Strollytelling: Coupling Animation with Physical Locomotion to Explore Immersive Data Stories

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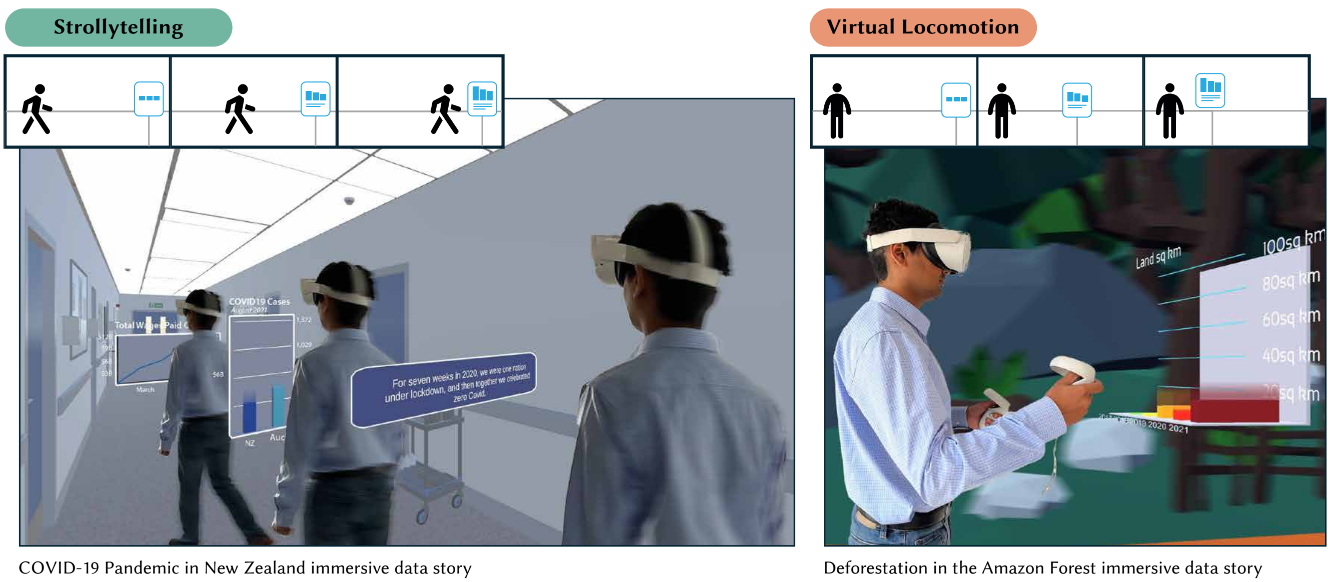

Figure 1: We propose and explore the concept of strollytelling, an immersive data storytelling technique that tightly couples physical locomotion to animation. In strollytelling, the user's position controls the frame of animation for visualisations that tween-in and out of the scene to support storytelling. Our experiment compares Strollytelling (Left) with Virtual Locomotion (Right) in two different data stories inspired by existing desktop-based scrollytelling (COVID-19 and the Amazon rainforest).

Abstract

With a growing interest in immersive data storytelling, there is an opportunity to explore story presentation and navigation techniques in virtual reality (VR) that can engage audiences as much as data story techniques have on conventional displays. We propose and explore "strolly"telling, a novel data storytelling technique that maps the story progression with the user/audience's physical locomotion. Inspired by the conventional web-based technique for scrolling-based stories (i.e. scrollytelling), our technique tightly couples the user's position in physical space to the animation frame of the data story. This technique leverages the natural tendency of humans to "walk and talk" while telling a story and requires users

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to engage with the content actively. This work defines strollytelling, design considerations, and a preliminary process for designing a strollytelling experience. A user study comparing strollytelling with virtual locomotion found that strollytelling was preferred by most participants and had higher self-reported immersion. We conclude with opportunities for strollytelling within the immersive data storytelling landscape.

CCS Concepts

• **Human-centered computing** → **Virtual reality**.

Keywords

Immersive Data Storytelling, Strollytelling, Narrative Visualisation, Design Considerations

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1 Introduction

Narrative visualisation combines data visualisation and storytelling techniques to engage and communicate a data story to an audience [43, 97]. Conventionally, narrative visualisation involves orchestrating charts, multimedia, and textual information, often in a linear storyline with several story points. *Scrollytelling* is a narrative visualisation technique that maps a data story to a vertical web page [98]. The progression of animations in the data story is tightly linked to the user's vertical or horizontal scroll within the data story rather than being controlled by a temporal framework. Scrollytelling provides a *sense of agency*, exploration and discoverability while offering a simple and intuitive interface [76, 109]. The users can control the pace of the narrative by scrolling through the web page.

