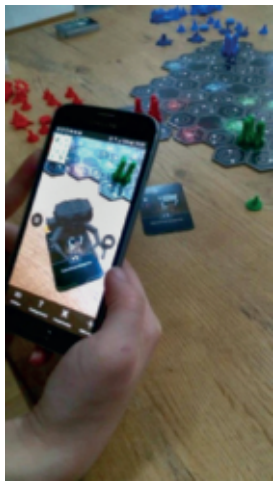

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1 Mit der AR-App Trompe-l'œil erkunden Museumsbesucher*innen die verborgenen Rückseiten eines Triptychons.
2 Arkio ermöglicht kollaborative Architekturplanung in Mixed Reality - gemeinsam im Raum oder remote - geräte- und softwareübergreifend.
3 Volumetrische Erfassung realer Personen und Objekte für VR/AR in einer Capture Stage mit Kameras und Sensoren.
4 Einzelne Spielelemente eines Brettspiels werden mithilfe einer AR-App visualisiert.
5 Das XRT im Staatstheater Nürnberg lässt Gäste via VR-Headsets das AR-Stück "Der Bau - Franz Kafka" in einer neuen, teils virtuellen Erzählform erleben.

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6 VR-Headsets erlauben es, medizinische Bildgebung als 3D-Modelle in virtuellen Umgebungen interaktiv erfahrbar zu machen.
7 VR-Headsets und haptische Systeme ermöglichen realistisches Chirurgie-Training an virtuellen Organmodellen.
8 Selfie mit Snapchat-Filter, der Kleidungsstücke augmentiert und vorhandene Elemente räumlich verzerrt.
9 Eine Person interagiert mit dem holografischen Modell eines Grundwassertiers.
10 Im Gait Real-time Analysis Interactive Lab (GRAIL) der TU Chemnitz werden mithilfe virtueller Umgebungen Ganganalysen durchgeführt.

Bildauswahl und Recherche: Julia Enders
Bildnachweis vorige Doppelseite

1 Ceren Topçu, 2020 (CC BY 4.0).
2 Arkio, www.arkio.is, 2023.
3 Christopher Remde, 2024 (CC BY NC 4.0).
4 Tashko Rizov, Jelena Djokic, Milan Tasevski: Design of a board game with augmented reality. In: FME Transactions, Jg. 47, 2019, Heft-Nr. 2, S. 255, Abb. 4.
5 Konrad Fersterer, 2024.
6 Karl Eisenträger, 2024.
7 Michelle Mantel, 2024.
8 Julia Enders, 2025.
9 Jacqueline Gitschmann, Voxon & Senckenberg Museum für Naturkunde Görlitz, 2022.
10 & Jacob Müller, TU Chemnitz, 2018.

Inhalt

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4D Imaging. Challenges of Spacetime Critical Image Practices

I. 4D – Making Physical Space Computable

Digital images influence how people interact with one another and with their physical surroundings. Today, navigation systems visually guide us through physical environments; sensors continuously capture and visualize physiological and biometric data that determine fitness routines; and video-based formats increasingly shape interpersonal communication. The shift from analogue to digital images has already significantly transformed the ontological and epistemological status of images. However, contemporary technological developments pose even more fundamental questions about the status and role of the image itself.

Ongoing debates around the concept of extended reality (XR) reflect a profound shift in the way images mediate human action and perception. This transformation is underscored by the increasing influx of capital and development efforts in this expanding domain. It appears that a new image type is evolving from a marginal phenomenon into an industrial-scale, multi-billion-dollar venture that claims to be the 'next medium' after the smartphone and mobile computing. Much like photography and film created and shaped a new technologically mediated iconosphere and visual culture,

Publiziert in: Friedrich, Queisner, Eisenträger, Schabbing (Hg.), 4D (Begriffe des digitalen Bildes, 8), München 2026, S. 7–20. https://doi.org/10.5282/ubm/epub.130131

today's emerging imaging technologies are on the verge of defining a new form of digital visuality, in which image, action, and space become intrinsically intertwined.

