# Developing the Spatial Computing Evaluation Framework: A Holistic Approach to Evaluate the User Experience in Mixed and Augmented Reality


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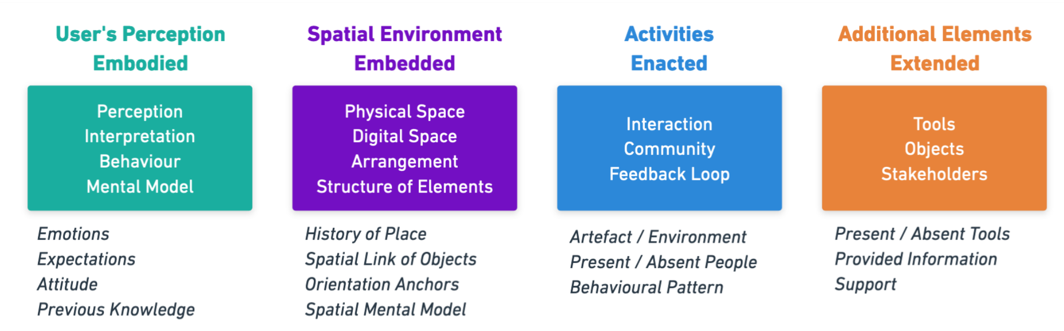


**Figure 1: The four dimensions of the Spatial Computing Evaluation Framework (SCEF) based on 4E Cognition theory with the key constituting elements and illustrative characteristics for each.**


## Abstract

The rapid technological advancements in Location-based Services, Augmented and Mixed Reality, Wearable Computing, and Sensor technologies paved the way for the new paradigm known as Spatial Computing. To date, little work has focused on user experience (UX) design and evaluation for Spatial Computing applications despite the emergent need for guidance and references for UX researchers and designers. We aim to address this gap by proposing the *Spatial Computing Evaluation Framework* based on a literature review and an initial empirical user study. Grounded in 4E Cognition theory, we unpack its Embodied, Enacted, Embedded, and Extended dimensions relevant to UX in Spatial Computing, emphasizing the interconnectedness of the digital, physical, and social environment. The framework can be seen as a valuable instrument for UX design and evaluation of Spatial Computing applications.



## CCS Concepts

• **Human-centered computing** → **User studies**; **HCI theory, concepts and models**; **Mixed / augmented reality**.




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## Keywords

Spatial Computing, User Experience, Evaluation, User Studies, 4E Cognition


## 1 Introduction

Spatial Computing extends reality through virtual worlds by enabling the digital representation of the physical world, either visually through Augmented Reality or implicitly through computation [11, 22]. The extension of the physical environment with digital content creates a conceptual space allowing interaction with spatial affordances [11, 13]. Spatial Computing is an emergent field with a large growth potential as its market size was estimated at USD 97.9 billion in 2023 with anticipated growth to USD 280.5 billion by 2028 [75].

Even though prior research has extensively looked at designing and developing user interactions and interfaces in Augmented and Virtual Reality (e.g., [40]), and conferences, like ACM CHI, ACM SUI, IEEE ISMAR, and IEEE VR, often feature related works, recent research still outlines existing gaps regarding understanding user experience (UX) in Spatial Computing, pointing out the lack of and incoherence in methodology for evaluating UX in Spatial Computing [1, 7, 75]. Most notably, Xu et al. [75] in their SIG on Spatial Computing at CHI'24 explicitly highlighted the gap in HCI research on Spatial Computing around UX and interaction aspects, specifically when it comes to considering a socio-technical perspective.