Immersive data storytelling, where immersive technologies are used to present data stories, is gaining interest within the research community [50, 51]. While there are several examples of immersive data stories that employ *Virtual Locomotion* to allow the user to move through the data story [55, 78], research suggests that *Physical Locomotion*, where the user is allowed to walk in the physical space, has benefits over virtual travel techniques [64, 117]. In this work, we present *strollytelling* (strolling + storytelling), a virtual reality (VR) technique where the user's physical movement controls the animation in an immersive data story. As the user moves through the physical space, their position determines the specific animation frame for data visualisations in the virtual environment. In this way, animation is entirely linked to the act of locomoting, creating a connection between the user's motion and the story progression. This dynamic relationship between physical movement and narrative elements aims to improve the user's immersion, story understanding, and information retention.

Strollytelling begs complex design considerations beyond conventional scrollytelling, from the sociological aspects of walking and storytelling to pragmatic factors such as the interplay between three-dimensional physical and virtual environments, embodiment, and story representations. The goal of this research is to *1) define and investigate strollytelling, a novel immersive data storytelling technique through a series of design explorations, and 2) understand its effects on user experience by comparing it to a non-Physical Locomotion technique.*

To provide insights into the value of *Physical Locomotion* tightly coupled to animation, we designed and conducted a controlled within-participant experiment with 26 participants (Section 5) comparing it to *Virtual Locomotion* (joystick-based movement), a commonly used continuous locomotion technique in VR [5]. The results of our study suggest that our method of strollytelling significantly enhances the user's narrative immersion and leads towards reduced simulator sickness compared to *Virtual Locomotion*. Qualitative results show that participants enjoyed the mapping between physical movement and visual animations, which contributed to a more interactive and engaging experience. Furthermore, participants strongly preferred strollytelling, describing it as more enjoyable, natural, and immersive than *Virtual Locomotion*. To summarise, the contributions of this paper are:

(1) *Strollytelling*, a novel immersive data storytelling technique that tightly couples the user's *Physical Locomotion* to the progression of the data story within an immersive environment;
(2) Design considerations, layouts, and a process for developing strollytelling experiences; and
(3) Results of an exploratory user study examining the benefits of the strollytelling technique compared to *Virtual Locomotion*.

The remainder of the paper is structured as follows: Section 2 reviews related work to our technique. We then introduce the concept of strollytelling by defining its core elements (Section 3), followed by the design considerations and a process for creating strollytelling experiences based on our experimentation (Section 4); an exploratory user study and results are presented comparing strollytelling to traditional virtual joystick locomotion (Section 5 and 6), and we end with a discussion and future work (Section 7).

2 Related Work

2.1 Narrative Visualisation

Segel and Heer [97] introduced the term narrative visualisation in 2010 as the use of visual design to communicate a consistent and coherent data story. Narrative visualisation can tell a data story based on the underlying data and other types of narratives or messages, such as historical narratives, and cultural stories Narrative visualisation uses a combination of data, visuals and narratives to present the insights of the data [29]. Segel and Heer identified seven distinct genres of narrative visualisation, including magazine-style layouts, annotated charts, partitioned posters, flowcharts, comic strips, slideshows, and videos. Each of these genres offers unique ways to structure and present narrative content, and they can be combined with interactive elements to create even richer and more engaging experiences.

The purpose behind curating data stories is to let the data engage, explain and persuade the audience [53]. Research shows that facts and figures become intriguing when presented as a story, leading to a "rush" of dopamine, enhancing audience attention and learning capability [113]. Several notable examples of data storytelling are available on the web [10, 17, 23, 24, 35]. However, recent research by Terrado et al. [108] shows that there is room for improvement with respect to how the data is presented using traditional data visualisation methods. To address this, Hao et al. [41] presented design patterns for data-driven news articles. They mapped various narrative design patterns to article type to present a framework for out-of-the-box data-driven news creation. Shu et al. [99] examined the understandability of *Data-GIFs*, data-driven storytelling with animation within a format of less than 15 seconds. They provide design suggestions such as, but not limited to, using animation to convey temporal processes, preserving previous data points, and signifying narrative progress to the reader. Wang et al. [114] developed *WonderFlow*, which allowed users to author animated data videos through a narration-centric pipeline using text-to-speech to simplify narration. These diverse approaches highlight the growing breadth and innovation in narrative visualisation as researchers and storytellers seek new ways to communicate complex information through data stories.

