Drawing Connections: Designing Situated Links for Immersive Maps

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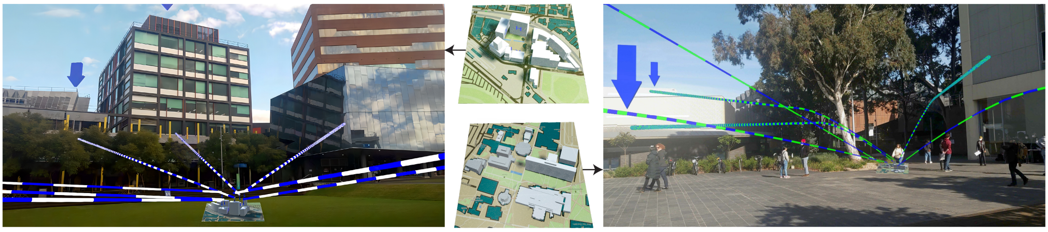

Fig. 1. Situated links to associate miniature buildings on a virtual map with real-world buildings for (left) quite and (right) busy environments. The center images show the 3D virtual maps of the environments. The links in the right image are curved upward to reduce occlusion of passing pedestrians.

We explore the design of situated visual links in outdoor augmented reality (AR) for connecting miniature buildings on a virtual map to their real-world counterparts. We first distill design criteria from prior work, then conduct two user studies to evaluate a set of proposed link designs to better understand users' preferences for different design choices of the links. In two user studies we evaluated, respectively, a set of link geometries in a virtual environment and a refined AR prototype in two different outdoor environments. The studies reveal that links help in identifying buildings in the environments. Participants prefer straight rather than curved links, simple and thin links to avoid information occlusion, and links and maps aligned with their direction of view. We recommend using a consistent color with a strong contrast to the background color for all links in a scene. To improve visibility, the diameter of links should grow with distance to the viewer and optional animated stripes can be placed on links. The findings of this study have the potential to bolster the development of various situated visualization applications, such as those used in urban planning, tourism, smart agriculture, and other fields.

CCS Concepts: • **Human-centered computing → Visualization design and evaluation methods**; *Mixed / augmented reality*.

Additional Key Words and Phrases: Visual links; Augmented reality; Immersive visualization; Situated visualization; Mixed reality.

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1 INTRODUCTION

Maps are a valuable tool for wayfinding, identifying features in the surrounding environment, and gaining an understanding of the layout of the area being explored. However, the abstract features on maps can be difficult to connect with their corresponding real-world features, and people may find it difficult to understand the spatial relationships between a map and its surrounding environment. This can be especially confusing in complex environments such as dense urban area or natural environments with numerous features [24].

Augmented reality (AR) allows us to address these challenges by creating explicit connections between the map and the physical context using visual cues (Figure 1). By linking digital objects to physical objects in the environment, AR can provide a more intuitive and immersive experience that helps people understand the spatial relationships between the map and the environment they are exploring.

To visualize relationships between virtual and physical features, previous work has used visual cues such as virtual arrows [26], 3D tunnels [6], and leader lines [10, 25, 34, 52]. However, these cues are mainly designed for indoor use and are not suitable for outdoor maps. For applications outdoors, some have placed visualizations near their corresponding physical objects to make it easier for users to relate visualizations with real-world objects. For example, virtual labels [25, 41, 62], solar radiation data [4], or historical information [60, 61] have been placed on real-world buildings. However, maps are not always close to the physical objects they represent and the challenge lies in designing visual cues that link objects at a long distances from the map. Such links should be easy to see and follow, minimize occlusion, and also reduce visual distraction.

There is limited knowledge about which visual cues are most effective in identifying features in the environment for outdoor AR maps, and what design factors should be considered. For instance, does the shape of visual cues affect user performance in identifying features in the environment? What is the most suitable color for visual cues to ensure high visibility? Is it preferable for visual cues to follow a curved or straight path to the features in the environment? How does the use of animation affect the user experience in identifying features and connecting virtual objects with real-world referents?

In this paper, we systematically address these questions. We are interested in the design of situated visual links in outdoor AR for connecting features on a virtual map to their real-world counterparts. We specifically focus on linking buildings on maps with real-world buildings, but the findings may have broader implications for other applications such as visualizing semantic connection between real objects. We first explore the design of situated visual links for outdoor AR to connect virtual features with corresponding real-world objects. We consider the limitations of head-mounted AR displays and aim to reduce search efforts when tracking and linking virtual and real-world objects, especially over long distances in outdoor AR applications.

We then conduct an evaluation of different link geometries in a controlled environment using virtual reality (VR). We investigate several criteria for situated visual link geometries. In this study (referred to as “VR user study” in the remainder of this paper), we presented participants with a set of candidate link geometries, connecting buildings on a 3D map to surrounding world-scale buildings. Study results show that situated links helped our participants to identify buildings in the environment with higher accuracy than a map without links. Our participants preferred simple and thin links to avoid information occlusion.

Finally, we perform a qualitative evaluation of situated AR link designs in two different outdoor environments (referred to as "AR user study" in the remainder of this paper). Based on the feedback received from VR study participants, we improved our design for situated links and implemented these for an optical see-through AR display. We conducted a qualitative evaluation outdoors with expert and non-expert participants, who generally provided positive feedback. All participants preferred data presentations to be aligned with their direction of view. Participants again preferred thin links to avoid information occlusion. They preferred straight rather than curved links to reduce head movements, and they commented that moving physical objects did not distract them from the links.

2 BACKGROUND

A common use of visual links in immersive environments is to connect data points in visualizations. For example, ImAxes enables users to manipulate embodied data axes like physical objects and creates sophisticated data visualizations [12]. In ImAxes, links are revealed when one data axis is held in proximity to another. A similar approach was demonstrated by Satriadi et al. [47] by revealing geospatial locations on a globe held adjacent to an abstract chart. Yang et al. [58] and Newbury et al. [38] used visual links to show origin-destination flow data between different regions on maps. They used various visual variables such as height, color, or width of links to encode information. Other examples that use visual links include revealing an association between 2D visualizations in 3D space [11], visualizing the association between data points for in-situ visual analytics in AR [18], and exploring multidimensional datasets by linking 2D scatter plots [30].

Others have used visual links to show relationships between immersive coordinated views. For example, 3D AR links were used to connect data on different large displays and were more easily perceptible than highlighted objects [43]. Similarly, Mahmood et al. [36] used augmented links to connect different data points in multiple coordinated views. Butscher et al. [8] facilitated collaborative multidimensional visualization with linked three-dimensional parallel coordinates. Prouzeau et al. [40] designed visual links between coordinated views in AR and VR that adapt to the perspective of one or more users while minimizing information occlusion and clutter. They proposed real-time, interactive routing of links considering the user's viewpoint, the degree to which links should be kept apart, and the crossing angles of links. A bundling method was applied to reduce information clutter.

Another use of visual links is to connect related objects. Ens et al. [17] presented situated links to visualize real-time data flows between smart objects and help users and authors understand the logical connection between objects. An early work by Rekimoto and Saitoh [44] used visual links to connect projected text and images on digital tables and walls to nearby related devices. Sandor et al. [45] designed augmented links to help users to reconfigure a hybrid user interface. They used visual links to connect real objects or their virtual representations to a controlling device and attached an iconic representation of the current operation to the links. Reality Editor, a screen-based AR system, used visual links to show the relationship between smart objects and help users to program and operate the objects [28].

Links also play a crucial role in graph visualization, where graph edges are displayed as connections between nodes. Previous research has emphasized the importance of edge design in improving the readability of graphs, suggesting that edges should minimize length and crossing angles [29, 56]. While different studies focused on comparing the effect of using AR for graph exploration to a desktop interface [2, 5, 13, 32], Buschel et al., [7, 9] explored using visual variables for edges in node-link diagrams in AR. They evaluated different edge styles by changing color, curvature, geometric primitives, and patterns of links. The result showed that straight edges had the highest performance in comparison to curved and dashed edges, as curved edges were difficult to follow, and dashed edges increased information clutter. Edges with animated segments led to fewer errors.