Consequently, designers and researchers need references and tools to design as well evaluate the new applications in Spatial Computing [75]. General-purpose UX evaluation questionnaires, e.g., SUS [33], NASA-TLX [23], UEQ [39], or AttrakDiff [24], assess perceived usability, workload, efficiency, and attractiveness of interactive systems but do not account for crucial factors in Spatial Computing, such as embodied interaction, digital-physical integration, and spatial immersion — core characteristics of Spatial Computing [53, 62]. Notably, Pott and Agotai [57] conducted a literature review to identify relevant aspects pertinent to the user experience in Spatial Computing. Building on their work, we enhanced and extended their findings by first analysing them through the lens of 4E Cognition theory from cognitive psychology (i.e. top-down approach). We then reviewed and refined our findings through an empirical user study with nine lay participants (i.e. bottom-up approach). In this work, we propose the *Spatial Computing Evaluation Framework (SCEF)*, which can be seen as a translational resource [10] to transfer knowledge from research for the benefit of UX practitioners. With this framework, we aim to provide novel considerations in the design of Spatial Computing applications and offer a practical instrument for UX evaluation.

## 2 Background

Spatial Computing encompasses various technologies such as Augmented and Mixed Reality, Ambient Sensing, Spatial Audio, Computer Vision, and Advanced Location-based Services. These technologies, especially when combined allow, the seamless combination of the physical and digital space [4, 6, 11, 19]. Spatial Computing differs from *Extended Reality* as it emphasizes the tight coupling of the digital and physical environment [19]. Therefore, fully immersive experiences are typically not considered within Spatial Computing.

In 2003, Greenwold [22] defined Spatial Computing as "human interaction with a machine that manipulates referents to real objects and spaces," emphasizing that digital content must meaningfully relate to the physical space. More recently, Balakrishnan et al. [4] added that in Spatial Computing, the digital content must be *perceptible* through the technology in order to enable users to interact with it and advocated for effective 3D UX design that unlocks the potential of Spatial Computing by integrating body gestures, eye or voice controls. However, it should also be considered that Spatial Computing not only changes the technical aspects of a *space* (e.g., by introducing digital content in physical space) but also the *place* that defines the user's perspective, taking into account their subjective and personal background[13].

To fully grasp the implications of Spatial Computing, it is crucial to understand how cognition operates within this context. Rather than existing in isolation, cognition emerges from the dynamic interaction between the brain, body, physical space, and social context [50]. The theory of 4E Cognition [51] aligns well with this perspective, encompassing four dimensions that resonate strongly with Spatial Computing: (1) *Embodied*: Spatial Computing relies on body movements, gestures, and eye tracking; (2) *Embedded*: Interactions take place within a dynamic physical-digital space, integrating real-world context. (3) *Enacted*: Users create meaning through interactions with digital and physical elements; and (4) *Extended*: External devices (e.g., AR/VR headsets, ambient sensors) become part of the cognitive process. 4E Cognition integrates concepts from several key HCI theories such as Situated Action [66], which posits that user actions are context-dependent and adaptive, Distributed Cognition [5], which views cognition as distributed across individuals, tools, and the environment, and Embodied Interaction [14], which emphasizes the role of physical interaction in digital spaces. This marks our salient motivation for employing 4E Cognition in our research.

## 3 Spatial Computing Evaluation Framework - the Four Dimensions of Cognition

Responding to the recent calls in the literature to explore the aspects of user experience in Spatial Computing [57], we developed the *SCEF*, a resource for UX practitioners to design and evaluate Spatial Computing applications. Grounded in 4E Cognition theory, the SCEF includes descriptive elements and reflective questions. To support its dissemination, we also created a Miro template with an example of its use [1].

### 3.1 Development of the Framework

At the inception, we analyzed Pott and Agotai's findings [57] through the lens of 4E Cognition (Embodied, Embedded, Enacted, and Extended) [51, 54] using a top-down analytical approach, interrogating their concept of Situatedness, which consists of five dimensions, while retaining key points from their work: (1) Place: Perception of the user, Previous knowledge, Emotions, Interpretation; (2) Space: Physical space, Digital content; (3) Community: People present or absent in the physical or remote environment; (4) Activity: Actions of the user, Goals of the user, Attitude; and (5) Time: Temporal flow, History. We choose this concept, as it interweaves with key HCI theories pertinent to Spatial Computing, such as Situated Action [66], Embodied Interaction [14], and Distributed Cognition [5] and emphasizes the contextual interaction between users and their environments. This approach allowed us to critically examine how the elements of Situatedness align with the cognitive processes that underpin user interaction in Spatial Computing.

