Exploring Phygitalization in Architecture

Comparative analysis of the reality of digital and physical experiences in relationships of humans and space

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Contemporary designers utilize extended reality (XR) to merge the physical and digital realms, aiming to create immersive user experiences, a concept known as "phygitalization." However, current studies predominantly focus on the visual aspects of XR, resulting in underdeveloped XR systems. This research aims to address this gap by examining the role of haptic experiences in enhancing immersion within the virtual environment, thereby bridging the divide between the physical and digital worlds. The research methodology involved a literature review to explore relevant terminologies related to physics, space, experience, senses, and human perception. Subsequently, an experiment was conducted to investigate the impact of connectivity between the physical and digital worlds on human perception. The experiment involved participants using a VR headset to interact with virtual "sand" and then directly interacting with different physical materials that have similarities and differences to the virtual environment, aiming to investigate (a) the incorporation of real objects in (b) interior and exterior virtual settings and (c) the disparities between physical and virtual materials. The study results showcased that by combining XR with physical haptic experiences, it is possible to enhance immersion in the virtual environment, contributing to the development of "Data-Driven Intelligence", while recognizing that it may not fully substitute the physical world. This research seeks to explore the relationship between humans and space in both digital and physical experiences and paves the way for investigating how the integration of XR in architectural contexts can influence human perception, sensory abilities, and experiential encounters.

Keywords: *Space, Phygital, Degree of realism, Material properties, Human perception*

INTRODUCTION

Architects and designers are increasingly using data-driven technologies to merge physical and digital spaces and provide users with immersive experiences. The term "phygital" combines physical and digital and originated from a marketing concept that combined physical point of sale with digital tools (Mele et al., 2023). Among its ambiguous definitions by various scholars, Andrade et al. (2020) defined it as a space or service encounter where physical and digital spaces overlap through a series of processes. By incorporating extended reality (XR) technologies into spatial designs, human interaction with virtual objects and physical materials is combined to create a data-driven environment. The process of phygitalization introduces new opportunities to influence human perception, senses, and experiences within architectural contexts. However, when it comes to XR technology in an architectural context, there have been uncertainties regarding its ability to create a spatial experience that effectively communicates with the real world (Lee et al., 2020).

When interacting with space, humans engage multiple senses, with over half of visual perception involved, regardless of whether the reality is physical or digital (Spenc, 2020; Heilig, 1992). The Reality-Virtuality (RV) continuum conceptualizes realities on a spectrum from purely physical to purely virtual (Milgram et al., 1995). However, incorporating multisensory experiences, especially haptics, into architectural design can provide significant benefits. The tactile aspects of architecture are often overlooked, despite Sennett's (1994) emphasis on the crucial role of tactile elements in multisensory architectural experiences, whether directly touched or visually perceived.

This study aims to conduct a literature review to explore the terminologies related to the intersection of digital and physical experiences in the context of human-space relationships. Consequently, we aim to address a hypothetical question: Can virtual environments potentially facilitate the substitution, coexistence, and exaggeration of human sensory experiences? To achieve this, the study will consist of three components, each with specific objectives: (a) investigating the effects of real objects in virtual experiences, (b) evaluating virtual environments in both interior and exterior settings, and (c) analyzing discrepancies between physical materials and virtual environments.

BACKGROUND

This section discusses definitions and related work of XR technology in the interactions, human perception, as well as architecture.

Extended reality and phygitalization

In recent years, the term "Extended Reality" has emerged as an inclusive lable encompassing Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), highlighting their role in advancing phygitalization by facilitating immersive experiences that seamlessly merge the physical and digital realms. However, as the literature discussing this evolving field expands, the term has become progressively ambiguous. To distinguish the relationships between various realities, Milgram et al. (1995) introduced Reality-Virtuality (RV) continuum, which defines realities on a spectrum from solely real objects in the real world to solely virtual objects in the virtual environment (Virtual Reality). With various technologies available to craft experiences within extended reality, it gives rise to the growth of phygitalization, which is a marketing strategy that effectively reaches customers seamlessly blending digital information into their physical world (Yüce et al., 2021). The intrinsic spatial nature of XR, coupled with its capacity for design freedom and complete experiential control, positions it as a well-suited medium for investigating spatial perception (Zhao et al., 2023). The convergence of XR technologies, phygitalization, and architecture invites a rich discussion on how the integration of digital elements reshapes human experiences within physical spaces.