Visual cues such as highlighting, arrows, and virtual tunnels [3, 6] have also been used as an alternative to visual links to guide users' attention toward a target. A straightforward approach is highlighting the real or virtual objects that are selected by linking and brushing [33, 51]. However, searching large environments for highlighted elements is difficult [1] and it is not easy to keep track of objects over long distances when relying only on highlighting in immersive environments [44]. Arrows and other visual cues are an alternative to guiding user attention toward target objects. This has been used in different AR applications, including pedestrian navigation [20], alerting car drivers of potential dangers [54], guiding tourists' attention to points of interest [48] and assisting mechanics with repair tasks with a combination of text and arrows [27].

Previous studies have established that visual links and cues are an effective means of conveying relationships between objects, either physical or virtual, and can reduce the workload and time involved in search tasks. Previous work used various visual variables to encode information with visual links, including color, height, shape of curve, thickness, or animation. However, the visual links in the aforementioned examples were mainly proposed for indoor environments and not for linking virtual objects with their distant targets at a real-world scale in outdoor AR applications. In such applications, where head-mounted displays are used, several limitations, such as the negative impact of environmental lighting on the legibility of color-encoded information, large workspace environments, occlusion or business of the environment can affect the visual appearance of links. Therefore, this work aims to design visual links for outdoor AR applications to help users identify features in the environment and link them to virtual objects.

3 DEFINING DESIGN CONSIDERATIONS FOR SITUATED LINKS

We aim to provide general guidance on the design of links in the context of situated AR. We design situated links based on the main components for designing situated tools introduced by Marriott et al. [53]. We use situated links to connect miniature buildings on a map with their real-world counterparts. This use case provides the context for creating and evaluating our designs, and we assume it will be relevant in other application scenarios. In this section, we present use case scenarios and propose design criteria for situated links connecting virtual map features with physical referents in outdoor AR visualization. We review visual variables applicable to situated links and demonstrate how they are applied to meet the design criteria.

3.1 Usage Scenarios of Situated Links

The following are three examples of scenarios (Figure 2) where situated links may be helpful.

Tourism: Tom is exploring a city and is situated atop a hill with a panoramic view. He has a map in front of him, but is struggling to locate the landmarks in the surrounding due to the vast number of buildings. He puts on his head-mounted AR display and selects landmarks on the map. Links appear that connect the features on the map with their corresponding real-world locations. With the assistance of situated links, he can easily locate the landmarks (Figure 2, left).

Smart agriculture: Alice is the owner of a large vineyard equipped with sensors that gather real-time data on crop health, growth and humidity. She needs to visit an area where a sensor reported vines with health issues and another area where a humidity sensor reported a critical level. Although she carries a tablet that displays a map of the locations she needs to visit, she knows that it can be difficult to pinpoint exact locations using just a map. Instead, she prefers to use situated links to locate the spots faster and more accurately (Figure 2, center).

In-situ collaboration: Anne is an architect who meets with investors, representatives of the local council and other stakeholders to inspect a site where a building is to be constructed. As they review the plans, Anne points out an issue with the infrastructure and identifies a building that is causing the problem. However, the other participants are having difficulty identifying the building which is partially hidden by other buildings. To make it easier for them, Anne decides to use situated links. She selects the building on the map and a virtual link connects the building on the map to its corresponding real-world structure, thereby enabling the other participants to quickly and easily identify the building in the physical environment (Figure 2, right).

Fig. 2. Example of scenarios where situated links are helpful, (left) tourism, (center) smart agriculture, and (right) in-situ collaboration.

3.2 Design Criteria

We can modify the design of the links to facilitate identifying the relationship between objects. Visual links in AR are rendered on top of the real environment and they can occlude the content in the background or increase information clutter. Previous work in graph visualization suggested short links [56] with minimum information occlusion [40, 50]. Moreover, the visibility of links is affected by the head-mounted display and daylight conditions [31] or a visually cluttered background [50]. Also, we are aiming at outdoor applications, where long links connect virtual objects with the real-world counterparts and these long links should be easy to follow for users. In addition, moving objects such as people or vehicles likely distract users from the virtual links. Therefore, we consider the following criteria for designing situated AR links. However, the criteria are interdependent, and we need to consider the trade-off between them.

- The situated links should aim at **minimum information occlusion** and should not pass through objects to which they are not connected.
- The situated links should aim at **maximum visibility**.
- The situated links should be **easy to follow** along the entire trajectory between the virtual object and the real-world object. Easy to follow means unambiguous, effortless and quick to follow.
- The situated links should **avoid moving objects** in the environment.

3.3 Visual Variables

The visual variables discussed in this section are commonly applied to visual links in previous work [7, 9, 31, 38, 40, 50, 58], however, applying them to optical see-through AR displays requires additional considerations.

Geometry or shape is an important factor in designing links in AR [7]. A good design makes it easier for viewers to follow the link geometry and can reduce information occlusion in the environment [9]. We distinguish two geometry components for a link; one is the path geometry and the other is the link geometry. The path geometry is either straight or curved, while the link geometry is the type of geometric shape that represents the link, e.g., a line, a tube, a string of spheres or other three-dimensional objects, or an arrow with two or three dimensions.

Color is a powerful visual variable to encode different attributes [45]. However, environmental lighting and the colors of the real-world background negatively affect the legibility of color-encoded information and user performance [21, 22, 35]. Color-blending happens because the light emitted from the AR head-mounted display is combined with light of the background [23, 49]. The resulting colors are likely reduced in saturation [37]. One solution to decrease the color-blending effect is modifying the color of the rendered virtual content by color correction. This approach tries to find an alternative color that, when blended with the background color, results in a color that is close to the intended color [14, 49]. Since such a color does not always exist with additive light blending, an alternative approach is to maximize the contrast between digital content and its adjacent region [59]. Color opacity and gradient can also be used to encode attribute values [38, 58]. However, semi-opaque links due to the color-blending issue are difficult to see, and perceiving color gradients along long links may be difficult.

Adjusting the **size (width, thickness)** of links in outdoor AR requires special care. While increasing the thickness of links increases link visibility, it also likely increases information clutter and occlusion. On the other hand, if links are too thin, they are difficult to distinguish and follow in an outdoor environment.

Animation can be used to show the direction of links [7]. Changing animation properties such as speed, velocity, and size of objects travelling along the link path can encode information and potentially also increase visibility.

Another visual variable for links is pattern or texture [19]. However, in AR applications, patterns likely interfere with the background or suffer from low resolution displays [9]. We leave the evaluation of patterns for links to a future study.

3.4 Adapting Visual Variables for Situated Links

In this section, we explain how we apply the visual variables of Section 3.3 to situated links to meet the design criteria of Section 3.2 and discuss the design choices we made for the user studies described in Sections 4 and 5.

Geometry of the link: The type of geometric shapes likely affect the amount of information occlusion, the visibility of the links and how easy they are to follow. By combining shape and animation variables, we designed different static and animated link geometries. We began our design process for the links with a simple design and progressively increased the complexity to evaluate the links at different levels of complexity.

- *Static 2D lines*: two-dimensional lines extend from the building on the map and terminate at the corresponding building in the physical environment. (Figure 3, a). We opted to use a static 2D line because it is a simple and commonly used method for connecting objects in VR and AR studies [18, 30, 40, 43]
- *Static 3D tubes*: three-dimensional tubes beginning at the building on the map and extending to the corresponding building in the physical environment (Figure 3, b). Similar to 2D line, the 3D tube is also a straightforward method that has been used in previous studies [17, 38, 58]
- *Animated 3D particles*: a string of three-dimensional spheres that move toward the target with velocity increasing with distance (Figure 3, c). We opted to use particles because they offer a range of parameters, including color, opacity, density, size, shape, and velocity, which we can use to encode information at a later stage.
- *Animated moving bird*: a string of animated birds flying toward the target; the speed of birds increase with distance (Figure 3, d). We selected moving birds to see whether animation affects user preference. Additionally, flying birds are familiar to all participants, which is not necessarily the case with other animated objects.