Research in narrative visualisation for desktop settings has flourished over the past decade. Several survey papers have explored various aspects, including narrative visualisation elements [110], visual narrative flow [70], the role of large models in automating narrative creation [44], and tools (design space, authoring tools, ML/AI-supported tools) [18]. This field has produced seminal works (e.g., [8, 46–48, 56, 61]). Our research is primarily inspired by the widely used narrative visualisation technique known as scrollytelling.

2.2 Scrollytelling

Scrollytelling (scrolling + storytelling) is a narrative visualisation technique in which a story unfolds as users scroll through a digital interface, typically a webpage, using a scroll wheel or swipe gestures [98]. It involves presenting information in a sequence, revealing content progressively and often using visual elements, such as images, charts and text, to convey a cohesive and engaging story. The following works [71, 84, 89] are notable examples of scrollytelling.

Scrollytelling allows users to control the pace at which they consume the information, fostering an engaging and immersive storytelling experience. The position of a user could also initiate multimedia occurrences such as video playback, animation, and transitions, creating a dynamic combination of text, visuals, and music [19]. Seyser and Zeiller [98] highlight that the narrative structure of scrollytelling articles is either linear or elastic. An elastic narrative follows a predetermined sequence. However, the story diverges at certain points, providing opportunities to dive deeper into the narrative. Scrollytelling remains prevalently explored within desktop display environments, with no current work exploring the paradigm within immersive environments.

2.3 Storytelling Techniques in VR

While our work focuses on data storytelling, it is important to provide an overview of work on general storytelling in VR. VR redefines traditional storytelling, requiring new approaches for creating and experiencing stories in immersive environments. Early work like Disney's Aladdin by Pausch [86] introduced VR storytelling, enabling users to navigate a virtual world on Aladdin's magic carpet by controlling the carpet's acceleration, pitch, and bearing. Navigation is a crucial element in VR storytelling. Mollet and Arnaldi [74] offer key takeaways for navigation in VR storytelling, including offering choices and branching paths and recreating real-world environments. Recent works by Bucher et al.[12] and Dooley[25] outline principles for VR storytelling, including purposeful design of story elements, the use of sound to guide attention and adapting traditional storytelling structures like the three-act structure [73]. Dooley also explores 360-degree VR storytelling, emphasising the viewer's active role and the importance of cues for attention without reducing the viewer's sense of agency. Similarly, Christofi et al. [20] show that embodying characters and experiencing narratives from their perspective can enhance empathy and engagement.

2.4 Immersive Data Storytelling

Immersion can be defined from technological [102] or psychological perspectives [36]. Nilsson et al. [79] noted inconsistencies in the use of immersion, presence, and engagement across the literature, proposing a taxonomy with three dimensions: *System, Narrative,* and *Challenge-Based Immersion. System Immersion* as described by Slater and Wilbur [102], refers to VR system capabilities (e.g., field of view, rendering) rather than the human perception, *Narrative Immersion* focuses on a psychological perspective, aligning with Georgiou and Kyza [36] who define immersion as a psychological process where the user becomes deeply involved in an experience both cognitively and emotionally. This view of immersion aligns with the goal of immersive data storytelling, which aims to tell "visually engaging *data stories* in an immersive environment, such as virtual reality, augmented reality, mixed reality, and 360 videos" [51], and is the definition we focus on.

Isenberg et al. [50] and Marriott et al. [68] hypothesise that immersive visual data stories enhance engagement, alter time perception, and increase emotional investment than through traditional mediums. Other works look at authoring tools [92], use of visceral sensation [60], cinematic narrative visualisation [22], and application of immersive storytelling to humanitarian data [27]. While there is well-established research in developing design spaces and frameworks for immersive storytelling and conventional storytelling methods such as cinema, games, and comics [4, 26, 43, 57], immersive *data* storytelling remains under-explored [50, 68]. Closely related, Immersive Analytics [28] uses embodied data analytics tools in immersive environments primarily for analysts to understand the data and make informed decisions. Immersive data storytelling, however, is primarily targeted towards presenting data-driven narratives for a wide variety of audiences.

Directly related, Embodied Cognition [116] is a theoretical perspective in cognitive psychology that emphasizes the role of the body and its interactions with the environment in shaping cognitive processes, such as *perception*, *memory*, and *problem-solving* [66]. Research has shown that physical movement can enhance cognitive abilities through various mechanisms. For example, Chu [21] demonstrated the positive effects of nature walks on cognitive performance. Additionally, Sullivan et al. [105] explored how movement can enhance learning and memory consolidation, and Kumar et al. [58] linked motor activities to improved mood and cognitive functions. These findings suggest a strong connection between physical activity and cognitive enhancement.

