Where Should We Put It? Layout and Placement Strategies of Documents in Augmented Reality for Collaborative Sensemaking

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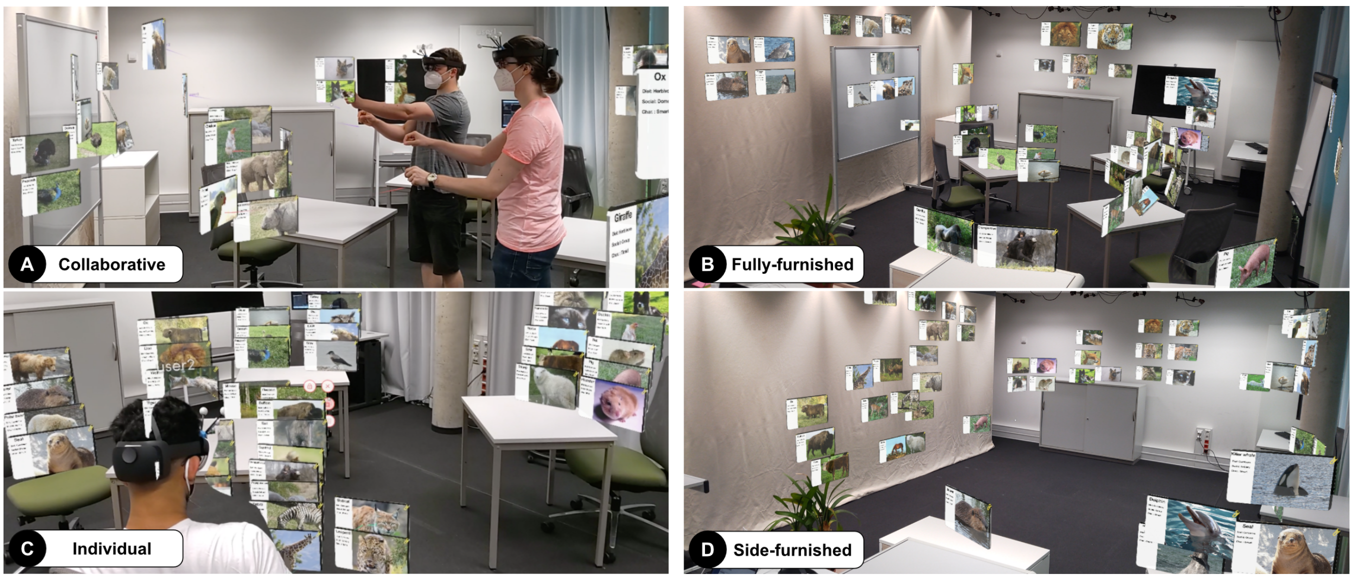

Figure 1: In our user study, placement and layout of virtual content are analyzed with regard to work style and room setting. Participants organized and classified documents both *Collaboratively* (A) and *Individually* (C) in either a *Fully-furnished* room (B) or a *Side-furnished* room (D).

ABSTRACT

Future offices are likely reshaped by Augmented Reality (AR) extending the display space while maintaining awareness of surroundings, and thus promise to support collaborative tasks such as brainstorming or sensemaking. However, it is unclear how physical surroundings and co-located collaboration influence the spatial organization of virtual content for sensemaking. Therefore, we conducted a study (N=28) to investigate the effect of office environments and work styles during a document classification task using AR with regard to content placement, layout strategies, and sensemaking workflows. Results show that participants require furniture, especially tables and whiteboards, to assist sensemaking and collaboration regardless of room settings, while generous free spaces (e.g., walls) are likely used when available. Moreover, collaborating participants tend to use furniture despite personal layout preferences. We identified different placement and layout strategies, as well as the transitions in-between. Finally, we propose design implications for future immersive sensemaking applications and beyond.

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CCS CONCEPTS

• **Human-centered computing** → **User studies**; **Mixed / augmented reality**; *Collaborative interaction*; **Computer supported cooperative work**.

KEYWORDS

spatiality, spatial layout, content organization, sensemaking, affordance, qualitative user study, Augmented Reality, Mixed Reality, collaborative sensemaking

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1 INTRODUCTION

Virtual and Augmented Reality (VR and AR) Head-Mounted Displays (HMDs) have the potential to reshape our present workspace and workflow. Future offices will likely be equipped and enhanced by Mixed Reality (MR) HMDs to enrich the current working environment with virtual content. Tasks such as brainstorming about an idea or sensemaking for document analysis will no longer be done with pen and paper alone. Instead, they will naturally take place in MR spaces, which allow for considerable display areas and a large interaction repertoire. However, complete isolation from the real world, like in VR, is far from being ideal, especially for brainstorming and sensemaking activities. In comparison, AR is more suitable for co-located collaboration [50], as it enables the user to have both the physical surrounding and collaborators in sight. This allows for easier adoption and integration into the existing workflow as well as support for collective activities with shared awareness. Additionally, brainstorming and sensemaking are fundamental tasks in many domains, such as design [22], journalism [62] and marketing [27], which are inherently multi-user activities. Furthermore, prior research [3, 13, 65] has shown that users are inclined to use space and position as methods to organize and structure ideas and thoughts throughout the sensemaking process. In combination, these factors highlight the great potential of using AR to support collaborative brainstorming and sensemaking.

With the vision of the future AR-enhanced office, two crucial questions arise: **(1)** How should multiple related visualizations be placed and arranged in MR? **(2)** How should MR applications for brainstorming and sensemaking activities be designed? Furthermore, such design implications might vary depending on whether tasks are performed collaboratively or individually. Despite the increasing interest in HMDs [5, 39, 48] for general office tasks, little research has been conducted regarding how AR content layout and placement are affected by the physical surrounding, the collaboration activity, and the general sensemaking workflow. Specifically, affordances provided by the geometric and semantic attributes of, e.g., furniture have not been sufficiently discussed. However, understanding affordances is crucial, as it might not only affect digital content placement but also facilitate the structuring and sensemaking process. Moreover, it has been seldom examined the adaptation of layout and workflow resulting from actions and behaviors of collaboration. Existing works [19, 25, 33, 56] have not considered brainstorming and sensemaking activities, which are highly position-dependent and intrinsically collaborative tasks that often serve as a foundation for high-level cognitive tasks.

We bridge this gap by conducting a mixed design study with two physical surrounding conditions (*Fully-furnished* vs. *Side-furnished*) based on the configuration of the room, and two work styles (*Collaborative* vs. *Individual*) based on the number of participants. We invited 28 participants to perform a typical sensemaking task in AR that consisted of analyzing and organizing digital multi-media documents into structured layouts.

We observed and recorded the placement and arrangement actions, the interaction between the participants and the environment, and the collaborative behavior. We also conducted semi-structured post-study interviews to identify factors and patterns of the document layout, the affordances of the physical surrounding, the adaptive behavior for collaboration, and the sensemaking workflow within these study conditions.

In our study, we found that regardless of the room setting, participants actively required furniture for placement, particularly tables and whiteboards, to assist and support their sensemaking and collaboration, while the generous free spaces were used when available (e.g., walls). We discovered that participants working individually realized creative and diverse layouts, which led to the usage of more types of furniture. Moreover, the collaboration resulted in more frequent use of furniture (consciously or unconsciously) for placements in general. We also identified general layout and arrangement strategies in AR and their associations with the sensemaking workflow. Lastly, we suggest design implications for future sensemaking and brainstorming systems in MR space and beyond.

To sum up, our main contributions are the following:

- A comprehensive study investigating AR usage for a collaborative sensemaking task.
- A systematic analysis of the affordances of physical surroundings for virtual content placement.
- A detailed comparison of multi-user and single-user sensemaking activities in AR.
- In-depth understanding regarding content layout, placement strategies, and the corresponding influential factors.
- Design implications for AR enabled-offices as well as AR sensemaking and brainstorming applications.

2 BACKGROUND AND RELATED WORK

Our research is related to sensemaking support systems, content placement and layout, and collaboration in immersive environments. We start with mentioning examples regarding the assistance of digital tools for sensemaking activities (Sec. 2.1). We then focus on virtual content placement and layout strategies (Sec. 2.2) as well as the computer-supported collaboration (Sec. 2.3) in the context of immersive environments.

2.1 Digital Support for Sensemaking Activities

The utilization of spatial layout has been extensively researched and has shown great value for managing information. As an example, people use spatial layouts to organize their desks in daily life when working with physical papers [43]. Sensemaking activities and document arrangements are cognitively intensive tasks [2, 58, 64], which can be improved by the involvement of digital tools [23, 35]. Previous works mainly concentrated on conventional desks or pinboards [26, 30, 65], traditional desktops [1, 13, 43], large vertical displays [4, 8, 29], or mobile devices [59, 67, 70]. Several content placement and arrangement strategies have also been introduced, for instance, piles or stacks [1, 13], incremental layout [65], and row-column-clusters layout [29].