Spatial perception in XR

While several studies have explored the use of XR technologies to create immersive environments, the focus has primarily been on visual aspects. Current studies have been striving to create realistic visual representations that are closer towards the real environment on the RV continuum, by examining and improving perceived depth perception presented in head-mounted display (HMD) technology, aiming to achieve more immersion and presence. Kelly et al. (2022) discovered that distances in Oculus Quest and Oculus Quest 2 are 68 to 82% under perceived egocentric distance, which refers to the perceived distance between the user's body and objects within the virtual environment. Spatial representation of such HMD models have even shown little improvements compared to previous ones (Renner et al., 2013). Studies showed recalibration in a virtual environment helps diminish such spatial representation error by manipulating accurate feedback Kelly et al. (2014). Apart from technological factors, Our findings revealed three experience factors that enhance distance estimation in virtual environments, resulting in a perception of absolute scale that closely resembles the real world: visual experience with the real-world environment, locomotor experience, and body-based experience including avatar or eye height (Creem-Regehr, 2022).

XR interactions

Acknowledging the prominence of vision as a primary human sense, gaze interaction has become one of the crucial features in XR. Studies showed that with the aid of eye-tracking interaction, it makes hand interaction in XR more effective. Combining both eye and hand interaction, Pfeuffer et al. (2014) investigated the integration of gaze-touch as a complementary methodology for multi-touch surfaces, aiming to explore the potential utilization of gaze-touch in conjunction with direct-touch. This thereby contributes to a deeper understanding of the design space encompassing these approaches.

Haptic interactions involve the use of touch and tactile feedback in virtual environments. Researchers have been exploring ways to enhance these interactions by incorporating realistic sensations of touch and movement. This includes developing devices that can simulate the feeling of touching virtual objects and providing feedback on muscle movements and skin sensations, where one focus has been on creating realistic virtual hands that can accurately mimic the motion and deformations of real hands. This involves addressing challenges such as complex hand modelling and accurate tracking of hand movements. Techniques like data-driven methods and subspace simulation have shown promise in improving the realism of these interactions (Tong et al., 2023). Though investigations of haptic interactions have been made, not only do they merely illustrate how haptics can supplement vision to create a more complete visual experience within the virtual environment, the development of it and other sensory stimuli, has been comparatively limited (Lyu et al., 2023). Those haptic interactions tend to merely enhance immersive experience within the virtual world, with little linkage to the real physical world. Therefore, it is crucial to examine the combination of physical haptics and virtual reality, in enabling more immersive experiences by incorporating tangible sensations and surpassing the limitations of the virtual realm (Gaffary et al., 2017).

This research aims to determine whether physical haptic feedback has the potential to alter human perceptions within VR environments or if it can amplify sensory experiences, thereby contributing to a more immersive and engaging virtual reality encounter (See Figure 1).

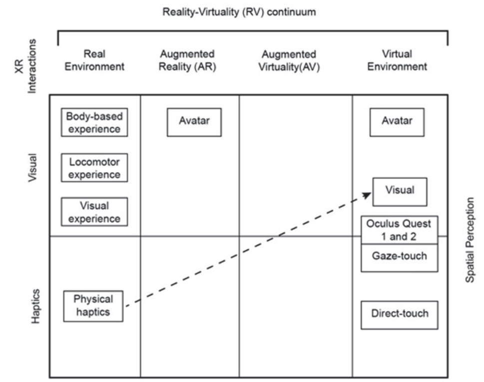


Figure 1
A model showing relationship between existing XR interactions and the Reality-Virtuality (RV) continuum Milgram et al. (1995) introduced, and factors that affect spatial perception.

METHODOLOGY

An experimental physical investigation was carried out to test a hypothesis from November 23 to December 2, 2023 (See Figure 2). The Experimental Physical Space, which measures 4.1 meters in length, 1.5 meters in width, and 4.4 meters in height, maintains a temperature between 23 and 25 degrees Celsius, serving as the controlled environment for the study. Participants of diverse ages, genders, and educational backgrounds began by completing a declaration form and a questionnaire. Subsequently, they received verbal instructions detailing the experiment. Each participant then undertook one of the experiment's components, guided by voice instructions generated by artificial intelligence.

