Spatiality and Semantics - Towards Understanding Content Placement in Mixed Reality

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ABSTRACT

Mixed Reality (MR) popularizes numerous situated applications where virtual content is spatially integrated into our physical environment. However, we only know little about what properties of an environment influence the way how people place digital content and perceive the resulting layout. We thus conducted a preliminary study (N = 8) examining how physical surfaces affect organizing virtual content like documents or charts, focusing on user perception and experience. We found, among others, that the situated layout of virtual content in its environment can be characterized by the level of spatial as well as semantic coupling. Consequently, we propose a two-dimensional design space to establish the vocabularies and detail their parameters for content organization. With our work, we aim to facilitate communication between designers or researchers, inform general MR interface design, and provide a first step towards future MR workspaces empowered by blending digital content and its real-world context.

CCS CONCEPTS

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

KEYWORDS

Mixed Reality, Augemented Reality, Content Organization, Layout, User Study, Design Space

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1 INTRODUCTION AND BACKGROUND

Immersive technologies like Mixed Reality (MR) and Virtual Reality (VR) might bring *"once-in-a-lifetime shift"*[1] and revolutionize our workspaces. MR is particularly promising as it supports environmental awareness and enables social awareness among coworkers [22], a low-barrier workflow integration [38], and flexible adaptions (e.g., mobile work [26, 28]). Another benefit of immersive environments is the nearly infinite display area. This can be especially helpful for aforementioned office use cases since multiple pieces of content are often presented simultaneously, such as general documents [18, 26], brainstorming notes [7, 22], sketches [14, 37], or data charts and diagrams [17, 19]. Therefore, investigating possible layout and distribution techniques for organizing virtual information becomes crucial for designing future workspaces. Research fields like immersive analytics have reported first insights, including that form factors of layout preferences can be associated with the number of visualization [19], the user task [20, 34], or the dimensionality of the visualizations [17]. Although these works have shown the value of spatiality for content presentation, they only focus on VR environments without considering physical surroundings, which is an inherent nature of MR.

In fact, integrating and contextualizing information into the physical environment in MR has been suggested, such as showing it in close spatial proximity to real-world objects [40]. Besides, to support placement decisions in the real world, heuristics like visual salience, spatial consistency [11], and real-world backgrounds [31] have been considered whilst techniques like automatic alignment [6, 27] and optimal areas detection [25] have been proposed. Furthermore, virtual content can also be aligned to real-world surfaces provided

[1]https://blogs.microsoft.com/blog/2022/10/11/microsoft-and-meta-partner-to-deliver-immersive-experiences-for-the-future-of-work-and-play/

Figure 1: The setup of our study. (A) shows the study environment including the used surfaces (highlighted in magenta). (B–E) display one of the four surfaces in combination with one of the four layouts (see Tab. 1): (B) with L1 on a big Whiteboard. (C) with L2 on a small Whiteboard. (D) with L3 on a big table. (E) with L4 on a small table.

by the environment (e.g., ceiling and floor [32]), specific objects (e.g., furniture) within the surroundings [13, 22, 23], or even other displays (e.g., monitors) [21, 29]. In particular, the orientation of these object surfaces can correlate to users' placement preferences [17, 22]. These works highlight spatial placement as the means to associate virtual content and its situated environment. However, a systematical understanding of its components is yet missing.

Aside from arranging spatially, the semantic association between virtual content and real-world environments has also been considered for photo presentation [5] and general interface layout auto-adaptation [6] in MR. In the working scenarios, the spatial analytic interface suggested that users should work in situ where information semantically connects with [10]. Recent discussions further explored such semantic associations regarding how to present and arrange content (like charts) considering its physical referent (such as design spaces [24, 35]) as well as the pros and cons of different layouts for coordination [33, 39].

Nevertheless, knowledge about how to present and place information in MR is still lacking [9]. Especially follow-up questions should be asked and investigated in order to better design the future MR-powered office, such as: What attributes affect content placement in MR? How does the semantic and spatial relation of information and physical surroundings play a role in this process? And eventually, how to best utilize available MR space for presenting virtual content? As an initial step to answering those questions, we contribute with this work:

- A preliminary user study gaining participants' feedback on the understanding of spatial relations between information (e.g., charts) and physical surroundings (e.g., surface types) for content placement and organization;
- A design space describing several types of content placement and summarizing these variants in a two-dimensional spectrum along the axes of spatial and semantic coupling, thereby highlighting the interaction between them.