Nowadays, digital support has been extended beyond desktop computers to immersive environments. For instance, Lee et al. [34] presented a VR system that allows users to create and organize virtual sticky notes by, e.g., snapping at a virtual flat layer. Yang et al. [69] demonstrated VR loci (e.g., a virtual cafe shop), which improved memorability compared to the baseline for retrieving knowledge. He et al. [25] presented a VR whiteboard platform for collective creation in which users showed a preference for a mirrored layout, which was similar to face-to-face interaction. Galati et al. [24] suggested that users' interactions and neural reactions increased during demanding sensemaking tasks, regardless of the content layout in immersive environments. Lastly, Lisle et al. demonstrated that large VR spaces proved to be helpful during a text-based sensemaking task [36] and that participants structured documents into specific layouts to create meaning [37].

These works have demonstrated the potential of immersive HMDs for some high-level cognitive tasks. Interestingly, the studied content arrangements from the aforementioned works [25, 34, 37] are essentially two-dimensional (2D) structures situated in a three-dimensional (3D) space. An exception [69] demonstrated the possible benefits of using the position and semantic attributes of virtual objects for memorization, which could possibly also be applied to the AR environment. However, most existing works focus on VR and do not consider the physical environment around the users.

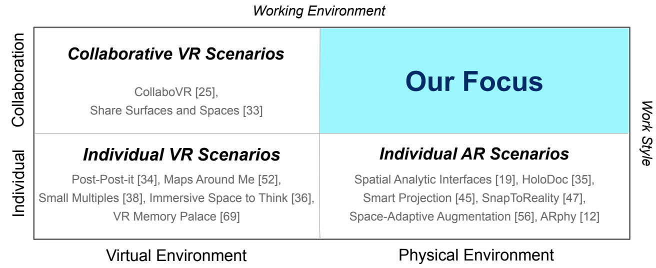

Figure 2: Existing works of virtual content placement have examined VR and AR environments (horizontal axis), as well as collaborative and individual work (vertical axis). Our focus is collaborative work in AR.

2.2 Placement and Layout in Immersive Environments

In the context of Immersive Analytics [44], previous research regarding immersive content organization [36, 38, 52], window layout [18, 21, 51] and view management [5, 32, 33, 63] has shown that the data analysis process can benefit from a proper design of the content layout. However, how to design and present the data, especially when dealing with multiple related visualizations, still lacks guidelines [17]. Specifically, Liu et al. [38] introduced multiple small data visualizations blocks in VR and found that users preferred a flat layout for fewer multiples while a semi-circular layout was preferred for a larger amount of multiples. Satriadi et al. [52] proposed hierarchical multi-view layouts for geospatial data analysis in VR, where participants were observed to prefer a spherical cap layout around themselves, and the views were often reorganized during the tasks. Derived from the concept of Multiple Coordinated Views (MCV), Spur et al. [57] designed a vertical stack layout in VR while Mahmood et al. [41] proposed Multiple Coordinated Spaces (a 3D counterpart) using AR, both for geospatial data analysis.

Moreover, prior works have highlighted contextual visualization and data analysis in-situ by considering the physical surrounding as a factor for virtual content placement [19]. For instance, Ens et al. [20] suggested using spatial constancy and visual salience as heuristics. Similarly, techniques for automatic alignment [47] and optimal areas detection [45] were presented. In addition to the geometrical features of real environments, the physical affordance of daily objects was suggested to be utilized for, e.g., AR photo organization [12]. Recently, Cheng et al. [14] presented an optimization-based method that automatically adapts MR interfaces to physical environments with the consideration of semantic association. On the other hand, Shin et al. [55] suggested that large spaces lead to a better AR experience while high density results in a higher perceived workload. Additionally, the layout of furniture can affect the narrative experience of the user [56].

Previous research has suggested possible layouts and explored factors from the real world. However, they did not focus on position-sensitive tasks such as sensemaking and brainstorming. Despite our early findings [40] regarding how users tend to use physical surroundings for placement in AR during a low-level sensemaking task in a preliminary study, further research considering how different placement strategies are performed based on different furniture setups, the work style, and sensemaking phases should follow.

2.3 Collaboration in Immersive Environments

One of the greatest potentials for Immersive Analytics is collaboration [31]. In comparison to VR, AR has advantages in co-located collaboration scenarios. In particular, AR HMDs can maintain the shared awareness between collaborators. Regarding the support of collaboration in AR, several comprehensive surveys have been conducted [31, 50, 54]. Here, we only highlight some aspects relevant to our research.

Despite the increasing popularity of HMDs for data visualization and analysis, using AR collaboratively has been largely neglected [54]. Recently, Mahmood et al. [42] presented a remote AR collaborative visualization system for geospatial data analysis featuring separated private and shared spaces. Likewise, the use of subjective views [53] and shared virtual landmarks [46] were proposed for co-located and remote AR collaboration. One of the most relevant works to this research is Share Surfaces and Spaces [33]. In this work, an exploratory study was conducted in VR, where teams of three co-located users were asked to freely structure their shared virtual workspace. A connection between space usage and type of visualization was found: Walls were used for organizing

Figure 3: The room settings in our study: (A) the *Fully-furnished* and (B) the *Side-furnished*.

2D visualizations while 3D visualizations were placed in the space around the users.

However, existing studies were mainly focusing on VR and did not fully consider the co-located scenario, the real-world context and the interaction between collaborators. Ideally, immersive technology should not only support single users but also empower multi-user scenarios for joint information processing, collaborative analytical reasoning, and decision-making [6, 28]. To the best of our knowledge, our work is the first attempt to investigate how AR-enhanced sensemaking activities are influenced by the physical surroundings and collaboration (see Fig. 2).

3 USER STUDY

We aim to contribute to the development of future workspaces, and provide findings regarding how AR can be used for collaborative work. Specifically, we are interested in *how the configuration of a room affects the layout and placement of virtual content, the sensemaking workflow, and the content placement strategies - also, whether differences exist between collaborative and individual work in this regard*. Therefore, we conducted a mixed design experiment (2×2), in which the work style (*Collaborative* vs. *Individual*) was a within-subjects variable and the physical surrounding setting (*Fully-furnished* vs. *Side-furnished*) was a between-subjects variable. Through the resulting four conditions, we studied participants performing a document classification task (i.e., organizing and grouping information cards) that was designed to simulate a typical sensemaking activity. We provide detailed study data as supplemental materials on our project page[1].

3.1 Setting and Apparatus

A spacious lab room with $8.6 \times 5.9m$ ($50.74m^2$) was selected for the experiment, where a furniture-made semi-open boundary was created to form a natural separation between the participants and the observing researchers[2]. Also, the biggest wall in the room was covered with fabric for technical reasons and formed a large, canvas-like area as a result.

Physical Surroundings: For the *Fully-furnished* condition (, Fig. 3(A)), we simulated a common office used for collaboration and workshops in a large, open room with three tables and four office chairs, as we wanted to encourage participants to move around while interacting with the virtual content. In addition, we placed multiple whiteboards (one landscape & one portrait analog whiteboard as well as one Microsoft Surface Hub as a digital proxy) and small cabinets in the room to create typical discussion areas. In the *Side-furnished* condition (, Fig. 3(B)), we removed the whiteboards, a small cabinet, two tables and two chairs, and placed the remaining two chairs and the table on the side of the room in order to create open spaces. In this way, participants would have higher freedom of movement, which could lead to different types of observable interaction. Such a setting also allowed the participants to rearrange the furniture in the room more flexibly if they desired. Moreover, a *Side-furnished* condition would be more anchored in reality than a completely empty room. Lastly, we decided the physical surrounding setting as the between-subjects variable in order to reduce the reconfiguration effort with regard to the room setting as well as to restrict the overall study duration for each participant.

AR Application: We used the software Spatial[3], a collaborative, spatially-aware working platform for HMDs, for the task during the study. In Spatial, two modes of interacting with virtual objects are supported: Ray-casting for objects out of reach, which is a ray starting from the palm of the user's hands, and direct manipulation by hand for objects within reach. With both interaction modes, the user is able to select and move or rotate objects by using one hand or to scale objects by using two hands. Furthermore, it supports combined interactions like simultaneously rotating and moving an object, which is very similar to the real-world experience. Spatial also offers multiple practical features for collaboration (e.g., colored rays for user awareness). We chose this application for our study due to its capability of performing our targeted task at a commercially available level and since it allows users to focus on content placement in AR instead of software usability. We used the application on four Microsoft HoloLens 2; two were assigned to the participants for conducting the study and two to the experimenters for observation.