To complement this, we conducted an empirical study with nine participants (3 were women) with limited AR experience, from backgrounds in languages, 3D modeling, or computer science. We employed an exploratory bottom-up approach to identify key UX dimensions in Spatial Computing and integrated a validated AR app [63] simulating a radio-pharmaceutical laboratory process on an Apple Vision Pro headset. We specifically chose the radio-pharmaceutical AR task from [63] because it requires users to manipulate physical objects (e.g., syringes and vials) while interpreting spatially separated AR instructions, engaging Embodied Cognition through real-world interaction. Furthermore, their structured workspace setup and step-by-step procedural nature of a task align with Embedded, Enacted, and Extended Cognition, as users must actively integrate AR cues with physical actions, construct spatial mental models, and rely on AR as an external cognitive aid to reduce memory load and enhance task accuracy. In order to further explore relevant aspects of user experience in Spatial Computing,

[1] https://miro.com/miroverse/spatial-computing-evalution-framework/

we created think-aloud protocols, transcribed user interviews, and conducted an affinity analysis [29].

From our user study and our analysis of Pott and Agotai's [57] findings, we created thematic clusters, visualized their relationships, and mapped them to the 4E Cognition theory. In what follows, we describe each cluster with its constituent characteristics, offer our analytical deductions, and support them with quotes from participants in our empirical study.

## 3.2 Embodied Dimension to Characterise User's Perception

In the 4E Cognition theory the *Embodied* dimension considers cognition not just a mental process, but involves the body and the mind and the interaction between the two [9, 50]. The SCEF accounts for this viewpoint with the elements of *Perception*, *Interpretation*, *Behaviour* and *Mental Model* as illustrated in Table 1. All of those elements are concerned with the User's Perception of the experience.

**Embodied**

| Elements | Characteristics | Reflective Questions |
|---|---|---|
| Perception | e.g., Emotions | How is the perception of the digital content in the physical space? Which emotions are visible? |
| Interpretation | e.g., Expectations | How is the interpretation of the content? Which expectations does the user have? Does this align with their experience? |
| Behaviour | e.g., Attitude | Which behaviour results from the interpretation? How is the personal attitude? |
| Mental Model | e.g., Previous Knowledge | Which prior knowledge characterises the mental model? |

**Table 1: Elements, Characteristics and Reflective Questions of Embodied Dimension from the SCEF**

*Perception* in Spatial Computing is influenced by a number of factors, such as the lighting conditions or the representation of the digital content [12, 18, 35, 68, 72, 73]. It can evoke a variety of emotions, such as feelings of joy, surprise, intrusion, or frustration, which in turn have an impact on target usability (e.g., memorability) and user experience goals (e.g., empathy) [27, 34, 46, 65, 77]. Embedding digital content into the physical environment changes the meaning of space and therefore affects the user's *interpretation* and *behaviour* [31, 32, 34, 44, 45, 64]. The user's *mental model* and preconceptions must also be taken into account, as they influence the interpretation of a situation, which in turn influences the user's behaviour [60, 62]. This was also corroborated in our user study, where counting behaviour of our participants differed according to their prior knowledge, as in the case of P9: *"I would have identified this opening as the second one because I would have started counting here and not here. But from the digital model, it should be this opening, the one next to it."*

## 3.3 Embedded Dimension to Characterise the Spatial Environment

According to 4E Cognition theory the dimension of *Embedded* considers cognition not in isolation from context, but as influenced and shaped by it [9, 50]. The SCEF considers this viewpoint with the supporting elements of *Physical Space*, *Digital Space*, *Arrangement* and *Structure of Elements* as illustrated in Table 2. All of those elements are concerned with the Spatial Environment of the experience.