To ensure consistency and impartiality, a set time limit was applied to each segment, minimizing the potential for biased data collection and ensuring equitable treatment of all participants. The procedural steps for each component are outlined below.

Setting

Within the realm of virtual reality, two meticulously designed environments have emerged. The initial setting unfolds on a beach, offering a spacious open-air landscape against the captivating backdrop of Hong Kong's renowned Victoria Harbor. This serene setting is further enhanced by the tranquil sounds of waves softly caressing the shore. The beach scene is adorned with palm trees and various beach amenities, elevating the immersive experience; In stark contrast, the second environment is situated within a workshop, an enclosed space resonating with the characteristic mechanical noises associated with industrial environments. Inside this space, four workstations are positioned amidst scattered wooden materials, emphasizing a utilitarian aesthetic. Configured to support a range of tasks, the workshop is thoughtfully equipped with an assortment of tools and machinery (See Figure 4), highlighting practicality and functionality. Similarly to the beach setting (See Figure 3), experimental setups are prominently featured in the core of this workshop environment, suggesting a focus on innovation or hands-on projects.

Participants

A physical experiment involved participants aged 18 or older with varying backgrounds, including design-related and non-design-related fields, possessing proficient tactile sensitivity in their hands and a basic comprehension of VR control techniques. An equal gender distribution was maintained, with 4 male and 4 female participants. The experiment comprised three components: (a), (b), and (c), with a total of 8 participants. Within this group, 2 individuals were design students, while the remaining 2 were non-design students.

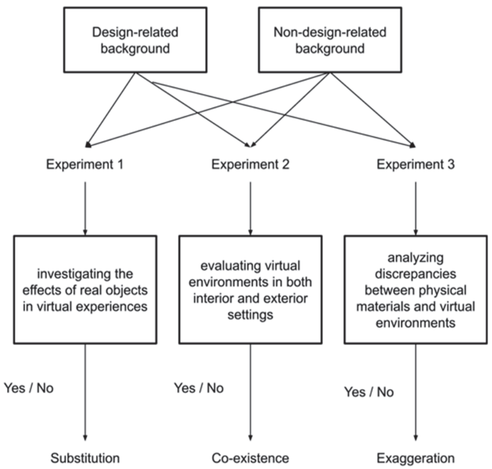


Figure 2
An experimental model consists of three parts and is used to examine the impact of the connection between the physical and digital worlds on human perception.

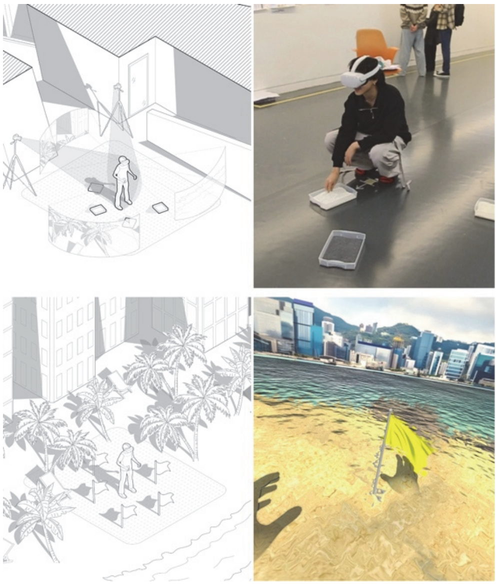
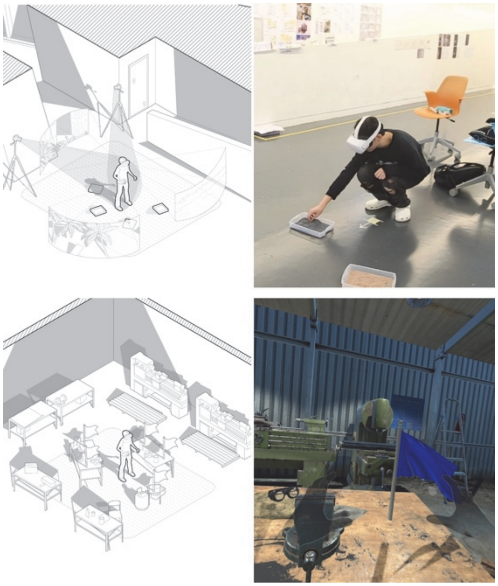


Figure 3
The diagram (top left) shows the physical setup with equipments in the real-world setting. The image (top right) depicts the participant's interaction within the physical environment. The diagram (bottom left) shows a virtual beach environment. The image (bottom right) showcases the participant's interaction in the virtual scene.