2 PRELIMINARY USER STUDY

In the following, we investigate how commonly used surfaces of workspaces can be utilized for different styles of content layouts, especially focusing on simple charts as an example of content used

Layout	Size	Position	Dimensionality	# Vis
L1	same size	on surface	2D	7
L2	same size	around surface	2D	7
L3	one special size	on and around surface	2D and 3D	8
L4	mixed sizes	on and around surface	2D and 3D	8

Table 1: Overview of the Layout Types (L1 - L4) used in our study and their corresponding properties. *"# Vis"* represents the number of visualizations presented per layout.

in an office use case. For that, we conducted a preliminary user study for acquiring the first insights.

Study Design. We focused on two main factors: the type of surfaces virtual content can be attached to (Surface Type) and the layouts of those virtual contents (Layout Type). With regard to the Surface Type, we decided on both horizontal and vertical surfaces with two specific instances differing in size each. Those are a small and big whiteboard, and a small and big table respectively (see Fig. 1A). Regarding the Layout Type, we created four layouts (L1 - L4) with seven to eight information visualization each (see Fig. 1B-E). These layouts were designed to be representative based on commonly used sets of properties, which are the size of visualizations (same size, one special size, mixed sized), spatial positions (on, around, and on and around a surface), and the dimensionality of visualizations (pure 2D visualizations, 2D and 3D visualizations). As this study was planned as an initial investigation, we only selected a small subset of possible property combinations, as seen in Tab. 1.

Participants. We recruited 8 unpaid participants (2 female, 6 male) per word-of-mouth for our study. All participants had an academic background in either engineering or marketing. The average age was 24 years (M=24.13 years, SD=4.88 years) and the self-reported height ranged from 167 cm to 186 cm (M=176.38 cm, -SD=6.48 cm). No specific knowledge was required to participate in this study. All participants had a normal or corrected-to-normal vision and no spatial perception difficulties. On a five-step rating scale, all participants had less experience with AR in general ($M = 2.13, SD = .93$), AR via head-mounted displays ($M = 2, SD = 1$), and Virtual Reality ($M = 2.13, SD = .93$). Additionally, participants

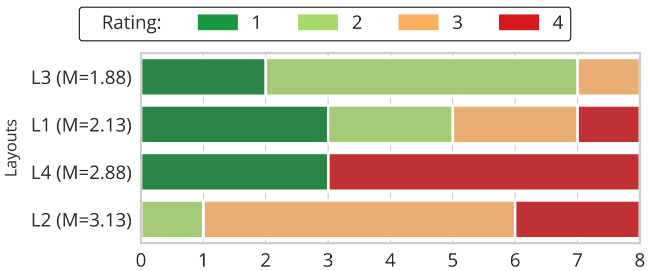

Figure 2: The order of preference participants chose for the four used Layouts (L1 - L4) in our study. The rating 1 represents the layout that was liked the most.

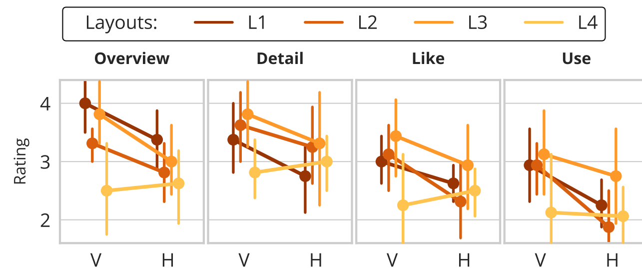

Figure 3: The ratings of the questions regarding the different features the presented layouts can provide. The visualizations are grouped by the vertical (V) and horizontal (H) orientation and the layouts (L1 - L4) themselves. All lines show the mean value and a 95% confidence interval.