We also designed hybrid links as a combination of three-dimensional tubes and particles (Figure 3, e).

Furthermore, we added a three-dimensional pulsating arrow (Figure 3, f) to all link geometries that slightly moves up and down and points at the location of the target with the intent of helping viewers to find the target more quickly [26].

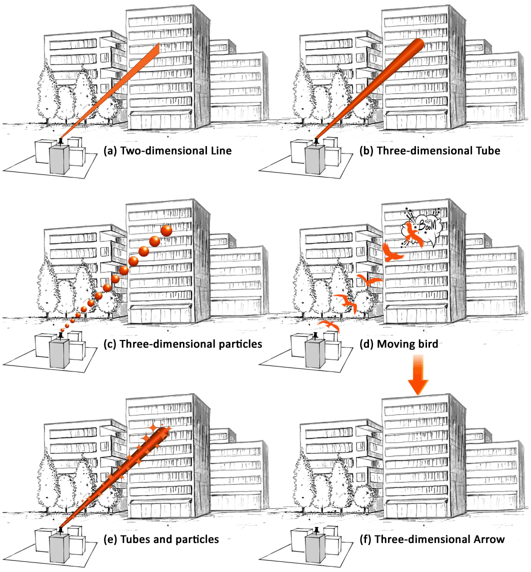

Fig. 3. (a – e) Five geometries designed for situated links between virtual miniatures and real-world buildings. (f) A three-dimensional arrow as an additional cue to indicate links.

We initially also designed linking geometries that were as large as the real-world targets: a three-dimensional tunnel, similar to an omnidirectional attention funnel [6] (Figure 4, left), a triangular two-dimensional surface (Figure 4, center), and a moving three-dimensional mesh model of the building which moved toward the real-world target while its size increased (Figure 4, right). However, because these geometries obstruct substantial parts of the environment, they conflict with the minimum information occlusion criterion. Thus, we chose not to include these designs in the study and do not consider them in the remainder of the paper.

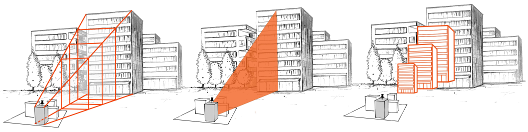

Fig. 4. Link geometries with the size of real-world targets: 3D tunnel (left), 2D surface (center), and moving mesh (right).

Geometry of the path: With the goal to make the links unambiguous, effortless and quick to follow, we adjust the path geometry. The path of linear links (as in Figure 3, a – e) can be straight or curved based on the visibility of the real-world target buildings. Real-world buildings have different levels of occlusion; they are visible, partially occluded, or occluded (Figure 5, left). For buildings with at least one visible façade, a straight path geometry toward the building is used (Figure 5, left, building B). If the building is partially occluded by other objects such as trees, the link is bent to move above the occluding objects (Figure 5, left, building A). For occluded and partially occluded buildings, if possible, links curve right or left to avoid occluding objects. Curving links left or right also avoids the normally bright sky (which has a detrimental effect on visibility due to color-blending) and reduces vertical head movement (Figure 5, left, building D), for fully occluded buildings where the links cannot curve right or left, they curve above the occluding object (Figure 5, left, building C).

The link path starts at the center of a building on the map and ends at the center of the physical building or the center of the visible part of the building because this is the simplest strategy for distinguishing the target building from neighboring ones. For quadratic Bézier curves in our user study, we position control points manually based on the level of occlusion of physical buildings. However, future systems should extract the level of occlusion of buildings in the environment with image analysis to automatically adjust the link path to the users' perspective. Also, moving objects in outdoor environments may intersect with links and distract users from following virtual links. If users find the moving object distracting, they can bend link paths above moving objects in busy environments. To bend the links upward, we use Bézier curves and set a control point at a distance of one meter from the start (Figure 5, right). To find the optimum height, we later ask participants to set the height of the link in an AR user study.

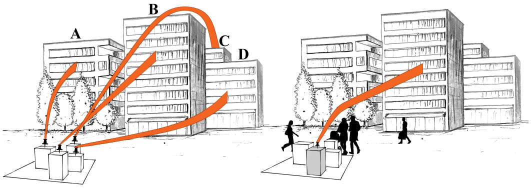

Fig. 5. Curved path geometry for occluded targets. Left: a visible building (B), a fully occluded building (C), and partially occluded buildings (A and D) from the user's perspective. Right: Upward bending to avoid moving physical objects.

Color: A careful choice of color and opacity increases the visibility of links. To mitigate the detrimental effect of color-blending, we improved color contrast [59] by adjusting the color of links to the real-world background in different daylight conditions. To achieve this, we first captured a photo with the RGB camera built into the head-mounted display. Then, we considered a neighboring buffer around the link and calculated the average color of the pixels in the buffer. We found the color with the highest contrast from a predefined color pallet and assigned it to the link. Assigning colors to links based on the background led to links with different colors. To increase visibility under outdoor lighting, links were rendered with full opacity, but they may still appear transparent due to color-blending.

Size: For all link geometries, links are small (thin) at the start and large (thick) at the end to increase their visibility at a distance. We set the thickness of links based on empirical tests in different daylight and weather conditions considering the trade-off between the visibility of links and information clutter. We settled on linearly varying the thickness of links with their length. Also, the size of other shapes, such as particles and bird geometries expand with distance to increase visibility. We set 0.1 m as the start size and 1 m as the end size of the links. We later ask participants to change the size values and provide feedback in an AR user study.

Table 1. Overview of The Tasks for the VR user study

Task	Visualization	Data collected	Length (min)	Task
T1	Map	Quantitative	20	Identify the building that is highlighted in the environment, on the map (Figure 6, top left)
T2	Abstract shapes	Quantitative	10	Identify the building in the environment that is connected to the abstract shape on a virtual table (Figure 6, top right)
T3	Map	Quantitative	20	Locate (estimate direction and distance) a hidden building in the environment by following a link (Figure 6, bottom left)
T4	Map	Qualitative	20	Explore and comment on varying numbers of links and varying link geometries (Figure 6, bottom left)

4 A USER STUDY TO EVALUATE LINK GEOMETRIES

We conducted a within-subject user study in VR to assess how fast and accurate various link geometries are for identifying buildings. We compared the link geometries introduced in Section 3 including 2D line, 3D tube, particles, moving bird and tube particles. We did not include the 3D arrow in the VR user study because it was not considered as a separate link geometry and it was combined with the other link geometry in the AR user study design.

We chose to run our initial user study in VR instead of AR for several practical reasons [15, 16, 42]: 1) VR allowed us to create a fictitious environment, which prevented the participants' knowledge of a real environment from influencing the study results. 2) It provided us with greater control over the study conditions, for instance over the number of buildings and over the different levels of occlusion within the environment. 3) Using AR in a real environment would introduce additional confounding factors, particularly moving objects and varying light and weather conditions, which would result in color-blending issues.

Based on the results of this VR user study, we then designed an outdoor AR user study (discussed in Section 5) to test other parameters that are affected by environmental conditions such as color (depending on daylight conditions and background color) or geometry of paths (depending on moving objects).

4.1 Description of Tasks

We designed three tasks (**T1**, **T2**, **T3**) to determine the link geometries that assist participants in identifying buildings more efficiently and rapidly and one task (**T4**) to collect qualitative feedback on using multiple links simultaneously. Figure 6 illustrates the scenes and link geometries designed for the four tasks in VR and Table 1 shows an overview of the tasks. The maps were positioned at 0.5 meter distance from the participants. Participants could rotate about their vertical axis to follow the links, but they were not allowed to walk during the VR user study.