While the vision of the – or at least a – 'metaverse' increasingly turns out to be a socio-technological imaginary driven by marketing narratives and investor interests, the media practices and technologies that give rise to this imaginary are already being used in a variety of real-world contexts. On a technical level, the idea of integrating physical and virtual spaces relies on new imaging and sensing technologies capable of registering, processing, and transmitting information about the physical world in real time. This concept is summarized under the technical term of *spatial and embodied computing*, or as we propose more succinctly, 4D imaging. 4D imaging techniques combine data visualization with the registering of the topographical properties of physical space and the tracking of user movement and position.

The core principle of 4D imaging is to render physical space into computational models. This spatial registration enables the alignment of digital visual content with the physical world based on changes in user movement and device orientation. As a result, what an image shows now depends on the temporal dynamics and spatial configuration of a scene. Unlike conventional spatial visualization methods such as 3D scanning, 4D imaging not only captures the structure of space but also incorporates its transformation over time, treating movement and interaction as integral components. In practice, this fourth dimension means that digital objects can be manipulated and explored as users move through space, shift their gaze, or engage with images through bodily interaction.

Beyond this predominantly technological framing, we propose a theoretical and analytical perspective on 4D imaging

that considers its capacity to generate new forms of mediainduced agency. Images generated through 4D imaging – a type of adaptive images[1] – are gaining importance in operational contexts due to their ability to support, extend, and control a wide range of human-machine interactions. Their distinct potential lies in the real-time integration of spatial information, enabling image-based interaction to respond dynamically to users and their environments.

These multidimensional images diverge fundamentally from conventional static, two-dimensional screen representations. Mobile applications, such as those on smartphones and virtual reality headsets, are particularly capable of adapting images based on the user's position and field of view. As a result, visual perception becomes a hybrid media practice in which physical space and objects are overlain with a layer of digital artifacts that integrates shape, motion, location, orientation, and perspective. Unlike traditional 2D displays, adaptive images actively shape how users perceive and engage with the physical environment. This is evident in everyday applications such as smartphone-based navigation systems that use gyroscopic and geolocation data to adjust orientation in real time, or augmented reality experiences in museums that overlay digital information on physical exhibits. These examples illustrate how interacting with images becomes both context-sensitive and embodied, shifting the image from a representational medium to an interface for spatial interaction.

1 Kathrin Friedrich, Moritz Queisner, Matthias Bruhn: Adaptive images: Practices and aesthetics of situative digital imaging. In: NECSUS_European Journal of Media Studies, Vol. 9, 2020, No. 2, pp. 51-76, http://dx.doi.org/10.25969/mediarep/15338.

II. Intersections Between Digital Image Theory and Digital Image Practice

The intersection of image and media theory with 4D imaging presents a productive tension. Theoretical insights from humanities-based digital image research can inform the use and design of 4D imaging, offering critical perspectives on both the potentials and limitations of these technologies. Understanding the capabilities of 4D imaging requires a systematic connection between theoretical findings from visual, image, and media studies and the real-world contexts in which these technologies are applied. Rather than constituting merely an enhanced imaging modality defined by technical parameters, 4D imaging introduces a fundamentally new mode of accessing and interacting with digital images, physical objects, and spatial environments.

Therefore, the focus must shift from digitized practices to digital practices. A practice-based approach allows us to understand what 4D imaging can – and crucially, cannot or should not – do. Conceptually, there is a growing need to develop both a practice-based theory and a theory-driven practice of 4D imaging – one that enables users to critically engage with and shape the socio-technical imaginary surrounding these technologies. To investigate the practical potential of 4D imaging from a media and visual studies perspective, we propose two interrelated layers of inquiry: first, to critically reflect on the socio-historical conditions underpinning 4D imaging; and second, to foster critical visual competencies by empowering users to engage with 4D imaging practices.

Discourses surrounding 4D imaging are embedded in broader socio-historical narratives that legitimize its development and adoption. These narratives generate what we call

the 4D mandate[2] – the perceived necessity of employing 4D technologies in specific domains and under particular conditions. This mandate is not neutral; it is shaped by historical genealogies, institutional frameworks, and socio-political conditions that must be critically examined. The proclaimed necessity, innovation, or efficiency associated with 4D imaging reflects not only a form of technological solutionism – or *technofix* – but also discursively attributes images with a formative power that exceeds their immediate application.