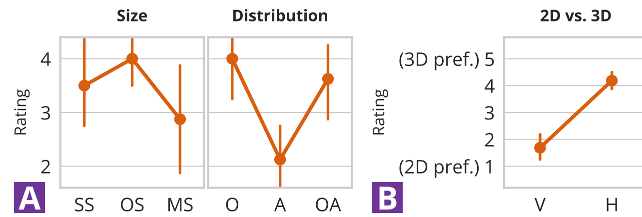

Figure 4: The ratings for the questions regarding the layout properties (A) and preferred visualization dimension(B). (A) shows the size properties of same size (SS), one special size (OS), and multiple sized (MS) visualizations within a layout, as well as the distribution of visualization with a layout: either on a surface (O), around a surface (A), or both, on and around a surface (OA). (B) shows the dimensionality preferences within a layout regarding vertical (V) or horizontal (H) surfaces. For both (A) and (B), all lines show the mean value and a 95% confidence interval.

worked regularly with visualizations for the purpose of information presentation ($M = 3.38, SD = .99$).

Setup and Apparatus. The study was conducted in a laboratory room with a size of 5.1 m × 8.5 m and a ceiling height of 2.6 m. Within this environment, we placed the four available Surface Types in such a way that they pointed toward the middle of the room (see Fig. 1A). The dimension of the surfaces are as follows: small whiteboard (68 cm × 97 cm, 134 cm above ground), big whiteboard (148 cm × 80 cm, 136 cm above ground), small table (80 cm × 80 cm, 72 cm above ground), and big table (160 cm × 80 cm, 72 cm above ground). A software prototype for the Microsoft HoloLens 2 was developed with the Mixed Reality Toolkit (MRTK), Unity 3D, and C#. QR codes were used to anchor different layouts to the Surface Types. The layouts presented several information visualizations based on a subset of the gapminder[2] dataset and were created via the u2Vis framework [30].

Task and Procedure. Within this study, the participants were asked to evaluate 16 different layouts (4 Surface Types × 4 Layout Types) while standing, assuming they needed to present the data of the layout during a fictitious meeting. This was done via a think-aloud method. After each layout, they were additionally asked to rate the given layout on four different five-point scales, considering the features of overview, detail, liking, and the likelihood of utilization. These ratings were orally collected and documented by the experimenter. Additionally, prior to the main task, participants should create several layouts on those surfaces to get familiar with the system and the targeted scenario of the information presentation. Lastly, to minimize a possible bias through training effects, we counterbalanced the order in which the layouts were presented to the participants.

With that, the study procedure was as follows: (1) A short introduction to the study; (2) A pre-study questionnaire and a declaration of consent; (3) Introduction to the system via a layout creation task; (4) The think-aloud assessment of the provided layouts; (5) A post-study questionnaire. In general, phase (4) of the study lasted approximately 27 min (M=26:56 min, SD=7:47 min).

Results & Findings. We analyzed the collected data by both quantitative and qualitative measures. In general, we performed repeated measures ANOVAs (if needed: corrected via Greenhouse-Geisser) and Bonferroni Post Hoc tests for the former. For the latter, we followed a thematic analysis approach [1] of the participant's comments (P1-8).

On a descriptive level, vertical surfaces were liked more than horizontal ones ($F(1,7) = 3.322, p = .111, \eta_p^2 = .322$). Rating the surface types for their use for 2D or 3D visualizations, we found a clear preference of 2D visualizations on vertical and 3D visualization on horizontal surfaces in the context of their mixed appearance ($F(1,7) = 63.64, p < .001, \eta_p^2 = .901$) (see Fig. 4B). Especially for horizontal surfaces, it was stated by P3 that *"you can move around them and look"* (P3-5, P8). Looking at the features of layouts and surfaces, we can see a significant difference ($F(1,7) = 6.243, p < .05, \eta_p^2 = .471$) for the overview horizontal and vertical surfaces provide (see Fig. 3). Such a difference can also be seen in the capability to show details ($F(1,7) = 5.223, p = .056, \eta_p^2 = .427$) and in the intention of use ($F(1,7) = 8.128, p < .05, \eta_p^2 = .537$) (see Fig. 3).