In the first task **T1**, one building was highlighted in the environment (the red building in Figure 6, top-left), and the participants were asked to find the corresponding building on the map. We used buildings that were visible from the participant's viewpoint for this task. When they selected a building on the map, a link appeared between the selected building on the map and the corresponding building in the environment. By following the link, they could recognize if the correct building was selected. If they selected a wrong building, they could continue selecting buildings till finding the highlighted building. To evaluate the utility of links, we also included a condition without links where participants had to rely on their map reading skills to identify the buildings.

The purpose of second task **T2** was to assess if the links correctly lead the participants to the corresponding building in the environment. In this task, participants were asked to find the relationship between abstract geometric shapes and buildings with labels in the environment. We replaced the map with randomly arranged abstract shapes including cubes, spheres, diamonds, 3D stars, and 3D octagons to prevent the participants from using their map-reading skills to identify buildings. They were asked to select an abstract shape to activate the link between the shape and the building and find the label on the building to which the link was connected. With randomly arranged abstract shapes, participants could not guess the approximate direction of the buildings in the environment and the links were the only cue for identifying the buildings. We omitted the no–link condition from this task, since it cannot be completed with only abstract shapes.

The purpose of task **T3** was to check if the links are useful in identifying occluded buildings. A building that was not visible from the participants' viewpoint was highlighted on the map. When participants selected the highlighted building on the map, a link appeared that connected the building on the map with the hidden building in the environment. Then they were asked to estimate the direction and distance to the hidden building using the link. In this task, we included the condition without links.

For **T4** we were interested in qualitative responses on the usage of multiple links. We asked participants to use multiple links simultaneously to connect buildings on the map with buildings in the environment. We recorded participant feedback on scenes with fewer than five, ten and more than 20 simultaneous links. We do not report performance metrics for **T4**.

4.2 Measures

We evaluate the following metrics through qualitative and quantitative assessment:

Time: For **T1**, **T2** and **T3** we collected task response times. For **T1**, we measured the time from the moment participants found the highlighted building in the environment and confirmed it by selecting a button, until they selected the "Next" button to move to the next building. For **T2** and **T3**, we started recording the time from the moment participants selected the abstract shape or highlighted a building on the map until they selected the "Next" button to move to the next building.

Accuracy: For **T1**, **T2** and **T3** we collected the selected building. To calculate accuracy, we divided the number of correctly selected buildings by the total number of buildings in each task.

Distance to hidden buildings: For **T3**, participants were required to use links to locate hidden buildings that were not visible to them. To accomplish this, we asked participants to estimate the distance and direction to the hidden building. We categorized the distance into five groups (0–100, 100–200, 200–300, 300–400, and more than 400 meters), and participants were asked to choose the group that they estimate the building fell into.

Preference ranking: We collected participant responses on preferred ranking of the different link geometries at the end of each task.

4.3 Apparatus

We created a VR application with the Unity 2019.4.2 game engine and the Mapbox SDK for Unity (Figure 6) running on a PC system with a GTX 1080 GPU, a Core i7 processor, and 16 GB of RAM. We used a Samsung Odyssey mixed reality headset with a field of view of 110°. We used data from OpenStreetMap.org to create a 3D model of a city in Unity. We textured the buildings and simulated structures ranging from 1 to 30 storeys high. An average of 72 buildings were included in the 3D environments, some visible while others remained hidden from participants' view. Participants

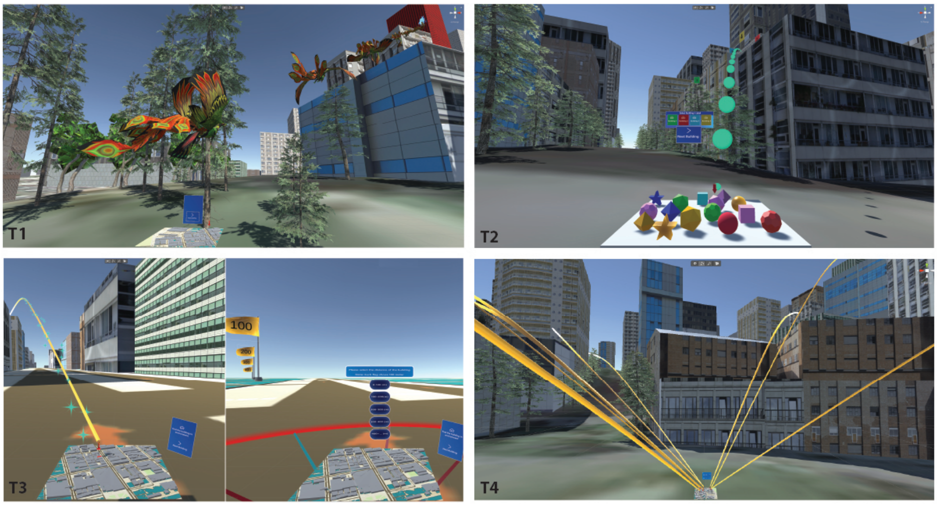

Fig. 6. Study tasks asked participants to (**T1**) find the corresponding virtual building on the map (example of moving bird), (**T2**) find the relationship between abstract shapes and surrounding buildings (example of particles), (**T3**) find the direction and distance of hidden buildings (example of tube particles), initial view of link to hidden building (left) and distance estimation phase (right), and (**T4**) use multiple links (example of 3D tube).

were positioned close to the center of the 3D environments. We also included roads, intersections and trees to enhance the realism of the environments. For tasks **T1**, **T3**, and **T4**, we utilized the same 3D model to create a map (0.5×0.5 m) with a uniform color and height for all buildings. This was done to prevent participants from using the texture and height of miniature buildings on the map to identify their physical counterparts. In task **T2**, we substituted the buildings with 15 randomly arranged abstract shapes to minimize the impact of participants' map-reading skills. The VR user study was conducted in a lab, in an area measuring 4×3 m in size, with the experimenter standing at the center of the study area.

4.4 Participants

We recruited 24 participants (12 females, 12 males, aged between 20 and 40 years) via email invitations. All participants were university students or academic staff and had normal vision with no color vision deficiency. Seven participants self-declared as experts in VR and AR, 11 were familiar with VR and AR and six had no experience in VR and AR. Nineteen participants used maps often or very often. The VR user study was approved by the local ethics committee, and participants received a $20 gift card for their time.

4.5 VR User Study Procedure

We used a Latin square design to balance the order of the visual link geometries, that was five different geometries plus one condition with no–link. We counter-balanced the first three tasks (T1, T2, and T3). T4 was the last task in all experiments. Therefore, the sample size should be a multiple of six (link geometries) and three (tasks). A group of 24 participants satisfies this condition. All participants worked with four different scenes (a different scene for each task) and all link geometries within each scene but in counterbalanced order based on the Latin square design.

We first introduced participants to the project and asked them to consent to participate in the VR user study by signing a form. Participants were able to stop at any time if they felt uncomfortable in the VR environment. An initial training step for each task helped them to become familiar with the task. During the training phase, we used a simple scene that was distinct from the environments used for the main tasks. Participants were presented with a simplified version of the main task involving fewer buildings, allowing them to become familiar with various link geometries and the process for completing the main task. After the training, we asked participants to start the main VR user study.

During the main VR study, the experimenter did not interact with the participants. After completing the task, participants were asked to take off the headset and fill out a questionnaire to record preference rankings of the link geometries for ease of use and effectiveness in identifying the buildings in the environment. The next task was then introduced to the participants, and they followed the same procedure. Each task was repeated for 18 buildings. After completing four tasks, a post-hoc questionnaire recorded feedback on (1) background information about the participant and (2) perceived advantages and disadvantages of each link geometry. On average, participants took one hour to complete the VR user study; 20 minutes for T1, 10 minutes for T2, 20 minutes for T3 and 10 minutes for T4.