3.2 Procedure and Tasks

For the document classification task (card sorting task similar to [65]), we used two datasets[4]; one with cards of plants and one with cards of animals. Each card consisted of an image, a title, and three phrases describing attributes about the plant or animal, which were designed to encourage sub-categorization and further arrangements. The images of plants and animals were chosen with the criteria that they should be familiar to most people and distinguishable. The plant dataset contained 50 cards of common plants such as different trees, fruits, vegetables and flowers, as well as textual information about the climate zone of the plant (tropical, moderate, or continental), the pollination method (wind, animal, or other), and the flowering season (spring, summer, or autumn). The animal dataset had similar characteristics. It included 50 cards of well-known animals including both birds and mammals with textual information about the diet (herbivore, carnivore, or omnivore), characteristics (fierce, timid, or smart), and social preference (group, solitary, or domestic) of the animal.

[1] https://imld.de/ARideas
[2] The study was performed under the COVID-19 hygiene regulations.
[3] https://spatial.io/
[4] The plant images are from https://pixabay.com and various projects on Kaggle (https://kaggle.com): /kritikseth/fruit-and-vegetable-image-recognition, /alxmamaev/flowers-recognition, /aelchimminut/fruits262, /bogdancretu/flower299. The animal images were collected from https://cvml.ist.ac.at/AwA2/ [68] and from https://pixnio.com.

Procedure: Upon arrival at the lab, participants signed a consent form, filled out a demographic questionnaire, and received a short introduction about the study. Then, a guide provided participants with a HoloLens and explained how to wear it as well as how to use Spatial in a training session. Next, participants were allowed to practice required operations freely with exemplary cards until they felt confident. We counterbalanced the order of the dataset (plants vs. animals) and the work style (vs.) across all participants to control variables and avoid learning effects. For both physical surrounding conditions, the subsequent procedure was identical. First, the participant completed the task and interview, which took 50 minutes. Afterward, this participant had a 20-minute break, and the second participant was asked to come to the lab to perform the introduction and training session. Then, both participants completed the task and interview, which also took 50 minutes. Afterward, the second participant had a 20-minute break followed by the task and interview. The whole duration for one participant was approximately 2 hours and 20 min (including breaks).

Task: During the study, 50 cards from either the plant or the animal dataset were displayed in stacks evenly spread around the room. The participants were instructed to group the cards into clusters in a way that made sense to them with no specific criteria and that they could rearrange the environment freely if they desired. The classification task took 25 minutes to complete. Moreover, we attempted to minimize any effect of time pressure, since we wanted to explore the intuitive behavior of the participants as they organized the virtual content. Thus, in the task, participants were told that it was not necessary to categorize all 50 cards. During the task, participants were instructed to think aloud while teams (the ones in the *Collaborative* condition) were encouraged to communicate. Additionally, the teams were instructed that they should both agree with the final outcome. In the end, the participants were asked to present their final classifications and arrangements to experimenters (5 minutes). Afterward, the semi-structured interview (20 minutes) was conducted.

3.3 Participants

We invited 28 paid participants (20 males and 8 females between 23-33 years of age) from multiple disciplines taught in our university including civil engineering, mechanical engineering, law and political science, environmental studies, and computer science. A team consisted of 2 participants (6 teams knew each other, 8 teams had never met). All participants felt positive working with other people, except two persons. In general, most participants had little or no experience using Mixed Reality mediums (VR, AR & MR); 43% of the participants answered they had never worked with AR HMDs in the past, 25% said they had only tested it and only 11% answered they had often used it. Moreover, 15 persons stated they had used VR before to varying extents, while 13 persons stated they had never used it before.

3.4 Measurements and Data Analysis

We followed the principles of semi-structured qualitative studies [7] for data gathering and analysis.

Measurements: For data gathering, two HoloLens were worn by the experimenters in order to capture the content placement in AR. An Apple iPhone 12 Pro Max was used to video record user behavior in the real environment, and a Huawei Honor 9 smartphone to record the audio. Additionally, the virtual environment was recorded using screen recording on two Samsung Galaxy Tab S4 tablets through the Spatial application. Next, observation notes with a semi-structured observation protocol were taken by at least one researcher during all sessions. After each session, a semi-structured interview was conducted to probe participants' attitudes and rationale, including topics like content placement (e.g., *did you use the spatial position between the documents to represent the classified groups?*), physical surroundings (e.g., *how did you perceive the furniture in the environment?*), collaboration (e.g., *what aspects did you like/dislike about working together?*) and general questions (e.g., *what is your general impression of using AR to arrange and classify documents?*). Participants were also asked to compare whether and how the aforementioned aspects differed when working alone and together. Furthermore, they were also asked additional questions informed by the study notes collecting interesting placement and reoccurring themes during the study. In the end, we collected data from 42 sessions (named as S01-S42); we had 21 sessions for each physical surrounding condition (N=21, N=21) and 28 and 14 sessions respectively for the work style condition (N=28, N=14). This resulted in different amount of sessions regarding both conditions (+ N=14, + N=7, + N=14, + N=7).

Data Analysis: The analysis of our study data was conducted on the basis of observation notes, video data, content placement records in Spatial, think-aloud and conversations comments, and interview answers. We sorted and categorized the observation notes of the experiments into four main topics **(1)** general sensemaking workflow, strategy, and the resulting classification, **(2)** placement and physical surrounding relation, **(3)** general layout and arrangement between and within clusters, **(4)** collaboration behavior and characteristic. Each of these topics was divided into multiple sub-topics that evolved during grouping. Two researchers then defined codes informed by the sorted observation notes and conducted a video coding analysis. All video recordings were analyzed in order to identify patterns with regard to the final layouts of the content placements, the arrangement strategies for separating and aggregating classified groups (i.e., clusters), the furniture usage, the created card classifications and the general workflow. The resulting placements and layouts were then reviewed by two researchers by revisiting the records of virtual content placement in its associated physical environment using HoloLens. For employing data triangulation, we transcribed the interview answers, gathered interesting think-aloud and conversation comments based on observation notes, and thematic analysis [9] was adopted for analysis by one researcher. Finally, all authors discussed the results and cross-checked together to reach consensus, and the overall process was iterative.

4 RESULTS

Based on our data analysis, we identified several patterns that provided insights regarding how users organize and spatially structure their virtual content in relation to the physical surrounding, i.e., *Fully-furnished* ( ) and *Side-furnished* ( ), in an *Individual* ( ) or a *Collaborative* ( ) AR space. First, we outline the sensemaking

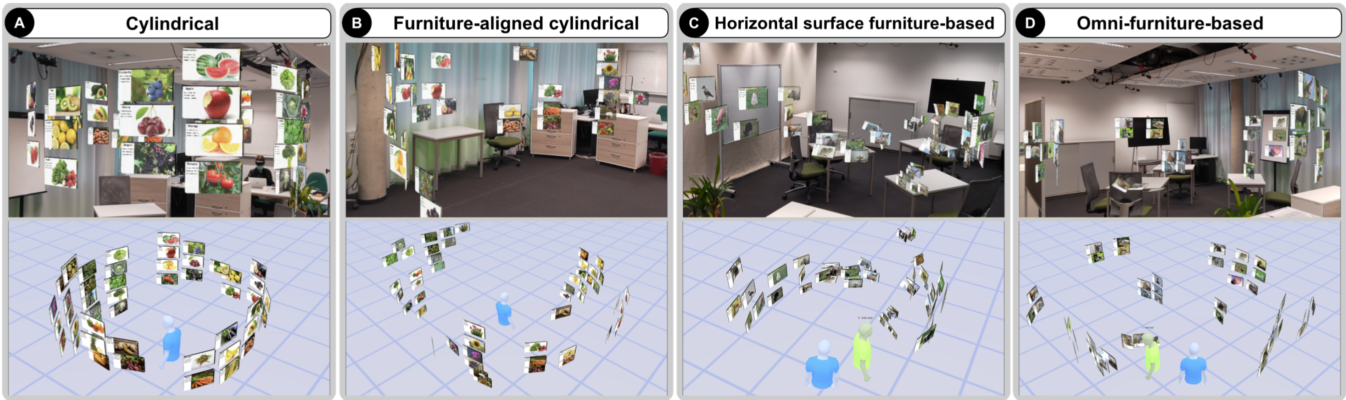

Figure 4: Examples of classified final layouts: (A) in study session 10 (S10), (B) in S24, (C) in S05, and (D) in S32. The upper row shows the AR space captured with the HoloLens and the bottom row the VR space captured through the SPATIAL application. In (C) and (D), the final layout is inspected by 2 people, while (A) and (B) depict single persons analyzing the content placement.

workflow in AR (Sec. 4.1). Next, an overview of the observed general layouts created for the card classifications in space is given (Sec. 4.2). Then, we zoom in on the spatial arrangements organizing the grouped cards into either clusters via separation or sub-clusters via aggregation (Sec. 4.3). Moreover, we further detail the analysis by describing the placement strategies with regard to the sensemaking workflow and furniture usage (Sec. 4.4). Lastly, we synthesize observed participant behavior and comments in order to shed light on their motivation and rationale for content placement (Sec. 4.5). In each section, the variations brought by the different physical surrounding settings and the different work styles are also compared and reported.