Furthermore, we asked the participants to order (1 - most liked) the seen layouts (L1 - L4) after the study, which resulted in the order seen in Fig. 2. Looking at the different properties of the layouts (see Tab. 1) we can see a similar trend. On a descriptive level, the

[2] www.gapminder.org

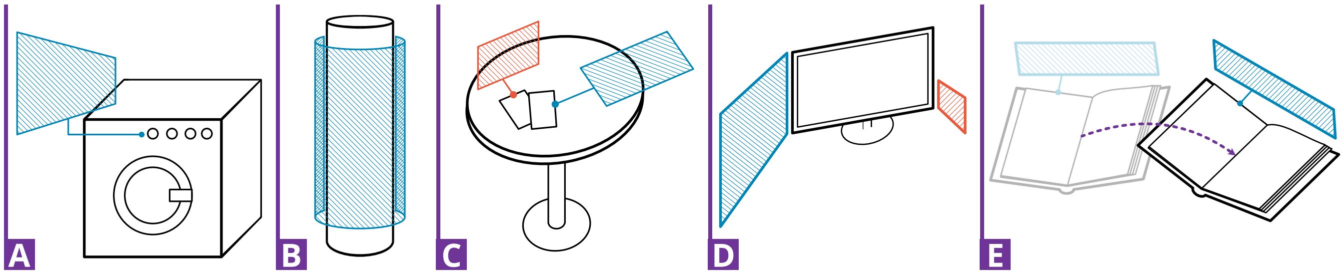

Figure 5: Illustration of described spatial attributes. In those figures, we show physical objects (black), correctly coupled virtual content (blue), and misaligned content (orange). (A) Positional Alignment: The virtual content is placed near a real-world reference. (B) Shape Alignment: The shape of the content conforms to the shape of the real-world referent. (C) Rotational Alignment: The content is rotationally aligned via leveling to the surface of the table. (D) Scale Alignment: the content is aligned in scale with the same dimensions as the surface of the referent. (E) Motion Alignment: The content follows the motion of the book simultaneously.

condition of multiple sizes were rated the worst (see Fig. 4A), as it is distracting (P3), confusing (P7), and creates smaller views (P7-8). Further, visualizations with the same size are better fitted for smaller surfaces (P1, P4-5, P8), while multiple sizes are better for bigger surfaces (P1-2, P4, P8). On the other hand, showing visualizations around a table was rated significantly worse ($F(2, 14) = 5.293$, $p < .01, \eta_p^2 = .492$) than showing them only on a table ($p < .05$) or both ($p < .05$) (see Fig. 4A). In general, *"it's kind of weird to only use the space around the [surface] because [normally you] have data on the [surface]"* (P2) and it makes the content hard to compare (P2-3, P5-7). Looking again at the features, we can find a significant difference for overview ($F(3, 21) = 5.293, p < .01, \eta_p^2 = .431$) with L4 being the worst, especially compared to L1 ($p < .05$) and L3 ($p = .06$) (see Fig. 3).

To conclude our study, we could see a clear preference trend for how AR content is placed in relation to real-world surfaces. We could find that a closer spatial coupling (i.e., visualization on surfaces) was perceived better, while a looser spatial coupling (i.e., visualization around surfaces) was not liked, as placing content around an empty surface *"is kinda counterintuitive"* (P2). However, it is possible to see *"some use cases [for such layouts], where I need the table for any data analysis on paper or my laptop"* (P7). This suggests the potential influences of other relations between the information and the surfaces, aside from the spatial relation. We carefully scrutinize our observations and findings and distill elements of these relations, which we present in the following.

3 DESIGN SPACE

Our study set an initial foundation for understanding elements that account for the layout in MR, particularly the specifications of spatial relations. On top of that, based on our observations of this study, our experience of previous studies [22, 23, 32], and our literature research, we consider the potential impact of semantic relations between information and situated physical surroundings for content organization. Especially, we argue that semantic relation could be essential in increasing the users' perception of unity, as it utilizes an understanding of the subject matter of the virtual content and the real-world referents that spatiality can not provide. Moreover, we are especially interested in the potential interplay between spatial and semantic relations, and how they collectively add up to a unity feeling. For this, we created a two-dimensional design space considering the dimension of *Spatial Coupling* and *Semantic Coupling* as factors for overall *Perceived Unity*, to inform and assist future layout design. Therefore, we define:

Spatial Coupling The geometric alignment of virtual content to physical objects in the situated environment, embodied by their spatial attributes (e.g., position, rotation).