**Embedded**

| Elements | Characteristics | Reflective Questions |
|---|---|---|
| Physical Space | e.g., History of Place | What is the connection to physical space? Which history does the physical space have? What narratives could be build around it? |
| Digital Space | e.g., Spatial Link of Objects | How are the digital objects linked to the physical space? Which anchor points do the digital elements have? |
| Arrangement | e.g., Orientation Anchors | How is the arrangement of the elements in the digital and physical space? Are there elements which serve as points of orientation? |
| Structure of Elements | e.g., Spatial Mental Model | How is the structure of the (physical/digital) elements? Does the structure correspond to the user's spatial mental model? |

**Table 2: Elements, Characteristics and Reflective Questions of Embedded Dimension from the SCEF**

Rather than viewing the *physical space* as simply the container of elements, it's about the cultural interactions that shape our perceptions of a place, which are made up of the physical, digital and social context [16]. It is necessary to consider how the *digital content* is embedded in the physical space [16, 41, 67, 74], as it is through this relationship that the user could gain meaning between the two [25, 26, 47–49, 53, 73]. Digital objects can be anchored differently in relation to their characteristics and those of the environment [53, 61]. Depending on how the elements are *arranged*, the ergonomics (e.g., body posture) or cognitive mental load can increase or decrease. During the user study, this became apparent when one of our participants placed the instructions too far away from the desk: *"For comparison, it would have been even better if I had moved the image, then I would have seen it directly in front of me, so then the comparison would have been even more direct"* (P8). Furthermore, the *structure of the elements* plays an important role in the creation of spatial mental model, influencing presence or mental load [58, 69, 78]. In the user study, the instructions did not correspond to the user's spatial mental model, either in the digital model or in the natural language guidance: *"It says 'turn the 2nd 3rd 4th and 5th valve' . . . aaaah from the right, ok got it. So I thought that was from the other side"*(P7).

### 3.4 Enacted Dimension to Determine Users' Activities

According to 4E Cognition theory the *Enacted* dimension explains that cognition is not passive but an active process in which the user interacts with the environment and other people, resulting in cognition through the actions and behaviour [9, 50]. The SCEF considers this viewpoint with the elements of *Interaction*, *Community* and *Feedback Loop* as illustrated in Table 3. All of those elements are concerned with the Activities of the experience.

**Enacted**

| Elements | Characteristics | Reflective Questions |
|---|---|---|
| Interaction | e.g., Artefact/Environment | What interactions are afforded with the artefact and the environment? |
| Community | e.g., Present/Absent People | Which people or digital agents are relevant in the process? Who is present or absent? How is the interaction with these people? |
| Feedback Loop | e.g., Behavioural Patterns | How is the feedback loop from the interaction to the perception? How does the interaction change the perception? |

**Table 3: Elements, Characteristics and Reflective Questions of Enacted Dimension from the SCEF**

Spatial memory, creativity and information recall can be enhanced by *interaction* with the artefact [15, 38, 43]. However, it also shows that the interaction can be tiring, leading to ergonomic problems, or it can be distracting, leading to information tunneling [2, 3, 21, 30, 52, 59, 71]. Interaction can also occur with the physical environment or *community* inhabiting the space, affecting social interactions, social learning or presence [34, 36, 62, 74]. The experience can be influenced by those who are present as well as those who are not, as in the case of asynchronous AR [8, 70], and by digital connections that can influence the style and quality of communication [25, 28, 56, 76]. Interaction affects how future steps are perceived, creating a *feedback loop* with the embodied dimension. In the user study, the feedback loop between interaction and perception became visible in the reading behaviour, which became less over time, as in the case of P3: *"but once I understood what the structure of the text was, how it would probably work, I didn't actually read much more [but mostly looked at the 3D model.]"*

### 3.5 Extended Dimension to Consider Additional Elements

According to 4E Cognition theory the *Extended* dimension describes that external elements outside the boundaries of the mind can also be an essential part of cognition, such as objects, tools or other people [9, 50]. The SCEF considers this viewpoint with the elements of *Tools*, *Objects* and *Stakeholders* as illustrated in Table 4. All of those elements are concerned with Additional Elements of the experience.