4.1 General AR Sensemaking Workflow

Similar to [49], we were able to observe the overall sensemaking process consisting of a foraging loop and a sensemaking loop, as well as a final presentation of the results.

Specifically, **(1) Planning stage**: Participants got an overview of the available data and considered possible organizing strategies. They used either an overview approach (i.e., (almost) all initial piles of cards were unpacked, then the first categories were planned) or an iterative approach (i.e., one to three initial categories were first formed then expanded by sorting and adding the remaining cards). **(2) Structuring stage**: Next, participants started arranging the cards into categories in AR space by iteratively creating main categories and assigning the cards to them. In the *Collaborative* sessions, the work was divided, and two participants were working simultaneously. **(3) Refinement stage**: After all or most of the cards were classified, possible subcategories were considered and structured by spatially distinguishing one from another, and often the relation of the clusters within the classifications was represented by spatial proximity. In some cases, already created categories or subcategories were rearranged due to, e.g., limited space. **(4) Finalization stage**: Here, a review and some fine-tuning of the created classification took place. In some cases, the cards were adjusted to align for a better visual organization or were reduced in size or overlapped for saving space. Overall, the planning stage covers parts of the foraging loop, while stages (2)-(4) are sensemaking activities in the sensemaking loop. Moreover, the resulting classifications were formed with 3-9 main clusters and 5-18 sub-clusters, with only 2-3 hierarchy levels created by the participants (see supplemental materials for more details).

Interestingly, although we could not observe any difference in the complexity between the two datasets used in the task from the resulting classifications, a difference could be observed in the workflow. The animal dataset was quickly structured by the participants in terms of the main categories (e.g., "living space" was quickly chosen as a category). In contrast, participants that worked with the plant dataset required more time to find structure (e.g., they zigzagged between placement strategies to differentiate the cards in terms of "growing area" or "fruits" and "vegetables").

4.2 Spatial Layout

Participants mainly used highly spatially structured arrangements for their classifications. This means that in addition to the planar structuring of virtual content (e.g., grid of cards), spatial placement was also considered (e.g., card grids were placed in different room locations). The usage of the physical environment varied: Some participants created geometry-shaped arrangements with less consideration of the furniture and the physical environment (e.g., Fig. 4(A)) while others highly considered it (e.g., Fig. 4(D)).

Through our data analysis, we could identify nine different layouts, which we structured according to their levels of *spatial structure usage* and *dependence on the physical environment* (see Fig. 6). The layouts with the high spatial structure for placement of virtual content, which took little or no account of the physical environment, were (A) grid-like, (B) cylindrical, and (C) furniture-anchored cylindrical (see Fig. 5). For the **grid-like** layouts, the clusters were arranged either very compactly in a small area of the room (2 sessions) or in the entire room, similar to a 3D matrix arrangement (2 sessions). For the **cylindrical** layouts, the clusters and sub-clusters were arranged in a circular pattern around the user, either as a panoramic-strip (1 session) or in the shape of a (semi-)cylinder (7 sessions). For the **furniture-anchored cylindrical** layouts (5

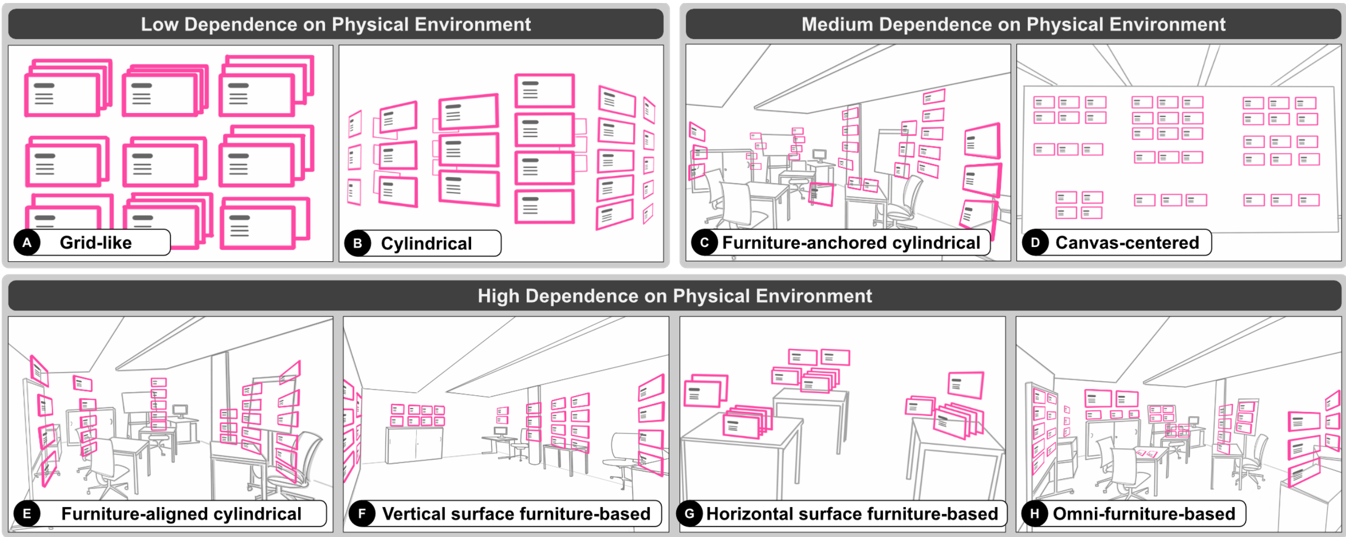

Figure 5: Illustrations of the final layouts, grouped according to the degree of dependence on the physical environment; low (A, B), medium (C, D), and high (E, F, G, H).

sessions), the physical environment had a moderate influence, i.e., the generated clusters were (often unconsciously[5]) placed in front of furniture to build cylindrical arrangements. In contrast, the identified layouts that were highly influenced by the physical environment and included high spatial structuring were: (E) furniture-aligned cylindrical, (F) vertical surface furniture-based, and (H) omni-furniture-based (see Fig. 5). For the **furniture-aligned cylindrical** layout, the clusters were placed on furniture or in-room areas and were gradually formed into curved or cylindrical arrangements (2 sessions, e.g., Fig. 4(B)). Notably, the differences of furniture-anchored cylindrical and furniture-aligned cylindrical layouts were the observed degree of dependence on physical environment and whether participants explicitly confirmed during the interview that they used furniture for placement. For the **vertical surface furniture-based** layout, the clusters were placed only on available vertical surfaces (e.g., whiteboards and above cabinets; 8 sessions). For the **omni-furniture-based** layout (6 sessions, e.g., Fig. 4(D)), all available surfaces of the furniture (e.g., tables, whiteboards, cabinets) and the room itself (e.g., stone pillar, wall) were used both vertically and horizontally.

We also observed a **horizontal surface furniture-based** layout (3 sessions with), which highly considered the physical surrounding, but had a low spatial structuring for the arrangement (see Fig. 4(C) and Fig. 5(G)). In these sessions, only the tables were used for the spatial arrangement of the clusters. Similarly, the **canvas-centered** layout (3 sessions with) only included the usage of a wall that served as a canvas where the clusters were organized (see Fig. 5(D)). Three of the sessions could not be assigned to a layout since the layouts of the created clusters were highly unstructured (see Fig. 6). We summarized these as others.

[5] This was confirmed by follow-up questions and comments in the post-study interview.

Physical Surrounding & Collaboration: Regarding the work styles, for the *Collaborative* task, most of the teams used a high spatial structure and highly considered the physical surrounding: Furniture-based layouts (like (E)-(H)) occurred in 8 of 14 sessions while geometry-shaped layouts (like (A) and (B)) appeared less frequently (5 of 14 sessions). For the *Individual* tasks, no such clear preference could be observed. However, we found that more furniture led to more physical environment usage. Specifically, mainly furniture-based arrangements were used in the *Fully-furnished* condition (+: 7 of 14 sessions) while more geometry-shaped layouts were used in the *Side-furnished* condition (+ : 6 of 14 sessions). Interestingly, the layouts which used a low spatial structure (lower half of Fig. 6) were mostly situated by the individual sessions.

Regarding the physical surrounding, in the *Fully-furnished* condition, the teams actively integrated the physical environment into their layout (+: 5 of 7 sessions). In contrast, for the *Side-furnished* condition, there was no such preference between the teams (+ : 3 respective sessions with high or low dependence on the physical environment of 7 sessions). Moreover, only in this condition, the canvas-centered layout was used as it was not partially obscured by other furniture.