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Procedures

The privacy, confidentiality, and anonymity of all participants have been meticulously safeguarded. Before commencing the experiment, participants completed a declaration form along with a questionnaire. Subsequently, they received verbal instructions outlining the experiment process and reminders. Each participant was randomly assigned to one of three experiment components without duplication. They followed AI-voice instructions to engage in physical interactions, ensuring uniformity. Interactions with materials were time-bound to 30-second intervals to promote clarity in instructions and fairness among participants, aiming to prevent data bias and maintain consistency across all participants.

Sampling and data collection

Before the test initiation, participants will receive instructions to do the VR headset and engage in a brief 30-second walking exercise. Subsequently, they will be directed to interact with virtual "sand" in the VR environment, focusing on evaluating its texture, material, temperature, and scale. Additionally, participants will assess its hardness, softness, roughness, and smoothness. The participants' actions and verbal responses will be recorded using two cameras for subsequent analysis. Following this phase, participants will remove the VR headset and directly interact with the physical material solely relying on their unaided vision and sense of touch. This stage aims to investigate the correlation between visual perception and tactile sensation, providing valuable insights into the interconnected nature of these sensory modalities (See Figure 3 and 4).

RESULTS

After each XR simulation in a virtual environment, participants were given instructions to complete a survey. The survey questions assessed the subjective perception of haptic experiences using a Physical and Virtual Haptics Scale (PVHS) that considered three parameters: Real and Fake, Exterior and Interior, and Discrepancies. Referring to Table 1, scores ≤ 5 indicated a perception of "very different or not that strong," a score of 5 indicated "different or strong," and scores ≥ 5 indicated "same or very strong." This scale provided insight into how participants perceived the materials. The study examined four variables (Dm, Df, Nm, Nf) and explored how participants' gender and occupational background influenced their material perceptions. The experiment included a total of 17 tested materials. Additionally, the study investigated the potential impact of participants' gender on their sensitivity to different materials.

Table 1
Survey form: measurements of 3 experimental objectives that rates a score from 0 to 10.

Set 1: Real and Fake *The two materials are (0 - 10) .* *0 …… 1 …… 2 …… 3 …… 4 ……5 ……6 ……7 ……8 ……9 ……10* *Very Different ……………………Different ……………………………Same*
Set 2: Exterior and Interior *The materials are (0 - 10) to the virtual environment.* *0 …… 1 …… 2 …… 3 …… 4 ……5 ……6 ……7 ……8 ……9 ……10* *Very Different ……………………Different ……………………………Same*
Set 3: Discrepancies *The materials are (0 - 10) to the virtual environment.* *0 …… 1 …… 2 …… 3 …… 4 ……5 ……6 ……7 ……8 ……9 ……10* *Not that Strong…………………… Strong ……………………Very Strong*

Measurement Model

The results of the conducted experiments provide insights into addressing the initial hypothetical question posed in the paper. The objective was to investigate the extent to which physical materials and virtual space impact human perception. The experiments encompassed evaluations of virtual environments in different contexts, exploring the impact of real materials on virtual experiences (Experiment 1.1 and 1.2), assessing both interior and exterior virtual environments (Experiment 2.1 and 2.2), and analyzing disparities between physical materials and virtual environments (Experiment 3) concerning human perception. The primary findings derived from these experiments are presented in Table 2.

In Experiment 1, two separate experiments (1.1 and 1.2) were conducted in a virtual beach environment using two sand-like materials. Experiment 1.1 involved the use of a real water material, while Experiment 1.2 did not include water. The results from the Physical and Virtual Haptics Scale (PVHS) indicated that without water, participants perceived the sand-like materials as "most likely" sand (Experiment 1.2: 7.375 ≤ M ≤ 8.5). However, when the real water material was introduced, the divergence in perception increased. Participants considered the materials to have "a small degree of difference" (Experiment 1.1: 6.875 ≤ M ≤ 7.625). The inclusion of the real material potentially diminished the impact of human perception on the synthetic materials (0.25 ≥ M ≥ 1.625).