Carving out the contours of the 4D mandate thus requires a historical perspective, drawing methodologically on the history of stereoscopic media[3], media archaeology[4], and historical discourse analysis[5]. This socio-historical foundation allows us to situate 4D imaging within a broader visual culture that aspires to extend agency over human perception and interaction. Through detailed, case-based analysis, this knowledge can be transferred into applied contexts. In particular, cultivating reflection-based visual skills can empower users to make informed decisions about when and how to use 4D imaging. Such skills include spatial awareness, visuomotor integration, and depth accommodation – competencies that are particularly relevant for embodied interaction with 4D images. Drawing on methods from design research[6], interface

2 We derive the notion 4D mandate from Halpern et al. (2017) who use the term "smartness mandate" to frame the promises, political agendas and infrastructural transformations of smart technologies and to illuminate, amongst others, "some of the key ways in which the history and logic of the smartness mandate are dynamically embedded in the objects and operations of everyday life (...)." Orit Halpern, Robert Mitchell, Bernard Dionysius Geoghegan: The Smartness Mandate. Notes toward a Critique. In: Grey Room, 2017, No. 68, pp. 106-129, here p. 109.

3 Luisa Feiersinger: Spatial Narration. Film Scenography Using Stereoscopic Technology. In: Luisa Feiersinger, Kathrin Friedrich, Moritz Queisner (eds.): Image Action Space. Situating the Screen in Visual Practice, Berlin and Boston 2018, pp. 69-78; Nick Jones: Spaces mapped and monstrous. Digital 3D cinema and visual culture, New York 2020; Miriam Ross: Virtual Reality's New Synesthetic Possibilities. In: Television & New Media, Vol. 21, 2020, No. 3, pp. 297-314.

4 Erkki Huhtamo: Screen Tests. Why Do We Need an Archaeology of the Screen? In: Cinema Journal, Vol. 51, 2012, No. 4, pp. 144-148; Jens Schröter: 3D. History, Theory and Aesthetics of the Transplane Image, London 2014.

5 Laurel J. Brinton: Historical Discourse Analysis. In: Deborah Tannen, Heidi E. Hamilton, Deborah Schiffrin (eds.): The Handbook of Discourse Analysis, Hoboken, NJ, 2015, pp. 222-243, https://doi.org/10.1002/9781118584194.ch10.

6 John M. Carroll: Making Use. Scenario-Based Design of Human-Computer Interactions, Cambridge, MA, 2000.

studies[7], and aesthetics, a taxonomy of 4D imaging skills can be developed. A skill system of this kind not only promotes conceptual and operational understanding but also facilitates access to 4D imaging in contexts with limited resources.

To foster a productive exchange between theory and practice, we propose the development of practice-based formats, such as How-Tos that guide the situated use of 4D imaging. These may include protocols, visualizations, or video instructions detailing how to implement 4D imaging in domains such as surgical planning or digital theatre. These tools would not only assist users in technical execution but also embed critical reflection, providing contextual background on technological affordances, scenario design requirements, and the visual skills involved. Other interactive formats – such as co-creation workshops and participatory trials – could support iterative, collaborative exchanges between experts and trainees.

However, the development and analysis of 4D imaging are inherently context-specific. Cultural production and medicine represent two domains in which the 4D mandate is particularly pronounced. Both fields demand new forms of immersion and instruction, yet the visual competencies and embodied knowledge required to work effectively with 4D often remain tacit, exclusive, and difficult to communicate. This underscores the urgent need for interdisciplinary approaches to articulate, transfer, and critically engage with the skill sets necessary to develop and apply 4D imaging use cases across diverse real-world settings.

7 Søren Bro Pold, Christian Ulrik Andersen (eds.): Interface Criticism. Aesthetics Beyond Buttons, Aarhus 2011; Noortje Marres, Carolin Gerlitz: Interface Methods. Renegotiating Relations between Digital Social Research, STS and Sociology. In: Sociological Review, Vol. 64, 2016, No. 1, pp. 21–46.

III. Making the Case – 4D Imaging in Cultural Production

In the field of cultural production, 4D imaging opens up new operational possibilities – particularly in relation to immersive storytelling in theatre practices. 4D technologies promise significant potential in making spatially complex situations more accessible. As the cultural sector traditionally relies on physical presence and the liveness of performances, the COVID-19 pandemic accelerated the development of new forms of representation, interaction, and immersion. Cultural productions such as music concerts, artistic enactments, and theatre performances were confronted with the challenge of translating live experiences into virtual environments.