4.3 Spatial Arrangement

Further zooming in, participants were observed to use different spatial arrangement strategies to separate between the clusters (Sec. 4.3.1) as well as to aggregate within the clusters (Sec. 4.3.2). Here we distinguish between arrangement strategies for separating grouped cards as categories (i.e., between-cluster grouping) and spatially aggregating grouped cards as subcategories (i.e., within-cluster grouping).

4.3.1 Patterns for Between-Cluster Grouping. In general, participants used three approaches to spatially separate their clusters

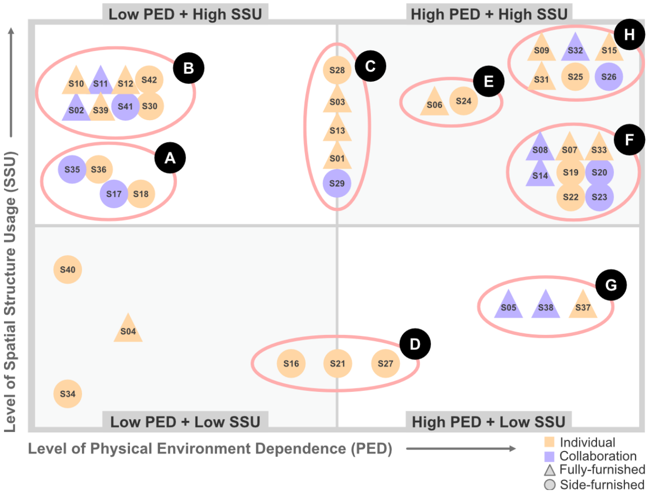

Figure 6: The identified final layouts (including session number) of all sessions in terms of the consideration of the dependence on physical environment (horizontal axis), and the degree of spatial structuring usage (vertical axis); (A) Grid-like, (B) Cylindrical, (C) Furniture-anchored cylindrical, (D) Canvas-centered, (E) Furniture-aligned surface-based, (F) Vertical surface furniture-based, (G) Horizontal surface furniture-based, and (H) Omni-furniture-based.

from one another: distance-only separation, geometrical separation, or furniture-related separation.

For the **distance-only separation** (occurred in 6 of 42 sessions), participants only used proximity to spatially structure their clusters. In contrast, the **geometrical separation** (14 sessions) consisted of a more spatially structured organization of the cards. Here, participants used a column-separated (8 sessions) or a grid-separated (8 sessions) arrangement for organizing their clusters (see Fig. 7(A)). For the **furniture-related separation** (20 sessions), participants used the physical environment to varying extents for their content organization, which included the following three strategies. In the purely furniture-separated arrangement strategy (8 sessions), each cluster or sub-cluster was placed on a piece of furniture (e.g., whiteboard, cabinet, table), creating a natural spatial structuring of the content (see Fig. 1(B) & Fig. 7(C)). Other participants used a combination of furniture and geometrical separation; major clusters were first placed on specific pieces of furniture and then arranged in sub-clusters divided by means of columns (furniture+column-separated: 7 sessions, see Fig. 7(B)) or grids (furniture+grid-separated: 2 sessions). In 3 sessions, we observed a mixture of between-cluster grouping strategies. For instance, furniture was used to distinguish clusters which were then subdivided into further clusters using different strategies such as columns, grids, or furniture parts.

4.3.2 Patterns for Within-Cluster Grouping. We observed the following different placement patterns for spatially structuring the sub-clusters. In the **1-dimensional aggregation**, cards were organized in a row-based manner (only 2 sessions) or in a column-based manner (9 sessions, see Fig. 7(D)). In one session, the column-based aggregation was also combined with an additional (horizontal) orientation for some cards to represent a sub-cluster (e.g., Fig. 4(D)). The **2-dimensional aggregation** included collage arrangements, i.e., an asymmetrical arrangement of cards (see Fig. 7(E)) and grid arrangements. In 3 sessions, we observed a combination of column-based and grid arrangements (e.g., grid placements on the canvas and column-based aggregation above the cabinet).

Notably, participants actively integrated depth as a part of their spatial organization strategy, i.e., cards were placed behind one another (8 sessions), which we named as **stack-based aggregation**. Similarly, cards were also observed to be placed behind one another but with slight overlapping for increasing visibility (6 sessions, e.g., Fig. 1(C)), named as a poker stack. Lastly, 6 sessions' sub-clusters were arranged arbitrarily without a clear spatial structure.

4.3.3 Physical Surrounding & Collaboration. Regarding the physical surrounding settings, it was observed that the room setting had a great influence on the between-cluster grouping strategy. In the *Fully-furnished* condition, furniture-related separation dominated (+: 5 of 7 sessions, +: 8 of 14 sessions), while in the *Side-furnished* condition, mainly geometrical separation strategies were used (+: 4 of 7 sessions, +: 8 of 14 sessions). For within-cluster grouping strategies in the *Fully-furnished* condition, teams used either the stack-based or 1-dimensional aggregation (+: 3 of 7 sessions, respectively). In the *Side-furnished* condition, all within-cluster grouping strategies were observed in the *Individual* sessions, but the arbitrary placement was not observed in the *Collaborative* sessions.

Regarding the work style, in the *Individual* sessions, participants were more likely to use the 2-dimensional or stack-based aggregation (+: 5 of 14 sessions, respectively).

Notably, the spatial layouts (Sec. 4.2) were shaped by the spatial arrangements (between and within clusters grouping strategies) in several ways, for example: **(1)** Participants used a grid-separated strategy for distinguishing between clusters and a stack aggregation approach for differentiating within a cluster, which resulted in the creation of grid-like layouts. **(2)** The cylindrical layout was formed by a geometrical or distance-only separation combined with several within-cluster grouping strategies (column-based, grid, collage, or poker stack). Furthermore, **(3)** the omni-furniture-based layout used furniture-related separation combined with several structured within-cluster aggregating approaches (rows, columns, or collages). **(4)** The vertical surface furniture-based layout was shaped by different furniture-related separation strategies, which were mainly combined with two within-cluster aggregating strategies (column-based and grid). In contrast, **(5)** the horizontal surface furniture-based layout was characterized by using a stack-based or arbitrary within-cluster aggregating strategy.

4.4 Placement Strategies For Sensemaking

Placement strategies were not independent of the context of ongoing sensemaking activity. Instead, they were changing and evolving along with the process. Thus, we further detail placement strategies with regard to the sensemaking workflow (Sec. 4.4.1). In addition, we will detail how specific pieces of furniture have been used for placement (Sec. 4.4.2).

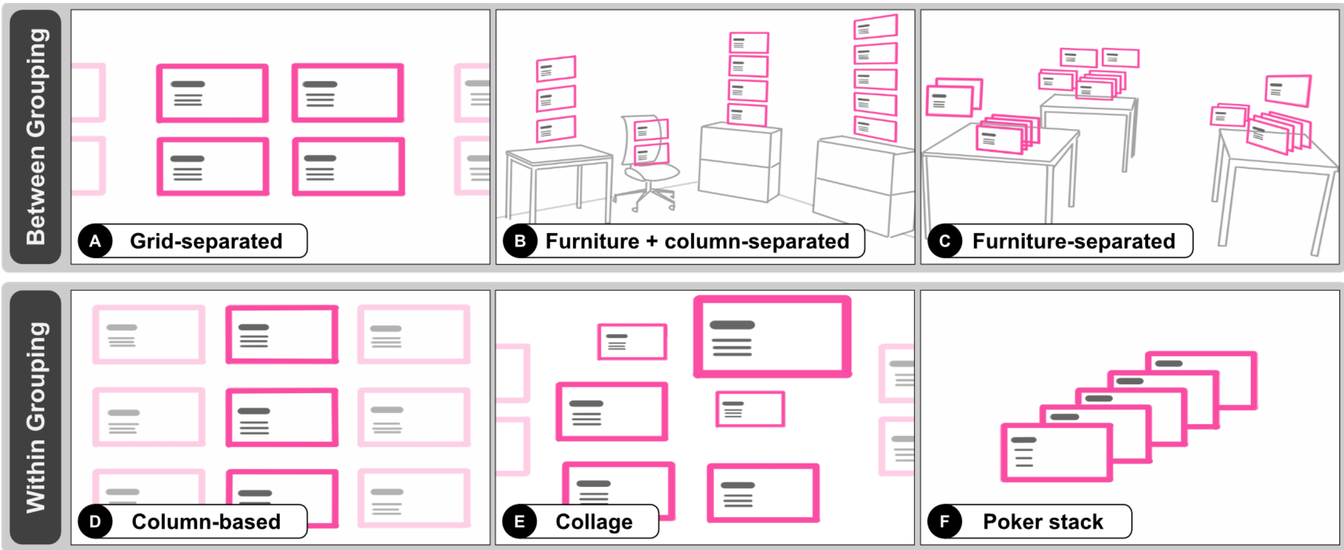

Figure 7: Illustrations of selected within and between clusters grouping strategies: (A) Grid-separated, (B) Furniture + column, (C) Furniture-separated, (D) Column-based, (E) Collage, and (F) Poker stack.