4.6 Results

We collected a total of 1,224 responses for time and accuracy measures (T1, T3: 6 link geometries × 3 buildings × 24 participants, T2: 5 link geometries × 3 buildings × 24 participants), 96 geometry ranking (4 tasks × 24 participants), along with 24 forms for qualitative feedback (24 participants). Shapiro-Wilk tests showed that the data was not normally distributed. Therefore, we used an Aligned Ranked Transform (ART) [57] with one-way ANOVA for accuracy and time. To analyze ranking data, we employed Friedman tests and conducted post-hoc tests using the Wilcoxon signed-rank test with Bonferroni-Holm corrections. Our analysis had a confidence level of $\alpha < 0.05$. We used SPSS to do the analysis. Supplementary material A includes the output of the analysis result. The remaining part of this section provides a detailed analysis of preference ranking, time, accuracy and qualitative feedback.

Preference ranking of link geometries: Figure 7 shows the participants' ranking for the geometries of the links. The preference ranking of the link geometries was collected after each task. Overall, all participants strongly agreed that links helped them to identify buildings in the environment. The Friedman test on link geometries showed significant differences in preference ranking for **T1** χ^2 (5, 24) = 59.8, p < .001, **T3** χ^2 (5, 24) = 73.8, p < .001, and **T4** χ^2 (5, 24) = 64.6, p < .001.

Table 2 in appendix A displays the p-values obtained from the Wilcoxon signed-rank test with Bonferroni-Holm correction for α values for all pair-wise comparisons. The post-hoc analysis revealed a notable difference between cases without links (no–link) ($\overline{X}$ 6, SD 0) and other link geometries in **T1**, and between no–link ($\overline{X}$ 5.9, SD 0.3) and and other link geometries, and moving bird ($\overline{X}$ 4.6, SD 1.2) and other link geometries in **T3**. In the case of **T4**, no significant difference found between 2D line ($\overline{X}$ 2, SD 1.3) and 3D tube ($\overline{X}$ 2.2, SD 1.1), 2D line and particles ($\overline{X}$ 2.9, SD 0.9), 3D tube and particles, and no–link ($\overline{X}$ 5.3, SD 1.4) and tube particles ($\overline{X}$ 4.8, SD 1.1), however, there was a significant difference observed in preference ranking for other link geometries.

Response time: Figure 8 shows the average values for the response time for the different link geometries for the first three tasks (**T1**, **T2**, **T3**) in seconds.

The ART ANOVA test revealed significant differences in the time participants spent identifying buildings using different link geometries for **T1** (F(5)=6.9, p<.001), **T2** (F(4)=24.2, p<.001), and **T3** (F(5)=3.7, p=.003).

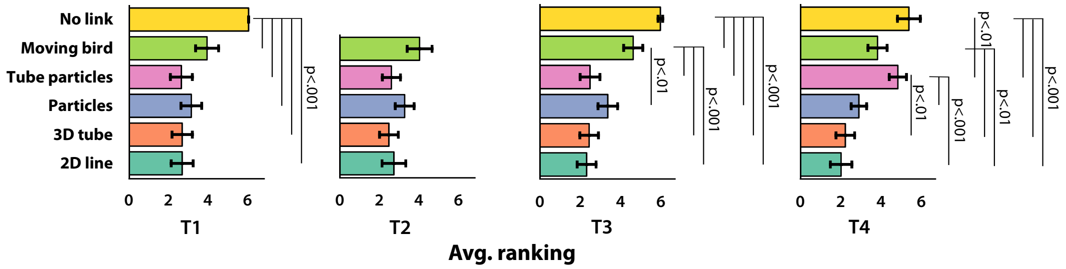

Fig. 7. Preference ranking of link geometries for tasks T1 to T4. Lower values indicate higher preference. Whiskers show 95% CI.

In **T1**, the post-hoc analysis showed a significant difference between moving birds ($\overline{X}$ 29.3, SD 21.6) and 2D line ($\overline{X}$ 17.3, SD 14.7), 3D tube ($\overline{X}$ 21.8, SD 24.8), and no−link ($\overline{X}$ 15.4, SD 15.6), while no significant difference was found between moving bird and particles ($\overline{X}$ 25, SD 21.2), and tube particles ($\overline{X}$ 21.4, SD 19.5). There was also a significant difference between no−link and particles (p<.01).

For **T2**, a significant difference was found between moving bird ($\overline{X}$ 10.1, SD 4.6) and other link geometries including 2D line ($\overline{X}$ 6.3, SD 4.2), 3D tube ($\overline{X}$ 6.3, SD 4), and tube particles ($\overline{X}$ 7.2 SD 3.7), except particles ($\overline{X}$ 8.6, SD 3.6). Additionally, a significant difference observed between tube particles and particles, as well as between particles and 2D line, and particles and 3D tube.

For **T3**, a significant difference was found between moving bird ($\overline{X}$ 22.5, SD 8.2) and 2D line ($\overline{X}$ 18.5, SD 7.7), 3D tube ($\overline{X}$ 18.9, SD 8), tube particles ($\overline{X}$ 18.6, SD 6.8), and no−link ($\overline{X}$ 18.6, SD 7.7), while no significant difference found between moving bird and particles ($\overline{X}$ 19.1, SD 6.1). There were no significant differences found between the other link geometries regarding the time participants spent finding the hidden building.

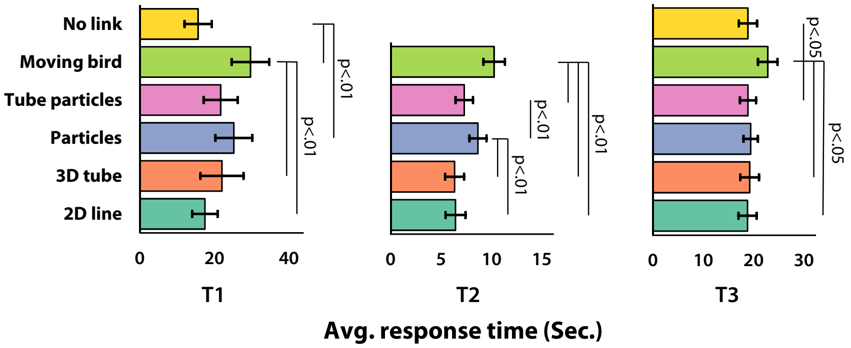

Fig. 8. Average response time in seconds for link geometries for T1, T2, and T3. Whiskers show 95% CI.

Accuracy: Figure 9 shows the average accuracy for different link geometries.

The ART ANOVA test revealed significant differences in accuracy for identifying buildings in the environment for **T1** (F(5)=9.1, p<.001) and **T3** (F(5)=6.5, p<.001) when comparing link geometries, while no significant differences were found between link geometries for **T2** (F(4)=2.2, p=.07).

For **T1**, according to the post-hoc analysis, participants were less accurate when there was no−link ($\overline{X}$ .4, SD .5) comparing to other link geometries including 2D line ($\overline{X}$ .8, SD .4), 3D tube ($\overline{X}$

.8, SD .4), particles ($\overline{X}$ .7, SD .4), tube particles ($\overline{X}$ .8, .4), and moving birds ($\overline{X}$ .7, SD .5), while no significant differences were found between link geometries. Similar to **T1**, in **T3**, participants were less accurate in the absence of links ($\overline{X}$ .6, SD .5) compared to other link geometries including 2D line ($\overline{X}$ .8, SD .4), 3D tube ($\overline{X}$ .9, SD .3), particles ($\overline{X}$ .9, SD .3), and tube particles ($\overline{X}$ .9, .3), while no significant difference was found between no–link and moving bird ($\overline{X}$ .8, SD .4).

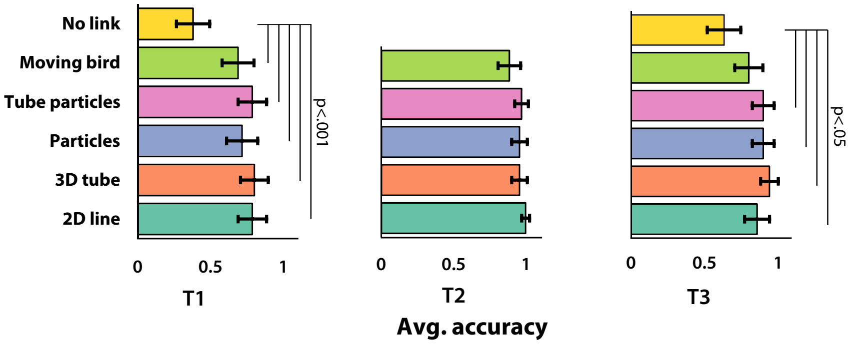

Fig. 9. Average accuracy for link geometries for T1, T2, and T3. Whiskers show 95% CI.