Semantic Coupling The presence of informational meaning (e.g., data source, related concepts) between virtual objects and the objects in the immediate environment.

Perceived Unity The state of forming a complete and harmonious whole from one or several (i.e., a group of) virtual contents and physical objects in the content's environment, similar to being perceived as "belonging" to each other or being embedded into those objects [40].

To elaborate, *Spatial Coupling* and *Semantic Coupling* are detailed in the following.

3.1 Spatial Coupling

Existing literature shows that content in MR can be placed on varying levels of relation to objects within the environment [29, 40]. For example, content can be shown in reference to the user (i.e., body anchored) [12], or to the general environment (i.e., world anchored) [5, 8, 39]. In fact, this could lead to applications with low [39], medium [29, 38], and high [5, 37] degrees of *Spatial Coupling* to the environment. Based on this, we decided to mainly focus on the environment and virtual content, and decouple from the viewer. While the position likely is the first step for manipulating *Perceived Unity*, other spatial attributes should be considered.

Positional Alignment refers to the spatial distance to (or the spatial gap between) the referent object (see Fig. 5A). In this case, the content can be placed only in close proximity to a referent (i.e., situated) or placed on top of available surfaces (i.e., embedded) [40]. *Positional alignment* is probably most essential, as otherwise, a general decoupled state will probably be perceived regardless of

[3]For [33]: ©2022 IEEE. Reprinted, with permission, from IEEE International Symposium on Mixed and Augmented Reality (ISMAR).
[4]For [15]: CC BY NC ND, see http://creativecommons.org/licenses/by-nc-nd/4.0

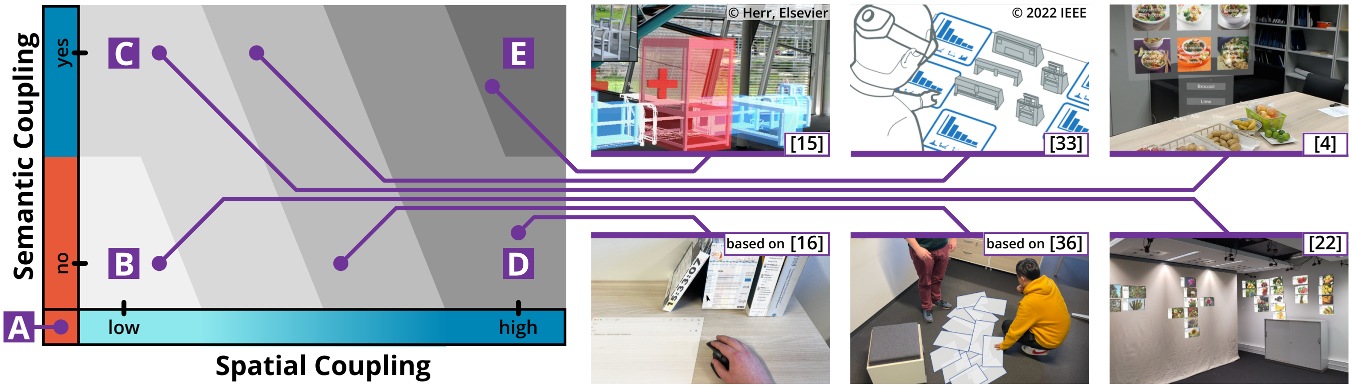

Figure 6: Schematic of the two-dimensional design space, highlighting important points (left side) and categorizing exemplary literature (right side), like [4, 15, 16, 22, 33, 36][3] [4]. The gray gradient within the design space illustrates the perceived unity, with a darker color corresponding to a higher "unity". (A) Decoupled content has neither *Spatial Coupling* nor *Semantic Coupling* and thus locates at the origin. (B) Content with low *Spatial Coupling* and no *Semantic Coupling* is called Situated. (C) Content with low *Spatial Coupling* and *Semantic Coupling* present is called Semantic Situated. (D) Content with high *Spatial Coupling* and no *Semantic Coupling* is called Integrated. (E) Content with high *Spatial Coupling* and *Semantic Coupling* present is called Semantic Integrated.

other following properties. This might also suggest that *Spatial Coupling* properties are likely not equally effective in conveying *Perceived Unity*.