Regarding Experiment 2, two experiments (2.1 and 2.2) were conducted in both exterior beach and interior workshop virtual environments. Four sets of materials (M1, M2, M3, M4) were compared. The most diverse material choice was dirt (M1), which was perceived as "very different" in both interior and exterior virtual environments (2 ≤ M1 ≤ 6). Participants found it challenging to associate tree powder (M3) with the virtual environments, describing it as "very different" (3.125 ≤ M3 ≤ 3.25). Clay (M2) was considered "somewhat different" (5.625 ≤ M2 ≤ 4.875) when participants interacted with the spaces. The most similar choice was fine granite (M4), which participants perceived as "nearly the same" (7.875 ≤ M4 ≤ 8) in both environments. These results suggest that material choice significantly impacts perception in virtual environments.

In Experiment 3, four sets of materials (M1, M2, M3, M4) were examined to determine which one evoked stronger haptic sensations. Participants reported stronger haptic sensations with wood dust (M4), scoring 7.625 on the PVHS scale. This was

Experiment	*Materials*	*Design Male (Dm)*	*Design Female (Df)*	*Non-Design Male (Nm)*	*Non-Design Female (Nf)*	*Average*
1.1	*Water*	*9*	*10*	*5*	*9*	*6*
	Fine Granite	*7*	*5*	*8*	*7.5*	*6.875*
	Gravel	*5*	*9.5*	*10*	*6*	*7.625*
1.2	*Fine Granite*	*9*	*7*	*8.5*	*9.5*	*8.5*
	Gravel	*7*	*5*	*8*	*9.5*	*7.375*
2.1	*Dirt*	*8*	*7*	*3*	*6*	*6*
	Clay	*7*	*4*	*7.5*	*4*	*5.625*
	Tree Powder	*6*	*3*	*0.5*	*3*	*3.125*
	Fine Granite	*7*	*7.5*	*8*	*9*	*7.875*
2.2	*Dirt*	*3*	*1.5*	*3*	*0.5*	*2*
	Clay	*6*	*4*	*9*	*1*	*4.875*
	Tree Powder	*0.5*	*3*	*0.5*	*9*	*3.25*
	Fine Granite	*9*	*8.5*	*8.5*	*6*	*8*
3	*Slime*	*9*	*2*	*3*	*0.5*	*3.625*
	Crystal	*2*	*6*	*5*	*1*	*3.5*
	Pepples	*8*	*4*	*5*	*9*	*6.5*
	Wood Dust	*9*	*8*	*9*	*4.5*	*7.625*

Table 2
Experiment results by using a physical and virtual haptics scale (PVHS).

Experiment	*Materials*	*Dm - Df*	*Nm - Nf*
1.1	*Water*	*1*	*-4*
	Fine Granite	*2*	*0.5*
	Gravel	*-4.5*	*4*
1.2	*Fine Granite*	*2*	*-1*
	Gravel	*2*	*-1.5*
2.1	*Dirt*	*1*	*-3*
	Clay	*3*	*3.5*
	Tree Powder	*3*	*-2.5*
	Fine Granite	*-0.5*	*-1*
2.2	*Dirt*	*1.5*	*2.5*
	Clay	*2*	*8*
	Tree Powder	*-2.5*	*-8.5*
	Fine Granite	*1.5*	*2.5*
3	*Slime*	*7.5*	*2.5*
	Crystal	*-4*	*4*
	Pepples	*4*	*-4*
	Wood Dust	*1*	*5.5*
Average		*1.235*	*0.44*

Table 3
Experiment results by comparing Design and Non-Design Participants.

Table 4
Vocabulary items described by Design and Non-Design Participants.

Backgrounds	Used vocabularies to describe materials during the experiments
Design (8)	Water, Sand, Granules, Dust Mat, Plaster, Flour, Quartz, Wood dust, Plastic
Non-Design (8)	Water, Sand, Rough salt, Shell, Gel, Quick sand, Jelly, Cotton, Seaweed

followed by pebbles (M3: 6.5), slime (M1: 3.625), and crystal (M2: 3.5), respectively. The use of materials that elicited stronger haptic sensations in the experiment indicated that the material's attributes can influence human perception in XR worlds.