For **T3**, participants chose from five groups (0–100, 100–200, 200–300, 300–400, and more than 400 meters) to indicate the estimated distance to hidden buildings. Figure 10 shows underestimation and overestimation of distance based on the overall accuracy. In Figure 10, zero indicates that participants selected the correct distance group, positive values show overestimation and negative values show underestimation of distance. In this figure, for instance, if the correct estimation group is 200-300, but a participant selects 300-400, they overestimated the distance by +1 group. In general, participants had 34 underestimations (8%), 133 correct estimations (31%) and 265 overestimations (61%) of the distance (out of 432 responses). The distance estimations for each link geometry are displayed in Figure 12, appendix A.

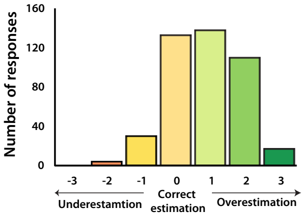

Fig. 10. Underestimation (negative values) and overestimation (positive values) of distance to hidden buildings based on overall accuracy.

4.7 Participants' Feedback

At the end of each task, we asked participants to rank the link geometries and explain the reason for ranking in an open-ended question. Also, at the end of the VR use study, we asked participants to explain the pros and cons of each link geometry. Participants' feedback revealed the following.

Several limitations of the moving bird and particles were discussed by participants. Twelve of the 24 participants did not like the delay caused by the time required to wait for bird and particles to traverse the entire distance of the link. Thirteen participants mentioned that the moving bird is “large”, “distracting”, and “difficult to follow”, especially for hidden buildings. Seven participants found the animation of particles distracting.

Thirteen participants commented positively about 2D lines for their “simplicity” and that they are “clear”, “easy to follow” and “not distracting”. Ten participants also had similar comments on the 3D tube, however, six participants criticized the 3D tube for its thickness and information occlusion. Seven participants mentioned that 2D lines and 3D tubes were similar.

Seven participants found the tube particles “astonishing”, “easy to follow” and “helpful in estimating the distance” because of animated particles. However, seven participants commented that the animation in tube particles was “slow”, “distracting”, and increased information clutter.

For multiple links (**T4**), 11 participants commented that animated links including moving bird, particles, and tube particles were “overwhelming” and “distracting” and “crowded” the environment. They all preferred to use a single or just a few links as they found it “confusing” to use many links simultaneously.

4.8 Discussion

In the VR user study, the purpose of the tasks was to find the link geometry that enables participants to identify buildings more quickly and easily through abstract tasks in a controlled setting before evaluating the findings in a more realistic setting in AR. The main finding of the VR user study was that all participants preferred using links rather than using the map to identify buildings in the environment. All commented that finding buildings was easier with links than without links. The preference rankings in **T1**, **T3**, and **T4** confirmed this, as participants consistently ranked the no–link option as the least preferred.

This comment that finding buildings was easier with links than without was also supported by the accuracy evaluation (Figure 9, **T1** and **T3**) that provides good evidence that using link geometries outperformed the no–link condition. Also, the purpose of **T2** was to evaluate if the links correctly lead the participants to the corresponding building in the environment. The high average accuracy for this task shows that link geometries could mostly lead the participants to the correct physical referent. A comparison of the average accuracy of **T2** and **T3** shows that the link geometries were less efficient for identifying hidden buildings compared to visible ones. This leads us to improving the link geometries for the AR user study to help participants to identify hidden buildings more accurately.

Regarding the participants’ preference, there was no significant difference between the rankings of link geometries in **T1** and **T2**. In **T3**, participants ranked moving birds as the second least preferred geometry. However, when using multiple links the preference ranking was different, and moving birds and tube particles ranked mostly fourth and fifth in **T4**. According to the participants comments, animated links increased information clutter and distracted them from the targets when using multiple links. This is likely the reason for the variance in preference ranking while using multiple links.

Furthermore, all participants preferred not to use more than ten links at the same time. Half of the participants preferred to use single links as they found it confusing to use multiple links simultaneously.

Almost half of participants preferred simple and thin links to avoid occlusion of information in the background. They also mentioned that large and animated links distracted them from the targets in the environment [9]. Participants commented that animated links worked well for close objects, but they found them slow for distant objects. The quantitative results confirm that moving bird had longer average response time (Figure 8) in comparison with 2D line and 3D tube.

Overall, based on the feedback from participants' and the quantitative results, there were no significant differences between 2D lines, 3D tubes, particles, and tube particles in terms of preference ranking and accuracy in **T1**, **T2**, and **T3**. However, for multiple links, participants preferred 2D lines, 3D tubes, and particles because they were simple and did not add to information clutter. Therefore, in designing links for AR applications, we should consider the positive features of each link geometry that participants appreciated, such as the simplicity of 2D lines and 3D tubes, and the animation of particles and tube particles that aided in distance estimation. However, it is crucial to avoid elements that participants find displeasing, such as introducing unnecessary information clutter and distraction.

5 DESIGN IMPLICATIONS FOR SITUATED LINKS IN AR

We used the results of the VR user study to build an AR application that links buildings on a virtual map with real-world buildings, and we used this application for a follow-up AR user study in an outdoor environment. In this study, we mainly focused on how the geometry of paths, color and size affect the efficiency of links in an outdoor environment. To create an optimal design for AR links, we incorporated the simplicity of 2D lines and 3D tubes, and the animation of particles and tube particles.

We designed the tubes to have a cone-like geometry, with a small diameter (0.1 m) at the near end and larger diameter (1 m) at the far end to compensate for the visual reduction of the size of the link due to the perspective foreshortening. Although increasing the thickness of the tube is the opposite of normal depth perception where distant objects are smaller than close ones, we chose the cone-like geometry for practical reasons: First, a large diameter at the start of the tube would occlude the small buildings on the virtual map. Second, a constant small diameter for the whole tube would make it invisible at a distance. Alternative techniques, including salient color or adding halos, did not work properly due to color-blending issues on bright days. Since participants in the VR user study preferred thin links to avoid occlusion of information in the background, we set the end thickness of the tube to be as thin as possible but still clearly visible. We chose to vary the diameter between 0.1 m and 1 m after testing in different weather conditions and at different times of the day. Participants in the AR user study were later asked to change the end diameter and provide feedback about the thickness of 3D tubes. We kept the start diameter constant, because changing it would have occluded other buildings on the map.

In the VR user study, animated links (moving bird, particles and tube particles) were overall less preferred link geometries, however, some participants found the animation helpful when using a single link. Based on feedback received in the VR study, we replaced the particles with stripes around the link tubes. The stripes moved towards the real-world buildings. We observed that compared to particles, the stripes reduce visual clutter. The stripes were optional; participants in the AR user study could enable or disable them. We used the speed of animation to encode the distance to buildings. We did this because in the VR user study, participants tended to overestimate the distance to hidden buildings (T3). Hence in the AR application, faster moving stripes indicate to users that the target building is further away.

We also added a pulsating arrow pointing at the target building (Figure 3, f) to make it easier for participants to find the building. The shape of the link differentiates between visible and hidden buildings, with straight links for visible buildings and curves for hidden buildings. For busy environments, participants could curve the links upwards to avoid moving objects and set the height of links. Figure 11 displays the panel that participants used to modify the parameters of the links.

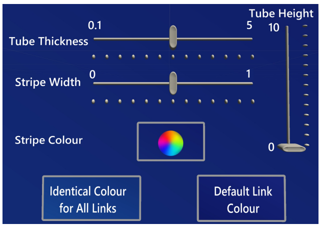

Fig. 11. The AR panel allowed participants to adjust the parameters of the links.