Shape Alignment means the suitableness of the content being placed with the surface of the referent object, i.e., how close the virtual content follows the general shape, contour, or texture of the targeted surface (see Fig. 5B). While this enables integrating [40] the content into real-world objects, it could increase the distortion of the same content.

Rotational Alignment characterizes the rotational distance or difference to be leveled to the surface of referent objects (see Fig. 5C). For instance, content placed either in close proximity or on top of surfaces can be placed level on or to a surface (see L1 and L2 of our study). However, this can lead to visual distortion (e.g., participants (P1-2, P5-6) wished that the content tilts towards them) depending on the rotational difference.

Scale Alignment refers to the similarity of the size or extent to the referent objects (see Fig. 5D). Specifically, the surface size, the space around, or the presence of real-world objects can affect content placement perception, for instance, content bigger than the surface while placed on it can lead to less *Perceived Unity*.

Motion Alignment considers if and how those properties also alter over time as real-world objects can change regarding their position, rotation, or (surface) scale in space (see Fig. 5E).

In our study, medium to high *Spatial Coupling* layouts were used. Specifically, we placed charts either on or around surfaces, rotated them to be leveled with surfaces, and scaled the single chart to avoid extending the bounds of surfaces.

3.2 Semantic Coupling

The *Semantic Coupling* describes a contextual connection and relation of virtual content items with other items, or, which is particularly important for our work, real-world objects. According to existing literature, *Semantic Coupling* is either present like presenting associated statistics of game characters next to them [39] and similar examples as [8, 37]; or not present, such as physical referents only being used as spatial anchors for semantically decoupled information [2, 3, 23].

***Semantic Coupling* present** is defined as the existence of a contextual connection stemming from the information of the content being either generated by, influenced by, or conceptually connected to the referenced object.

***Semantic Coupling* not present** results from the absence of the contextual connection described above, meaning the information of the content is unrelated to its referent.

3.3 A Combinative 2D Spectrum

Aside from the individual dimension, it can be beneficial to combine both dimensions into a spectrum (see Fig. 6), which enables to describe a broader version of coupling, assume possible interactions between both dimensions, and create a more complete view of possible options to increase the *Perceived Unity* for MR content. In general, this means virtual content can gain a higher degree of *Perceived Unity* with a surface or the general environment by adding a *Semantic Coupling*, without changing the degree of *Spatial Coupling*. Similarly, virtual content with a semantic connection to a surface can increase *Perceived Unity* by raising the degree of *Spatial Coupling* to the same surface.

To better demonstrate the wide range of applicability of our proposed spectrum, we shortly illustrate how existing research work can be aligned with the design space (see Fig. 6). First, looking at non-semantic coupled examples, pictures grouped in AR [22] and only placed in relation to the immediate surrounding can be called Situated (see Fig. 6B). As virtual content gets deformed based on the presence of real-world objects or persons [36], we move toward a higher *Spatial Coupling* (see Fig. 6, bottom-middle). Next, virtual content that fully aligns on the surfaces of the surroundings and even allows to move, e.g., a mouse cursor across the surfaces [16], can be seen as Integrated (see Fig. 6D). On the other hand, looking at semantic coupled examples, a low *Spatial Coupling* allows presenting information to groceries in a supermarket [4] and can be called Semantic Situated (see Fig. 6C). As virtual content aligns itself with the available surfaces while the surrounding objects control the content [33], we move towards a higher *Spatial Coupling* (see Fig. 6, top-middle). Next, supporting the architectural and furniture changes that align and respect the environment, like for an industrial production plant [15], can be seen as Semantic Integrated (see Fig. 6E). Lastly, there also exists research areas that neither engaged with a spatial nor *Semantic Coupling*, i.e., Decoupled (see Fig. 6A), like small group multiples in MR [19].