Table 3 presents the results of an experiment aimed at examining participants' sensitivity while interacting with virtual spaces and physical materials. The measurements, expressed as Xm - Xf, where X represents either design (D) or non-design (N), provide insights into the range of sensitivity using the PVHS scale. When the value is close to 0, it indicates that males and females exhibit similar haptic responses to materials within a virtual space. Conversely, when the value becomes negative, it suggests that female participants may have stronger sensitivity compared to males in the given measurement. The findings in Table 3 reveal that in several experiments (1.1, 1.2, 2.1, 2.2), female participants from non-design backgrounds demonstrated a stronger sensitivity than their male counterparts (score < 0). On the other hand, in most of the experiments (1.1, 1.2, 2.1, 2.2, 3), male participants exhibited stronger sensitivity than females (score > 0). By comparing the average scores between design and non-design participants, it is observed that the scores of non-design participants are lower than those of design participants. Furthermore, a hypothetical hierarchy of sensitivity between virtual space and physical materials can be deduced as follows: Nm < Nf < Df < Dm.

Table 4 displays the participants' use of vocabulary to describe materials throughout the experiments. The survey findings indicate that participants with a design background provided more precise descriptions that aligned closely with the actual materials used in the experiments (Granules, Plaster, Flour, Wood Dust). In contrast, participants from a non-design background attempted to associate the experimental materials with more common and natural elements (Cotton, Shell, Rough salt, Seaweed). These results suggest that participants' background has an influence on the haptic sensory experience and the cognitive understanding of materials.

DISCUSSION

This section aims to discuss the main findings of this research, presented in Tables 1 to 4, and examine the potential impact of phygital effects in XR technology on Architecture, Engineering and Construction (AEC) industry.

The data collected in this study demonstrates the importance of integrating physical sensory feedback to create truly immersive virtual environments. Table 1 demonstrates that participants' haptic perception is influenced by the presence of physical materials in the virtual environment. The inclusion of real materials, such as water in Experiment 1.1, led to divergent perceptions compared to the absence of such materials in Experiment 1.2. This suggests that the water in real life plays a significant role in enhancing the overall immersiveness, with aid of visuals in XR. In terms of user feedback, integrating physical interactions in XR design environments enables clients to better immerse and envision the final design in real life. This tactile engagement contributes to a data-driven understanding of human-environment interactions.

Moreover, Tables 2 and 3 highlight the significance of material choice and participants' background in shaping haptic sensitivity and perception. Participants with a design background exhibited a more precise understanding and description of the materials used in the experiments, while those from a non-design background associated the materials with familiar and natural objects. Given that those with a design background have more tactile sensitivity due to nuanced understanding of materials, integrating physical haptic interactions into virtual design suggests design workflow enhancement. These findings underscore the potential for physical haptic interactions to enhance immersion by providing users with a more realistic and intuitive interaction with virtual materials. Being able to physically experience virtual components could lead to more informed design and data-driven decisions.

This research represents a foundational step towards leveraging data-driven insights to inform the design of immersive XR experiences. Further comprehensive investigations are warranted to fully explore the potential of phygital interactions in XR and advance the boundaries of immersion. The multi-modal user interaction data collected in this study could be combined with other sensor information, such as physiological responses, to develop predictive models of human-environment experiences. Such a data-driven approach would enable the creation of more responsive built environments that cater to the embodied needs of occupants.

Furthermore, the implications of this work extend beyond enhancing immersion in VR. Haptic XR has the potential to revolutionize architectural design and evaluation workflows. Combining XR technology with haptics could generate valuable data to inform the optimization of design, construction, and operations.

In conclusion, the results in this study suggest that physical haptic interactions hold promise for enhancing immersion in VR, thereby bringing virtual experiences closer to reality on the RV continuum. This experiment serves as a foundational step for future investigations, paving the way for in-depth explorations that can unlock the full potential of physical interactions in creating more compelling, realistic, and immersive digital experiences. Ultimately, a refined understanding of the relationship between haptic feedback and user experiences in virtual environments will enable the AEC industry to develop data-driven design and methodologies that prioritize the embodied needs of building occupants.

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