4.4.1 Placement Strategies for the Sensemaking Workflow. In general, participants either created a highly spatially structured organization of their classifications from the beginning or initially classified cards in a less spatially structured way to spatially order their arrangements later. For example, starting from **(1)** the planning stage, some participants distributed the clusters among the *furniture* and kept this *furniture-based* placement strategy until the end. In contrast, participants were also observed to start with an unstructured organization (e.g., *arbitrary* and *proximity* arrangement) or a low structured one (e.g., *stack* and *collage* arrangement). In **(2)** the structuring stage, participants organized their clusters in a more structured way where, e.g., a *cylindrical* or a *canvas-centered* layout was observed. However, *furniture-based* arrangements (including the *furniture-anchored* arrangement) were most frequently used to organize the main clusters and the first sub-clusters during the classification task. In **(3)** the refinement stage, the *furniture-based* arrangements were broken up again by some participants and changed to a more *cylindrical* arrangement. The *furniture-based* arrangements were also observed to be split into *poker stacks* or *column-based* arrangements for the organization of the sub-clusters. In **(4)** the finalization stage, participants focused on improving visibility through, e.g., *column* or *grid* arrangements. Some space-saving strategies, like *stack* and *poker stack* aggregations, were also often used.

We found a certain consistency of chosen placement strategies through the sensemaking phases. Specifically, when starting from a *furniture-based* arrangement, such a structuring strategy would be continued throughout the whole process by participants, which resulted in layouts with high dependence on the physical environment (see Sec. 4.2). Such a pattern was also observed from, e.g., participants beginning with the *cylindrical* arrangements and sticking with it, which resulted in *cylindrical* or *furniture-anchored cylindrical* layouts.

Physical Surrounding & Collaboration: Regarding the physical surrounding settings, we found that the *Fully-furnished* condition led to an increased usage of the physical surrounding for placement during the sensemaking process. Specifically, in the planning and structuring stages, participants (in) most often used a furniture-based strategy for the content organization, whereas some participants also used a less spatially structured approach. In the refinement and finalization stages, poker stacks or column-based arrangements were frequently used, in part to save space for content organization. In the *Side-furnished* condition, participants quickly ended up using the stacking arrangement. Lastly, in the refinement and finalization stages, participants used various placement strategies, and thus, we observed no common patterns.

Regarding the work styles, we found that spatially unstructured placement strategies were only observed in the *Side-furnished* condition and were mainly used in the *Individual* sessions. Besides, the *Individual* strategies were more diverse, whereas teams tended to use a more structured strategy earlier on.

4.4.2 Furniture Usage. Participants used the available furniture in various manners during the sensemaking activity (see Fig. 8). Regarding the work styles, in the *Individual* sessions, there was a more diverse usage of the furniture, i.e., most spots were used for placing clusters or sub-clusters. Moreover, participants tended to be creative in the spatial organization of their categories. However, teams tended to focus on efficiency with regard to the use of their space. For instance, in the *Fully-furnished* condition, teams tended to use the more traditional shared surfaces such as *whiteboards* and *tables* (see Fig. 4(D) & Fig. 8(D)), whereas in the *Side-furnished* condition, the *canvas* and the space above the *big cabinet* were used (see Fig. 1(D) & Fig. 8(F)). Furthermore, the periphery (in +) was also used for the spatial organization of the content in addition to the *canvas*, which was partly due to the division of labor in the workflow.

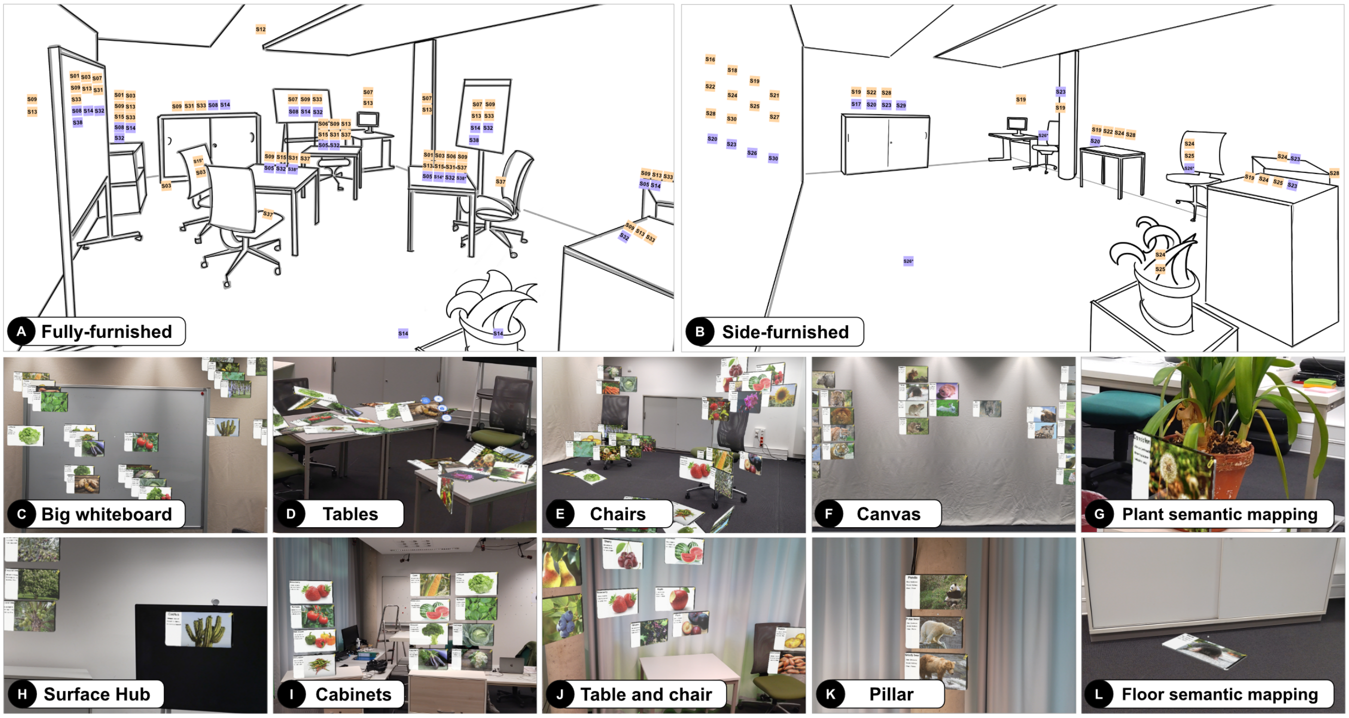

Figure 8: Sketches showing the distribution of the furniture usage in the *Fully-furnished* (A) and the *Side-furnished* (B) condition. The small colored squares (indicating session numbers) in the sketches represent final placements of virtual objects in the *Individual* (yellow) and *Collaborative* (purple) conditions. The two bottom rows show placements on the vertical surfaces (C, H, F), the horizontal surfaces (D, I, J), the chairs (E), the pillar (K), and the use of semantic mapping (G, L).

Interestingly, participants were more engaged in using furniture for placement in some of the *Collaborative* sessions. For instance, participants explicitly moved the furniture to adjust the physical surrounding to meet their organizational structuring needs. For instance, one team (+: S26) moved two *office chairs* to serve as visual landmarks for placing clusters and used the geometry of the chairs for the arrangement of the sub-clusters (see Fig. 8(E)). Two other teams (+: S14, S38) moved the tables together in order to have more physical space for their placement of clusters (see Fig. 8(D)).

Regarding the physical surrounding settings, in the *Fully-furnished* condition, participants preferred to use the *small cabinet* instead of the *big cabinet*. The *big cabinet* was, however, more often used for the initial placement of larger clusters that were later divided or rearranged. Moreover, due to the difference in vertical surface space, the *big whiteboard* (e.g., Fig. 8(C)) was used more than the *small whiteboard* (e.g., Fig. 4(D)), while the *Surface Hub* (e.g., Fig. 8(H)) seemed less suitable for placing virtual content. Lastly, the two *small cabinets* that separated experimenters and participants were rarely used for placement (see Fig. 8(I)).

Notably, *semantic mapping* placements were observed. For example, the card with the mole (see Fig. 8(L)) and cards displaying root vegetables, which are associated with the underground, were placed on the floor to visualize a semantic link between the virtual content and the physical world. Also, cards depicting fruits growing on trees were placed near the ceiling, while cards depicting fruits growing closer to the ground were placed near the floor. Additionally, a sub-cluster of flowers was observed to be placed in front of the real plant in the room (see Figure 8(G)).