5.1 Apparatus

We implemented situated links for outdoor AR with the Unity 2019.4.2 game engine for a Microsoft HoloLens 2 headset with a field of view of 54° diagonally. The display brightness of the HoloLens was at the maximum level to increase the visibility of virtual objects in outdoor lighting conditions. We covered the HoloLens face shield with a window tint film to improve the visibility of links on bright days. The film can be removed without damaging the visor and leaves no residue.

We used the 3D model of two university campuses. The 3D models were geolocated with Vuforia markers. We also used the 3D models to create virtual 3D maps (0.5×0.5 m). Participants could walk in the environment, move and rotate the virtual 3D map, such that they could always place the map between themselves and the target.

5.2 Participants

We conducted an AR user study with 12 participants (five experts in AR and VR, three experts in VR, and four users with no expertise in AR and VR) to obtain qualitative feedback about the situated links and to better understand users' preferences for different design factors in an outdoor environment. All participants had normal vision with no color vision deficiency. The AR user study was approved by the local ethics committee. The participants were recruited from university students and staff via invitation email. They did not receive any compensation. Three participants already participated in the VR study. Participants ran the evaluation at different times throughout the day so we could test the application with different weather and lighting conditions (sunny and bright, semi-cloudy and cloudy) and varying numbers of pedestrians moving in the environment. Table 3 in Appendix A shows an overview of the study participants, weather conditions and average number of pedestrians during the AR user study.

5.3 AR User Study Procedure

We first introduced participants to the project. An initial training session helped them to become familiar with the task. For participants with no experience in AR, we had a training step in the office to familiarize them with HoloLens interactions. Each participant tested the AR application for 30 to 40 minutes on average. During the studies, the experimenter asked the participants to test different elements in the application and give feedback.

The application allowed participants to switch between different design options including changing the end diameter of the tube, switching between curved and straight links to avoid potentially distracting moving objects, changing the stripe color and activating or deactivating stripes (Figure 11). We first asked participants to select buildings on the virtual map to create links to buildings in the physical world. They could use a pinch gesture to select or deselect a building. We then asked them to change the end diameter of the tube between 0.1 and 5 meters with a slider.

They were also asked to switch between an identical color for all links and the color determined from the background using the color contrast method (Section 3). We asked them to turn the stripes on and off to evaluate the effect on the visibility of the links and distance estimation. They were exploring straight and curved links by changing the height of the link to avoid moving objects. After each step, they were asked to provide feedback and their preferred option.

5.4 Participants' Feedback

We had a semi-structured interview with the participants during the AR user study. We used open coding for qualitative analysis to categorize and label participants' feedback [39, 55] using Delve qualitative coding software. All participants were asked the same questions. The open coding started with a set of initial codes derived from the questions, including "Color", "Stripes", "Path geometry", "Moving objects and trees", and "Thickness". We went through the feedback sentence by sentence and assigned a code to each sentence based on its content. Then, we continually refined and revised the codes until we reached a point of saturation, where no new codes emerged from the data. We identified 16 codes, including "Moving people", "Trees", "Static features", "Thickness", "Link height", "Visibility", "Stripe speed", "Stripe color", "Animation", "Link color", "Arrow", "Usefulness", "Curved link" "Straight link", "Comparing with VR user study", and "Other feedback". The codes were then categorized into six groups based on their similarity, including "Usefulness", "Visibility", "Path geometry of links", "Thickness of links", "Feature in the environment", and "Other feedback". During our data analysis, we noticed that some codes, including "Thickness of links" and "Visibility", were interrelated and could be grouped together. However, we segregated them into distinct groups as they held individual significance for our AR study. The qualitative analysis revealed the following for the six categories.

Usefulness: Overall, all participants provided positive feedback about situated links, e.g., P9 “this is very astonishing”, P12 “it helps me to find the buildings in the physical world”, or P1 “the links are complementary to my navigation map”. All participants found it easy to associate virtual buildings on the map with corresponding real-world buildings.

Visibility: This category includes feedback about the link color, animated stripes, stripe speed, stripe color, and arrows. We asked participants to comment on the "link color". Under all tested daylight conditions, they agreed that the links were clearly visible. Ten out of twelve participants (all participants except P2 and P3) found it confusing that links had different colors (e.g., P1 “different colors mean there might be different buildings” and P5 “at the beginning I thought that different colours mean different groups of builidings”). Two participants (P6 and P10) mentioned they “guessed different colors had a meaning but could not recognize the reason.” Ten participants preferred a consistent color for all links and two participants P7 and P12 suggested using an alternative color for activated links. P1 suggested “using a continuous color scale to encode height of the buildings.”

Using "animation" was found to be helpful to increase the visibility of links. Eleven participants preferred links with stripes to links without stripes, (e.g., P2 “the animation and moving stripes are really helpful in the visibility of the links”). Two participants (P8 and P9) mentioned stripes helped with distinguishing links, especially if the links were crossing or close to each other. However, P6 found the animated stripes distracting. Four participants (P2, P3, P6, and P8) commented that encoding distance with the speed of the animated stripes was not informative, because they found it difficult to compare animation speed of links with different orientations. However, eight participants found the speed of stripes helpful to compare the distance to buildings. Regarding the color of stripes, six participants (P1, P6, P7, P9, P10, and P11) suggested using bright colors and six participants suggested using complementary colors to the link colors to increase visibility.

Regarding the pulsating "arrow", P2 commented that the pulsating arrow provides a sense of depth and helps to differentiate between the distances to the buildings. Meanwhile, P3 and P12 observed that the arrow's direction aids in identifying which building is visible and which one is occluded.

Path geometry of links: This category includes feedback about link height, curved link, and straight link. Considering the path geometry (curved or straight tube), nine participants preferred straight links. They found it difficult to follow curved links because they had to move their head due to the small field of view of the HoloLens, which they found to be "fatiguing when I have to look up and down to follow the curved tube". P6 and P7, however, suggested having a small curvature because it helped them to identify links and perceive depth, but they did not want links to curve out of the field of view. P8 had no preference for a curved or straight link. Also, all participants preferred the links to be aligned with their direction of view. They suggested keeping the height of links in their eye line to reduce mental and physical effort.

Thickness of links: Regarding the thickness of tubes, nine participants preferred thin links because they were visible and did not occlude other information. They preferred 0.5 to 1.5 m for the end diameter. Three participants (P2, P10, and P12) preferred thick tubes (3 to 4 m for end diameter) because they could easily identify the links. They mentioned that targets are large buildings in the physical world and even thick links could not occlude them.

Features in the environment: This category includes feedback about moving people, trees, and static features. All participants mentioned that moving objects did not distract them from the links, e.g., P9 "I have not noticed people moving around," and P1 "when I see the tube, I only concentrate on the tube and ignore the physical world because these are two different presentations," or P3 and P11 "I always see the line because in HoloLens the links are overlaid on the real-world objects." Also, ten participants commented that trees did not block their view and they could follow the link even through trees, e.g., P7 "I only pay attention to the start and endpoint of a link and it doesn't matter if it goes through trees" or P8 "as long as the color of the link has a high contrast with trees in the background, I can follow the link." P6 and P10 commented that trees only matter when they look like a solid object due to the leaf density.

Other feedback: Following the completion of AR user study, we asked participants to provide us with feedback for potential improvements. Some of the suggestions received include: P1, P4, and P9 recommended adding the name of the building to the map. P2, P3, and P5 suggested incorporating a vanishing point at the end of the link, such as a circle or spider net on the building, P4 proposed including a button to switch between curvature for crowded and not crowded environments, P6 suggested using a dashed pattern for the occluded portion of the link and a solid pattern for the visible part, and P9 suggested connecting the application to a mobile phone for interaction purposes instead of relying on mid-air gestures.