The emphasis on liveness provides a lens through which to investigate the historical, technological, and socio-political conditions of 4D live performances as historically "variable effects of mediatization."[8] This perspective raises critical questions such as: How has the development of 4D imaging altered the dimension of liveness? Or: Which bodies, abilities, and collectives are excluded from immersive experiences due to digital inequalities?

The often-celebrated promise of in particular virtual reality (VR) – to effectively mediate affective spatial interactions, whether by reproducing physical events in virtual realms[9] or immersing users in entirely virtual scenarios[10] – demands critical scrutiny. Theoretical reflection on these developments has only just begun to grapple with the pivotal role of 4D imaging in producing, experiencing, and archiving performances across diverse cultural contexts. Existing scholarship on mediated performances[11], screen-based immersive

8 Philip Auslander: Digital Liveness. A Historico-Philosophical Perspective. In: PAJ. A Journal of Performance and Art, Vol. 34, 2012, No. 3 (102), pp. 3-11, here p. 3; cf. Philip Auslander: Liveness. Performance in a Mediatized Culture, London (2nd Edition) 2008.

9 Joshua A. Fisher (ed.): Augmented and Mixed Reality for Communities, London 2021; Laura Gemini, Stefano Brilli, Francesca Guiliani: Theatre Dispositif and the Challenge of Covid-19: Mediatisation, Liveness and Audiences. In: Mediascapes Journal, 2020, No. 15, pp. 1-15.

10 Kathrin Friedrich: Therapeutic Media. Treating PTSD with Virtual Reality Exposure Therapy. In: MediaTropes, Vol. 6, 2016, No. 1, pp. 86-113.

11 Auslander 2008 (see note 8); Steve Dixon: Digital Performance. A History of New Media in Theatre, Dance, Performance Art, and Installation, Cambridge, MA, 2007; Karin van Es: Liveness Redux. On Media and

technologies[12], and the temporality of media[13] provides essential insights for evaluating and implementing 4D imaging within the cultural sector.

Beyond large-scale, high-budget productions with advanced technological infrastructures, smaller theatres and performance collectives are increasingly exploring 4D imaging as a tool for recording and reimagining live performance. In addition to virtual reality, augmented reality applications are enabling new forms of immersive storytelling that bridge physical and virtual spaces, enhance audience participation, and facilitate innovative artistic interventions.

A compelling example is *XRT Nürnberg's* production of *Der Bau*, based on Franz Kafka's text. Here, augmented reality (AR) operates as a 4D imaging tool that extends the physical stage through adaptive layers of digital imagery and video. This production blurs the traditional boundaries between actor and audience, allowing for new types of spatial and narrative interventions through the agency of 4D imaging technologies. In *Der Bau*, the audience is immersed in the protagonist's fragmented and schizophrenic inner perspective, which is rendered visible through layered visualizations. These multidimensional realities create novel modes of theatrical encounter, expanding both narrative structure and perceptual experience (fig. 1).

The visual and embodied skills required to interact with such environments still need to be theorized and systematized.

their Claim to be Live. In: Media, Culture & Society, Vol. 39, 2017, No. 8, pp. 1245-1256, https://doi:10.1177/0163443717717633; Steve Benford, Gabriella Giannachi: Performing Mixed Reality. Cambridge, MA, and London 2022; Daniel Jernigan, Stephen Fernandez, Russell Pensyl, Lee Shangping: Digital augmented reality characters in live theatre performances. In: International Journal of Performance Arts and Digital Media, Vol. 5, 2009, No. 1, pp. 35-49.

12 Ken Hillis: Digital sensations. Space, identity, and embodiment in virtual reality, Minneapolis 1999; Michael Madary, Thomas K. Metzinger: Real Virtuality. A Code of Ethical Conduct. Recommendations for Good Scientific Practice and the Consumers of VR-technology. In: Frontiers in Robotics and AI, Vol. 3, 2016, http://journal.frontiersin.org/article/10.3389/frobt.2016.00003/full [accessed 08/2025]; Nanna Verhoeff: Mobile Screens. The Visual Regime of Navigation, Amsterdam 2012.