4 DISCUSSION

In this section, we further discuss our study observations, the benefits of the proposed design space, the necessity to consider the two dimensions jointly, and the future plan.

Observed Content Layout Trends and Future Work. While the study remains preliminary and more general conclusions would require further investigation, we could find several trends for content placement. Specifically, the current study mainly focused on virtual content with medium to high *Spatial Coupling* to the environment without *Semantic Coupling*. Under this condition, we found the preference for 2D content on vertical surfaces (aligning with [22]) and 3D content on horizontal surfaces (aligning with [17]). Additionally, while empty surfaces significantly negatively impacted the layout ranking, participants explicitly said they would rank those oppositely if the surface were used. Thus, how the presence of contextual real-world objects on surfaces affects content placement decisions and preferences is worth further investigating. Besides, as the study was conducted in the context of analytical tasks with charts, other use cases should also be examined, such as productivity, entertainment, and general everyday uses.

Spatial and Semantic Coupling as MR Placement Design Vocabularies. The proposed two-dimensional design space with two types of coupling dimensions, particularly the actual location on the dimensions, can be used to communicate more precisely about the relationship of content to its environment. Combining the two factors allows a simultaneous examination, which is important as they are responsible for *Perceived Unity* in conjunction and not completely independent from each other. The design space also allows users to identify ways to increase or decrease the overall *Perceived Unity* as needed. In particular, for use cases like storytelling and presentations, the connection between virtual content and a referenced object likely becomes more critical. To tackle such needs, it is possible to identify potential properties of coupling and manipulate the *Perceived Unity* according to our design space. However, optimizing for *Perceived Unity* alone could result in less user-friendly placements. For example, placing content flat on a ceiling can lead to less favorable viewing conditions [32]. In contrast, the readability could be increased by moving content closer to viewers and away from the surface at the cost of *Spatial Coupling*. Such a trade-off of *Perceived Unity* can be examined through the design space that allows for an informed decision.

Future Extension and Evaluation for the Design Space. While we provided initial insights with our design space, dimensions and parameters within it can be further refined. For instance, the individual weight of the spatial properties, as well as the binarity of the *Semantic Coupling*, are not clearly known. The former can be important to inform design decisions, especially the trade-offs, such as between readability and available space. For instance, while tilting content upwards from a horizontal surface might increase content readability, it might also lower *Spatial Coupling*. With that said, it becomes important to understand how strong a change in parameter factors into the *Perceived Unity* and relates to other requirements like readability. On the other hand, a binary *Semantic Coupling* might not be enough to differentiate a contextual connection in detail. For example, information placed on a heater could show the temperature development of the heater (strongly coupled), the weather forecast (somewhat coupled), or notifications from a messenger (not coupled). Therefore, a deeper understanding of a potential finer-grained dimension for describing the semantic relation between virtual content and a referenced surface is needed, which could result in additional discrete levels or a continuous *Semantic Coupling* dimension. Lastly, other form factors, like the color similarity between content and physical referents, are not included in the design space and could be further considered.

5 CONCLUSION

Understanding virtual content placement in MR is key to the future MR-powered office and beyond. In this work, we presented a preliminary study suggesting spatiality as an influential attribute and semantics potentially as another factor, affecting the user perception formed jointly by MR content placement and the physical environment. We proposed a two-dimension design space to operationalize these factors and highlighted the interweaving relations between virtual content placement and referent surfaces, i.e., *Spatial Coupling* and *Semantic Coupling*. In particular, *Spatial Coupling* is characterized by the properties of *Positional Alignment*, *Shape Alignment*, *Rotational Alignment*, *Scale Alignment*, and *Motion Alignment*. In contrast, *Semantic Coupling* might play a decisive role in *Perceived Unity*. The combinative spectrum establishes the vocabulary of MR system design, supporting designers and developers to communicate, reason, and finalize design decisions. With this, we wish to inspire the discussion of the universal design guideline for future workspaces with the co-existing of the digital and real world.

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