Three participants (P1, P2, and P12) took part in both VR and AR user studies. This is the feedback they provided about the comparison of situated links in the two studies. All of them expressed a preference for moving stripes over particles, citing that the stripes are "less distracting" (P1), "improve visibility" (P2) and do "not add to information clutter" (P12). P2 and P12 also compared the effectiveness of a pulsating arrow placed above a building in AR with that of an explosion in VR. They commented that the pulsating arrow was more helpful because it helped them to "perceive depth", "know the direction to occluded buildings", and "distinguish between occluded and visible buildings".

5.5 Discussion

We received positive feedback from the participants about the idea of connecting buildings on a virtual map with their physical referent using situated links, and the situated links were found to be useful for identifying buildings in the surrounding environment. We present the key findings of the AR user study below.

A consistent color hue for all links avoids confusion. Adapting color to the background resulted in links with different color hues, however, most participants preferred a consistent color for all links. The method for adjusting color described in Section 3.4, can still be used, but we recommend using the two most common colors for links (the most common color) and stripes (the second most common color).

Animated stripes improve the visibility of links. During the VR user study, participants reported that the animated particles in tube particle geometry led to visual clutter and distractions when using multiple links. However, in the AR user study, participants preferred animated stripes, which they found to improve the link visibility, particularly when multiple links were visible. This aligns with a previous study [9], which found that incorporating animated links in node-edge visualization using AR reduced errors.

Growing the diameter of links with distance improves visibility. We tasked participants to choose a diameter between 0.1 and 5 m, and all of them chose to increase the diameter with distance. While most participants preferred overall thin tubes to avoid information clutter, we could not determine a specific value for the start and end diameters of tubes. The diameter of tubes should be further evaluated by considering varying weather and lighting conditions, and different environments.

Straight paths indicate visible targets and curved paths indicate occluded targets. The study participants preferred straight paths (Figure 1, left) over curved paths (Figure 1, right). This finding aligns with Buschel et al.'s study [9], which showed that participants performed better with straight links than with curved links in AR network visualization. In our AR user study, participants even preferred straight links that go through vegetation to curved links curving above vegetation. To accommodate this preference, we recommend straight links for visible buildings or buildings with trees in front of them. Additionally, participants indicated a preference for links to be at eye level. This is likely because of the small field of view of the HoloLens, which increases the need for turning one's head up and down when links curve above features. As a result, when dealing with buildings partially occluded by other buildings, we recommend curving the links to the right or left sideways around obstacles as much as possible, unless it is not feasible due to a high level of occlusion (Figure 5, left, C). Future systems should include image analysis to make these adjustments to link curvature when necessary.

Moving real-world objects seems to not be distracting. Participants reported not to have been distracted by moving pedestrians in the environment. They explained they were aware that the links were overlaid on the physical world, and that the movement of objects did not result in a loss of connection between the map and the buildings. It is to note that there were not many pedestrians during the testing period (Table 3, appendix A). This finding aligns with a recent study that explored how real-world environments affect AR visualizations. The study revealed that the background had only a marginal influence on user performance [46].

6 LIMITATIONS

We acknowledge several limitations in our evaluation of situated links for outdoor environments. We used a VR headset in the first user study that provides a larger field of view than the AR headset in the second study. This might potentially influence the perception of out-of-view objects and limit the transferability of findings from VR to AR and the generalizability of findings. We tested the application on our university campuses, which were not busy during the testing period. We also acknowledge that the demographic of participants was biased towards younger and more educated people, as well as toward the local culture, which may also limit the generalizability of our findings.

7 CONCLUSION

We explored the design of situated links to associate features on a virtual map with their real-world referents for an outdoor AR application. We conducted a VR user study and an AR user study to evaluate the design of situated links. The results of the VR user study revealed that situated links led to higher accuracy in identifying buildings in the environment compared to the situation without links, which required participants to rely on their map-reading skills. The participants' feedback showed that they preferred simple and thin links, such that links minimize occlusion of the physical environment.

The AR user study provided qualitative feedback and baseline results on how situated links work in the real world. We recommend the following design considerations: 1) simple and thin links with the diameter of links growing with distance; 2) a single color for all links (unless color is used to encode additional information) that has high contrast with the background; 3) alignment of a link should be aligned with the users' direction of view so that the entire link is visible without requiring head movement; 4) animated stripes to improve the visibility of links and facilitate distinguishing links. We do not make any specific recommendation on the thickness of links, as participant preference varied.

This work is not limited to connecting buildings on the map with real-world counterparts, but it is a step towards a future where situated links can be used to show the relationship between various virtual and physical objects, including the semantic relationship between objects, as well as quantitative flows between real-world objects.

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A APPENDIX A

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Table 2. P-values resulting from pairwise comparisons of link geometries along with α values obtained from Bonferroni-Holm corrections.

Geometry Pairs	T1		T2		T3		T4	
	p	α	p	α	p	α	p	α
No link–2D line	p<.001	.004			p<.001	.004	p<.001	.004
No link–3D tube	p<.001	.004			p<.001	.003	p<.001	.003
No link–Particles	p<.001	.003			p<.001	.003	p<.001	.004
No link–Tube particles	p<.001	.004			p<.001	.004	p=.026	.01
No link–Moving Bird	p<.001	.003			p<.001	.004	p=.002	.008
Bird–2D line	p=.009	.005	p=.07	.008	p<.001	.005	p<.001	.005
Bird–3D tube	p=.02	.005	p=.007	.006	p<.001	.005	p=.002	.006
Bird–Particles	p=.02	.006	p=.06	.006	p<.001	.006	p=.002	.007
Bird–Tube particles	p=.02	.007	p=.006	.005	p=.002	.007	p=.003	.01
Tube particles–2D line	p=.2	.008	p=.6	.02	p=.7	.02	p<.001	.004
Tube particles–3D tube	p=.9	.05	p=.7	.05	p=.8	.02	p=.002	.005
Tube particles–Particles	p=.2	.008	p=.08	.01	p=.02	.008	p<.001	.003
Particles–2D line	p=.4	.01	p=.2	.01	p=.03	.01	p=.06	.02
Particles–3D tube	p=.4	.01	p=.07	.007	p=.07	.01	p=.066	.02
3D tube–2D line	p=.7	.02	p=.3	.02	p=.8	.05	p=.3	.05

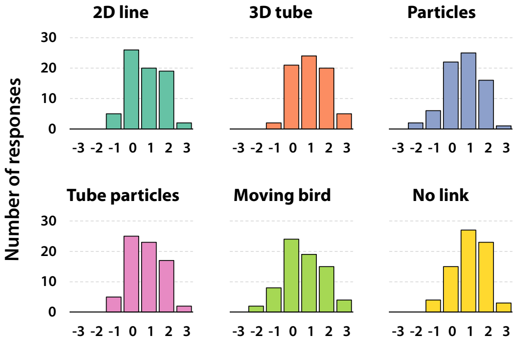

Fig. 12. For task 3 (T3) in VR user study, participants chose from five groups (0–100, 100–200, 200–300, 300–400, and more than 400 meter) to indicate the estimated distance to hidden buildings. The figures show underestimation (negative values) and overestimation (positive values) of distance to hidden buildings. Zero indicates that participants selected the correct distance group, positive values show overestimation and negative values show underestimation of distance. In general, participants overestimated the distance.

Table 3. Overview of the AR user study conditions

Participant number	Expertise	Time	Weather Condition	Moving pedestrians*
P1	Data Visualization	4:00 PM	Cloudy	7
P2	Data Visualization	11:00 AM	Semi-cloudy	8
P3	AR/VR	2:00 PM	Cloudy	6
P4	AR/VR	3:00 PM	Cloudy	7
P5	VR	10:00 AM	Sunny	5
P6	VR	1:30 PM	Semi-cloudy	11
P7	AR/VR	9:00 AM	Sunny	4
P8	Data Visualization	2:00 PM	Sunny	5
P9	AR/VR	12:00 PM	Semi-cloudy	9
P10	VR	3:45 PM	Cloudy	7
P11	Data Visualization	9:00 AM	Cloudy	5
P12	AR/VR	3:00 PM	Cloudy	7