To summarize, the highlights of observable results from Sec. 4.1 to Sec. 4.4 are:

(1) AR sensemaking workflow involved a foraging loop and a sensemaking loop whilst a general consistency of placement strategy can be observed.
(2) Diverse layout strategies can be observed from purely geometrical based to physical environment based arrangements.
(3) Physical environments were generally used for placement while a relatively extensive usage was observed in the *Fully-furnished* condition.
(4) Teams tend to use physical environments for collaboration.
(5) Tables, whiteboards, and generous free spaces (when available, e.g., empty walls in) were frequently used for placement. Besides, semantic mapping placement was observed.

4.5 Participant Behavior and Comments

Based on our observations, the interview comments (), the think-aloud comments (), and the conversation comments (), we present our findings as following themes: the general impression of using AR for sensemaking (Sec. 4.5.1), the usage of furniture for sensemaking (Sec. 4.5.2), and the factors affecting decisions of placement (Sec. 4.5.3).

4.5.1 General Impression. Most participants enjoyed and felt positive about using AR for sensemaking (e.g., P19: "Amazing! I love it", P28: "Compared to VR, AR allows me to navigate through the room since I can see obstacles"). Some participants also commented about the efficiency of AR (e.g., P7: "AR is more efficient compared to desktops due to the better overview"). However, some also thought AR might be slower than traditional desktops (e.g., P22: "Using a PC is faster because we are already familiar with how it works"). Several participants felt slightly frustrated using direct manipulation by hand since it did not work as smoothly as intended (e.g., P12, P26). The field of view (FoV) of the HoloLens 2 was also experienced as problematic by some of the participants (e.g., P13, P14). Lastly, all participants liked or preferred working together with others collaboratively in AR, except for P26 (personal preference). All in all, we believe the idea of using AR HMDs for collaborative sensemaking and brainstorming is promising.

4.5.2 Using Furniture for Sensemaking. In the following, we outline the affordances and benefits of physical environments for AR sensemaking.

Affordance of Physical Surroundings: We could observe different understandings of how to make use of furniture, which can be summarized as a spectrum of furniture dependence. Specifically, **(1)** for the highest level, participants treated the furniture as a **sensemaking tool** actively for grounding abstract thoughts and for making the sensemaking process more tangible, e.g., by moving chairs (+: S26). For example, P17 later explained: "I need these chairs for aiding this [sensemaking] process". **(2)** Next, many participants were seeking available furniture surfaces, mainly **horizontal or vertical surfaces** for "holding" or "attaching". For example, P5 "attached" virtual documents to vertical surfaces, like whiteboards and the Surface Hub, while P25 primarily utilized tables for "holding" virtual content. **(3)** In addition, some saw the furniture as **landmarks** and mainly focused on the relative spatial position of furniture in the room (e.g., P17: "I used small cabinets as landmarks to orient the direction of classifications"). Furthermore, combinations of strategies were also observed. For instance, P5 mentioned: "I used the big whiteboard for placing the final, sorted results (**vertical surfaces**) while using the canvas behind as the playground (**sensemaking tool**) for figuring out the possibility of categories". Lastly, a transition of mindset could also be observed. For example, P3 mentioned: "I used to treat the furniture as obstacles but I changed my mind after seeing how my partner worked with tables", which might imply that more explicit visual guidance could be helpful.

Benefits of Using Furniture for Sensemaking: Participants reported that there were several general advantages driving them to utilize the furniture. **(1)** Participants could be overwhelmed by the available placement options in AR, and hence, the pieces of furniture were used as **visual anchors** to facilitate the placement process and allowed for a better-structured layout. For example, P3 mentioned: "I had problems finding a place for my classifications in my last session, but I realized that furniture can make documents more organized". **(2)** The rendering color can be affected by the physical background due to the display mechanism of optical see-through AR HMDs. Furniture, or more generally speaking, monocolored surfaces, offered an apparent **color contrast** and improved the visibility of virtual objects. For instance, P10 mentioned: "Tables allow for a better contrast for me" and P17: "I tended to use the bright color of the cabinets to create a contrast". **(3)** Moreover, some participants stated that the furniture worked as **mnemonic symbols and position markers**, which could likely compensate for the limited FoV of HoloLens 2 (e.g., P22: "The furniture can always be seen in my periphery view, even though the AR hasn't rendered yet ... [This] allows me to memorize my classifications"). Also, P9 mentioned: "Furniture helps me remember my classifications ... [which is] also good for the navigation and orientation in the room". Surprisingly, we also noticed that text-based information as classification criteria was used mainly in the *Side-furnished* condition. Based on our findings, we suspect that the *Fully-furnished* environment can better support creativity (e.g., mentioned by P5, P6) while a *Side-furnished* environment helps with concentrating on the data.

Moreover, we also found advantages regarding using the furniture for collaboration. **(4)** During the planning stage, the overall layout of the furniture helped **specify workspaces** (or territories) for collaborators and distribute the workload within teams naturally. For instance, as suggested by P19 to P20: "I can start to arrange documents to the canvas while you could find and arrange sea animals to the cabinet". **(5)** Another common usage of the furniture was for **referring** during the collaboration, e.g., for orientation. P13 explained: "It could be advantageous to have furniture in the room that facilitates collaborative communication while in an empty room you have to find other designations", and P22: "Furniture can be used for referring between partners".

4.5.3 Factors Affecting Decisions of Placement. Combining with the analysis of furniture usage (see Fig. 8), we sum up three factors that lead to different placements: physical surroundings influence, use case and task influence, and user perspective influence.

Physical Surroundings Influence: Firstly, we found that physical surroundings, particularly furniture, could affect the decisions of placement. **(1)** One possible explanation for the distribution of the placements between the different pieces of furniture is the **perceivable available space** of the furniture. For instance, the whiteboard-like surfaces (big whiteboard, small whiteboard and Surface Hub) were used differently (see Fig. 8). Moreover, this could also partly explain the need to use the canvas for placements in the *Side-furnished* condition, as both P16 and P18 pointed out. **(2)** However, we also found that the small whiteboard was preferred over the Surface Hub, despite the comparable size. A conceivable answer is that the **material and texture** of furniture also played a role (e.g., P6: "I don't want to put pictures on a TV" and P27: "nobody wants to pin a picture on a monitor"). In contrast, the materials of the whiteboards and the canvas were more inviting to interact with, like a pinboard.

Use Case and Task Influence: We identified that the use case and the task could make an impact on placement decisions. **(1)** We observed **transitions of placement strategies along with the sensemaking stages** during the study. For instance, P22 started with creating a cylindrical layout around himself in the planning stage for getting an overview, then assigned corresponding documents to furniture (+: S33). **(2)** Moreover, the **number of items in the cluster** could affect the placement. For instance, some participants (P3 & P4) started from the centered tables and then moved some clusters to the whiteboard or used vertical space to build columns when the number of clusters increased. We also suppose that the visualization and content of the data could affect placement. **(3)** Specifically, some participants suggested that if the virtual content was represented more **3D model-like and photo-realistic**, they would probably put it on the furniture. For instance, P8 stated: "If the render quality was better, I would use a flat surface instead of "floating" documents". **(4)** Moreover, perceived connections between the documents and furniture led to **semantic mapping** placements, which were observed with the plant (P9, P10, P16 and P17), the floor (P2, P9 and P10), and the ceiling (P24).

User Perspective: Furthermore, the users themselves could affect placement in the following ways. **(1)** Particularly, users' **prior experience** influenced the decisions, either consciously or unconsciously. For instance, participants mentioned that whiteboards were meant for presenting and for attachments (P5, P6) while the function of tables is to hold objects (P4, P10, P13, P15). Interestingly, P10 also mentioned: "I don't have whiteboards in my home, so I didn't use them. [For] tables, you are supposed to put stuff on". **(2)** Another interesting comment came from P8: "Since there was no real interaction with the furniture, the virtual object was decoupled from the physical environment ... However, it would probably be different if I could write something on the whiteboard using a real pen and then place associated virtual objects nearby". We believe that the **degree of real and virtual world integration** is a potential factor affecting placement. **(3)** During the study, participants also expressed different **perceptions regarding AR**. For instance, P19 stated: "There is no connection between the real world and virtual world ... [So] I didn't use furniture." and P23: "I didn't put much attention on furniture. [Instead] I focused on my tasks". The placements of these participants were decoupled from the physical surrounding, which resulted in grid-like and cylindrical layouts. Lastly, user demographic aspects might have an influence. For example, P7 (around 193 cm) constructed a cylindrical layout adjusted to his height without any involvement of the lower located furniture.

5 DISCUSSION

We discuss our findings regarding how users adapted their behavior depending on collaboration, space, and content visibility (Sec. 5.1) and regarding space and physical environments for AR content placement (Sec. 5.2). Subsequently, we provide design implications for future research and design (Sec. 5.3).