13 Wolfgang Ernst: Chronopoetics. The Temporal Being and Operativity of Technological Media, London and New York 2016; Mark B.N. Hansen: Feed-forward. On the future of twenty-first-century media, Chicago 2015; Svetlana Chernyshova: Bilder auf Zeit. Zur Bichronizität von Augmented Reality in künstlerischen Settings. In: IMAGE. Zeitschrift für interdisziplinäre Bildwissenschaft, Vol. 20, 2024, No. 39, pp. 103-125, https://doi.org/10.25969/mediarep/23195.

This involves carving out a specific "mediated habitus"[14] – a subjective disposition that emerges in response to the technological affordances of these tools. It also invites us to rethink formats for the iterative exchange between theory and practice in the production and understanding of live performance.

While technical implementation may be conveyed through straightforward How-Tos (e.g., for programming a specific virtual scene), the transmission of embodied knowledge – such as how actors interact with both technology and co-performers – requires different forms of observation and instructional methods. This points to a broader issue: the concept of agency, central to the very idea of 4D, challenges conventional image theories and practices. It necessitates deeper theoretical engagement, particularly in relation to embodied knowledge and the complex dynamics of applied performance contexts.

Fig. 1, Interaction on the stage. The stage design is enhanced by adaptive image and video material (Konrad Fersterer, Der Bau, XRT Nürnberg 2024)

14 Nick Couldry: Liveness, "Reality," and the Mediated Habitus from Television to the Mobile Phone. In: The Communication Review, Vol. 7, 2004, No. 4, pp. 353-361, https://doi.org/10.1080/10714420490886952.

IV. Making the Case - 4D Imaging in Medicine

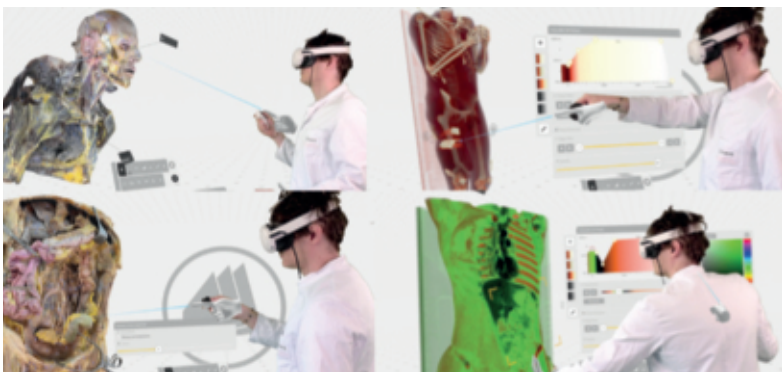
In medicine, 4D imaging techniques hold significant potential for enhancing the quality of clinical decision-making. In fields such as surgery and radiology, a key competency lies in interpreting medical images to accurately identify anatomical structures and diagnose pathological conditions. While imaging modalities like computed tomography (CT) and magnetic resonance imaging (MRI) generate volumetric data, they are still predominantly presented as sequential two-dimensional tomographic slices – typically in standardized anatomical planes such as axial, sagittal, and coronal planes – rendered in greyscale on conventional monitors. This presentation method, while clinically established, creates a fundamental disconnect between the inherently three-dimensional nature of the acquired data and its two-dimensional visual representation.

However, surgical decision-making fundamentally depends on comprehending the three-dimensional spatial relationships between anatomical features. To prepare interventions, surgeons must mentally reconstruct 3D anatomical volumes from these 2D slices – a cognitive effort that relies heavily on visual-spatial reasoning and pattern recognition. Traditionally, this skill is acquired through extensive training that involves a bidirectional learning process between digital imaging and physical anatomy. Clinicians scroll through cross-sectional images while simultaneously correlating these representations with direct anatomical experience gained during surgical procedures, cadaveric dissections, and physical examinations. This creates a continuous feedback loop: surgeons learn to interpret CT/MRI slices by referencing their tactile and visual knowledge of actual anatomy, while their growing

imaging expertise actively deepens their understanding of physical anatomical relationships encountered in the operating room. Through this iterative process, clinicians gradually develop the ability to mentally assemble three-dimensional models that bridge the gap between digital representation and physical reality. Yet, this cognitive translation process is not without limitations. It carries the risk of misinterpretation or incomplete modelling, both of which may adversely affect surgical outcomes. Effective planning therefore requires not only deep anatomical knowledge but also advanced graphical literacy and spatial imagination to bridge the gap between digital image slices and the physical structures encountered during surgery.