**Extended**

| Elements | Characteristics | Reflective Questions |
|---|---|---|
| Tools | e.g., Present/Absent Tools | Which tools are available in the environment? Which tools are substituted by behaviour of the user? |
| Objects | e.g., Provided Information | Which objects are used? Which information is provided or missing for the objects? |
| Stakeholders | e.g., Support | Are there people who provide support? Which support is provided? |

**Table 4: Elements, Characteristics and Reflective Questions of Extended Dimension from the SCEF**

Spatial Computing has the potential to enhance extended cognition by reducing the mental load of certain tasks, allowing for the transfer of cognitive processes to an alternative medium [26, 27, 48] as for example the use of visual instructions overlaid on a device instead of textual information on paper [63]. Analysing which objects are used in cases of doubt or uncertainty can yield interesting results. For example in our user study where people misinterpreted the text and only understood the instructions with the help of the digital model as P8: *"And sometimes I started off wrong, [...] then I looked at the picture ... oh no, that's the [wrong] one"*. Some participants also mentioned that some information was missing, leading to uncertainty: *"The connections could be visualised even better at the end. 'This is how it should look now', [...] then I would have been sure [that I have done it right]* (P3). When it comes to support, if there were any technical problems, the participants asked the moderator for help: *"I see that I obviously made a mistake earlier. Can't go back, can I?"*(P4).

## 4 Discussion and Conclusion

The SCEF's cognition-centred structure, which integrates bodily interaction, environmental context and social presence, distinguishes it from general-purpose tools (e.g., SUS [33] and UEQ [39]), as well as AR-specific scales (e.g., HARUS [59] and ARI [20]) or questionnaires addressing specific issues in virtual environments (e.g., IPQ Presence [62] or Simulator Sickness Questionnaire [37]). By addressing how spatial and temporal contexts shape user perception and behaviour, the SCEF provides designers and researchers with a valuable resource for deriving heuristics and informing UX design in Spatial Computing. A design template and an evaluation example (see Supplementary Materials) demonstrate its practical application.

While the SCEF offers broad applicability, its dimensions may not fully address bespoke UX goals. As a living artefact based on related work and a small-scale empirical study, the SCEF provides a finite set of considerations but does not capture all possible factors influencing UX in Spatial Computing. We envision its use alongside other methods: expert reviews and heuristic evaluations [55] to refine its elements to better align with specific goals; qualitative interviews or think-aloud protocols [17] to provide deeper insights into user reasoning. In addition, incorporating cognitive walkthroughs [42] during the development process can help identify specific usability issues in early phases.

In a qualitative user evaluation study, a UX designer can employ SCEF as a lens during think-aloud sessions and post-task interviews, walking through its four dimensions. The Miro template, available online via https://miro.com/miroverse/spatial-computing-evalution-framework/, facilitates organised note-taking across the *Embodied, Embedded, Enacted, and Extended* dimensions, enabling designers to flag usability issues during an evaluation session. We successfully field-tested this approach in an industry pilot, where the SCEF helped identify discrepancies between digital content placement and users' spatial expectations. The UX team then used these observations to refine interface anchoring and task flow. However, further validation with real users is needed, as there are still outstanding questions regarding its usefulness and comprehensibility among both novice and seasoned UX practitioners working with Spatial Computing. We anticipate that wider dissemination of the SCEF will encourage further adoption while allowing us to gather valuable feedback for continuous improvement. In future work, we aim to transform the qualitative framework into a quantitative questionnaire, which could assess users' subjective experiences with Spatial Computing applications, complementing the SCEF.

With the development of the SCEF we bridge the gap between Spatial Computing research and UX practice and contribute to the body of knowledge in this emergent area. We envision that it will spark relevant discussions on further improvements and on how to support designers and developers in creating compelling and meaningful user experiences with Spatial Computing applications.

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