5.1 Strategies for Collaborative AR Sensemaking Activities

During the study, we found that participants used different strategies accordingly for collaboration and for dealing with limited placement space while maintaining the visibility of virtual content.

Collaborative AR Sensemaking: Several participants reported during the *Individual* sessions that they felt relaxed and could try out placements freely, e.g., making the appearance more attractive (P18), decorating the room (P5), or showing personal preferences (P6). In contrast, ***Collaborative* sessions felt more formal**, and the participants focused on the efficiency of the placement (P6, P18 and P28). Such a difference is in line with the actual distribution of the furniture usage (see Fig. 8 and Sec. 4.4.2). Moreover, ***Collaborative* tasks encouraged a more active usage of the furniture**, e.g., the tables (P9 & P10, P25 & P26) and the chairs (P17 & P18) were moved around. This could be the result of the potential benefits of using furniture for collaborative content placement (see Sec. 4.5.2). To our surprise, such a tendency can be **prioritized above personal preferences** of content placement. For instance, during the *Collaborative* sessions of P3, P18 and P26, clear furniture-based layouts were observed, while in the *Individual* sessions, their layouts were decoupled from the physical environment.

Trade-off between Space and Visibility: During the experiment, participants used several methods to cope with the limited space while maintaining an overview of their layouts. **(1)** The construction of **columns** was a method often used to take advantage of the immersive environment, which helped expand the available spaces for placements while maintaining visibility. For instance, P3 and P4 extended their table placements vertically when they started to run out of space, which formed a column-based structure. However, column placement unavoidably requires more visual space. **(2) Stacks** were also observed (e.g., P12, P24), which could help compact spaces and allow for quick distinction between clusters. However, such placements might prevent participants from further iterating clusters or creating sub-clusters due to occlusion. A potential solution is the **poker stack** placement which combines the advantages of columns and stacks (e.g., used by P5, P6, P10, and P14). **(3)** Lastly, two teams (P9 & P10, P25 & P26) expanded the available areas by **rearranging the physical surrounding**, e.g., combining tables to form a bigger space. Also, several participants (e.g., P4, P5 and P25) **reduced the size** of the documents so they could fit them to particular places in the room.

5.2 Understanding Space and Physical Environments for Placement

Space can be a powerful cognitive tool, which allows offloading and alleviating the limited working memory of human beings [61]. Our results are generally in line with the theory of spatial cognition [60, 61] as we found, e.g., people use surrounding space to represent literal or metaphoric space. Also, the layouts of documents in our study are essentially the embodiment of abstractions, i.e., the thoughts in participants' minds, and the strategies of arrangements and placements reflect the process of thinking and externalization. Moreover, two fundamental facts about space, proximity and gravity [61], presumably played essential roles during the study. First, our results support that using proximity is an essential approach to signify correlation on abstractions. Second, most participants used column-based aggregations for organizing cards neutrally within clusters (12 of 42 sessions, the second most often used aggregation strategy). Therefore, they used vertical space instead of horizontal space, suggesting the implicit influence of gravity, even without the functional necessity for virtual content. However, this contradicts the description of spatial directionality [61], which states that vertical space (top-bottom) is loaded and often delineates the hierarchical relation of content, while horizontal space (left-right) is neutral and often depicts the neutral relation of content. This controversy requires further research, e.g., by observing and eliciting the AR spatial layout of data which inherently has hierarchies, in order to verify the generality of the theory. Lastly, we additionally found that the depth (front-back) can be encoded for articulating the high cohesion of abstractions (14 of 42 sessions, the most often used aggregation strategy).

Regarding the usage of physical environments for sensemaking and placement, in contrast to [40], we observed more proactive engagement with the furniture (e.g., as a sensemaking tool). This may have been driven by the larger space that allowed the participants to move the furniture and rearrange physical environments to fit their needs. This also suggests that the room size could have an influence, which is in line with [55]. Moreover, the central tables were more often used for placement, possibly due to the number of tables. We suppose that multiple homogeneous physical objects are equally weighted with regard to suitability for placements which intuitively embodies the hierarchy of information when classifying documents. Interestingly, several participants mentioned that the number of available furniture could help increase the number of classifications they created (e.g., P5, P8, P10, P17), which requires further investigations.

5.3 Design Implications

Based on our results, we propose further design implications for guiding the development of AR sensemaking and brainstorming systems. First of all, **(1)** we suggest that future AR-enabled offices should have **furniture** in the environments instead of using purely empty rooms. Particularly, it is beneficial to have several instances of the same type of furniture such as tables (e.g., to represent neutral relation between the contents), but also have some different types of furniture (e.g., to better distinguish the contents). Another reason is that the physical environment can act as a method of loci during cognitively demanding tasks like literature sensemaking (e.g., [16, 69]). Also, furniture can be used as a natural orientation aid (e.g., [46]), off-screen visualization aid (e.g., [15]) for facilitating collaboration and for mitigating the current limited FoV of AR devices. **(2)** We propose that future AR-enabled offices should provide **plenty of empty surfaces** while keeping these surfaces approachable, e.g., by choosing a proper texture and material, so that intuitive placement in AR can be supported, very much like in reality. **(3)** We recommend that an AR-enabled office should be **a large room**. It provides users with plenty of opportunities for content placement, the flexibility of reconfiguration of the physical environment, and the availability of free movement.

Regarding virtual content layout, **(4)** future AR sensemaking and brainstorming applications should offer **an automatic layout mechanism**, which allows for the distribution of content naturally according to the furniture, particularly with regard to available space, texture, and color contrast. Moreover, a proper automatic layout should also consider use cases, visual representations, and user perspectives. **(5)** Moreover, context-based **automatic alignment functions** should also be considered, e.g., the possibility of snapping virtual content to furniture depending on the proximity (e.g., [47]), as suggested by P11, P12, and P21. **(6)** Next, **additional visual assisting functions** such as annotating and making visual links, should be provided to further enhance the AR sensemaking and brainstorming experience, as suggested by P25 and P26. **(7)** Lastly, future systems should consider **physical environments as design opportunities**, which aligns with the ideas of situated data analysis [10, 66]. For instance, AR provides the flexibility of content placement, e.g., semantic mapping placement strategy, which in turn allows for a more intuitive and ubiquitous workspace. In addition, future systems should support the communication and presentation of sensemaking results using the room and furniture for data consumption in-situ (e.g., [10, 11]) as well as the asynchronous collaboration [54] by using physical environments as a common ground.

6 LIMITATIONS AND FUTURE WORK

While our findings offer insightful ideas regarding how physical environments are used and how collaboration is performed in AR for sensemaking, our work has some limitations. Firstly, the direct manipulation by hand has room for improvement with regard to the functionality, which was also mentioned by a few of the participants (see Sec. 4.5.1). This was because of limitations of the current hardware, specifically the tracking precision and the FoV of the HoloLens 2, which led to undetectable and unintended interactions. This could also partly explain why the orientation of documents mainly was perpendicular to the floor as SPATIAL will automatically adjust the image orientation once selected by ray-casting. Also, in the task we designed, the creative process of brainstorming and the structuring process of information foraging were less addressed. However, since the cognitive process unfolds differently for different people during creativity-demanding tasks, users might also adopt different layout and placement strategies and use physical environments differently.

In the future, we are planning to extend our study by examining collaboration mode (e.g., remote and co-located) and also taking the relationship of collaborators into account. Besides, an in-depth investigation of the conversations between collaborators with regard to the negotiation and decision process, will be interesting to better understand the collaboration patterns. Moreover, we would like to further study the ideation process involving brainstorming tasks in AR, e.g., by measuring the quality and quantity of ideas affected by physical environments.

7 CONCLUSION

In this study, we examined how physical environments and work styles affect content layout and placement, collaboration behavior, and general workflow in AR for sensemaking during a document classification task. Results showed that participants actively used furniture, especially tables and whiteboards, for sensemaking, regardless of the physical environment setting. On the other hand, generous free spaces like empty walls were often used in the *Side-furnished* condition. For the collaboration scenario, participants were more inclined to utilize a furniture-based layout despite their personal preferences. In contrast, participants were keener to try out different placements when working alone, which resulted in more diverse furniture usage and more varied layouts.

Furthermore, we identified layout strategies and approaches used for organizing between and within clusters in AR, and identified distinguishable stages in the workflow that took place during the sensemaking activity, associating with the different placement strategies. Lastly, we recommended design implications regarding AR-enabled offices as well as AR sensemaking and brainstorming applications. With our work, we aim to inform and inspire the design and application of future immersive technology for sensemaking and brainstorming. Ultimately, we hope to enrich the repertoire of placement and layout strategies for general immersive environments and to motivate future research regarding intuitive and collaborative mixed reality systems.

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