4D imaging technologies challenge these traditional workflows by introducing new visualization strategies grounded in VR (fig. 2). As a form of computer-generated imagery, VR is specifically designed to convey spatial information. Unlike conventional 2D displays, which lack binocular depth cues, VR-based visualizations offer stereoscopic rendering of medical images. This enhances clinicians' depth perception of anatomical structures with different images for each eye (binocular disparity) and depth cues due to positional tracking (motion parallax). Although 3D datasets can be displayed on standard screens with depth cues such as shadows, contrast,

Fig. 2, VR visualization of photogrammetric cadaver models (left) and computed tomography data (right). The software used for rendering is Medical Holodeck, https://www.medicalholodeck.com/en/ (Karl Eisenträger 2024)



relative size and perspective, conventional monitors do not provide the binocular disparity that drives human stereoscopic depth perception. This is why stereoscopic visualization makes VR an especially effective medium for presenting volumetric data.

This advantage is further amplified by VR's capacity to support embodied interaction with medical imaging. Head-mounted displays (HMDs) equipped with motion tracking synchronize a user's physical movements – translational (forward/backward, up/down, left/right along the x, y, and z axes) and rotational (pitch, yaw, and roll around those axes) – within the virtual environment. This dynamic coupling between bodily motion and image manipulation adds a sensory dimension absent from conventional 3D display technologies. Through vestibular and proprioceptive feedback, VR enhances clinicians' spatial awareness and fosters a stronger integration of sensorimotor input with spatial perception. By enabling direct, embodied interaction with volumetric data, 4D imaging has the potential to significantly deepen spatial understanding of anatomical relationships. In turn, this promises to advance both diagnostic precision and procedural planning in surgical contexts.

V. Further Perspectives for Image Theory and Image Practice

From the perspective of image and media theory, the design, production, and application of 4D imaging challenge existing theoretical approaches. Integrating space and time dynamically into an image constitutes a novel ontological condition of digital visuality. Traditionally, images represent spatial properties in ways that do not dynamically correspond to physical

space. This is due to two key reasons: first, in material terms, most images are two-dimensional objects – even if they depict three-dimensional scenes. Second, what an image depicts is typically spatially detached from the image's physical presence. Consequently, relating an image to physical space requires cognitive effort and visual literacy to interpret parameters such as scale, perspective, rotation, or volume.

In contrast, digital images produced through 4D imaging cannot be analyzed as singular, static, or generalizable research objects. Instead, they are embedded in diverse media practices ranging from mobile, real-time, and embodied applications to data-driven techniques such as volumetric scanning. These practices enable the creation of dynamic digital twins as multimodal reconstructions of physical objects and environments. As a result, the classical theoretical question of 'what is an image?' must be reformulated into 'what becomes image space, when, and from whose perspective?'. This shift demands a rethinking of both the ontology and the epistemology of the image, placing emphasis on the media dispositive and the distributed agencies and temporalities that shape image production, reception, and circulation.

To contribute meaningfully to the development and implementation of 4D imaging technologies, image and media theory must move beyond static, representational concepts and instead consider the image as a relational, adaptive, and processual form. The emergence of adaptive images – images that respond in real time to user position, orientation, and interaction – calls for a theoretical framework that recognizes the image as an interface between the user and the physical world. In 4D imaging, the image no longer simply represents space: it becomes an active component of the spatial configuration it helps to shape. Image theory is thus tasked not

only with conceptualizing what an image shows but how and when it becomes operational within specific technological and sociocultural contexts.

We propose a programmatic agenda to advance the intersection of image theory and image practice. In addition to the aforementioned How-Tos – open, low-threshold tools that translate analytical insights into accessible, practice-oriented instructions for working with 4D imaging – this agenda includes the development of further interdisciplinary formats. These could involve speculative design thinking, co-creation labs, and applied theory workshops that facilitate an iterative exchange between conceptual reflection and technological implementation. Such efforts must be grounded in a critical understanding of the 4D mandate and the historical and sociocultural conditions under which 4D imaging is conceived and applied in real-world contexts. Rather than reinforcing techno-solutionist narratives, 4D imaging users must be empowered to critically engage with the adaptive quality of visual media. In this sense, 4D imaging becomes not only a subject of theoretical analysis but also a catalyst for developing new forms of spatial and visual literacy.