While immersive data storytelling is still emerging, we anticipate a strong relationship between embodied cognition, embodied storytelling [64], and immersive data storytelling.

2.5 Locomotion in VR

Locomotion can be defined as a self-propelled movement using controllers or one's own body in virtual environments [9]. Through locomotion, users can change their viewpoint in an immersive virtual environment [88]. Locomotion in VR can be broadly classified as *physical* or *virtual* [7, 115]. *Physical locomotion* involves using one's body, such as walking or simulating gait. In contrast, *virtual locomotion* relies on controller-based movement, which can be divided into continuous (e.g. joystick movement) and non-continuous (e.g. teleportation) [3]. In controller-based movement, the user remains physically stationary while the virtual viewpoint moves. Riecke and Zielasko [94] suggest that these different approaches may offer varying levels of immersion. They can influence user experience, with implications for cybersickness and spatial cognition. *Physical locomotion* remains challenging due to the space needed for natural walking. However, solutions exist, such as repositioning systems [80], redirection techniques [91], and proxy gestures [93].

The following works highlight several advantages of *Physical Locomotion* across the reality-virtuality continuum [72]. Liu et al. [64] developed an interactive embodied storytelling system and found enhanced user engagement and knowledge through physical involvement. The book *Travelling Bodies* [69] describes how a self-guided Augmented Reality (AR) tour, where the users physically locomote across the city at their own pace, allows for a more engaging sensory experience and creates bodily feelings for the atmosphere and today's cityscape. Additionally, Usoh et al.'s [112] found that real walking offers a higher sense of ease (simplicity, straightforwardness, and naturalness) than virtual walking and found that subjective presence was rated significantly higher by participants in physical walking than walking-in-place (*proxy gesture*) and flying (*virtual travel*). Slater et al. [101] found that simulated walking, i.e. "walking-in-place", can enhance presence in VR, especially when users feel connected to their virtual bodies. This early work highlights the importance of matching physical actions with virtual movement to enhance immersion. While real walking offers an effective way to explore virtual environments, other methods like teleportation may be more practical when physical space is limited or precise movements are required [119]. Nabiyouni et al. [77] explored the relationship between interaction fidelity and performance in VR locomotion, comparing real walking, a gamepad (controller-based locomotion), and the Virtusphere (omnidirectional treadmill). The study found that the medium-fidelity Virtusphere technique was significantly slower and less accurate than both real walking and the gamepad.

Similarly, Chance et al. [16] found that *Physical Locomotion* leads to higher spatial knowledge and less motion sickness than *Virtual Locomotion* for traversing complex virtual environments. Recently, Haliburton et al. [40] found physical walk-in-place using a treadmill evokes more positive emotions and presence and increases mindfulness compared to teleportation. Furthermore, recent research focuses on assisted walking in VR to make *Physical Locomotion* accessible to everyone [75].

Inspired by Usoh et al. [112], Zanbaka et al. [117], and Nabiyouni et al. [77] as a preliminary investigation, we sought to re-examine and contrast *virtual* and *physical* locomotion to determine if a high-fidelity approach would be effective in an immersive data storytelling environment compared to a well established low fidelity approach.

3 Strollytelling

Immersive data stories are typified by immersive environments containing data visualisations that support the underlying storytelling. We propose strollytelling, a new technique for immersive data storytelling that is defined by two key aspects:

(1) the user must physically travel [59] (whether by walking or with the assistance of mobility aids) through the physical environment to progress through the story, and
(2) animation tweening [15] within the environment, including animation of data visualisations, is tightly coupled to the user's position within the virtual world.

In a strollytelling experience, for example, as the user moves along an authored path, visualisations (including charts, text, and images) will gradually appear relative to the user's position within the world through animated transitions such as scaling and fading. If the same user physically travels backward, the visualisations will animate backward and gradually disappear from view (Figure 2). Animations within the visualisations themselves are possible, for example, with bar charts dynamically changing the closer a user gets.

Integrating physical travel with the storytelling progress aims to actively engage the user in the presented data through the physical space. As demonstrated by Ortiz and Elizondo [83], giving VR users control over actions enhances their sense of agency. Strollytelling builds on this by letting users physically navigate the data story, actively exploring and uncovering data representations through their movement. The motivation for strollytelling becomes more tangible when drawing parallels to the real-world experience of guided tours. In a typical guided tour, participants are given audio headsets, allowing a narrator to narrate a story about the surroundings as the participants explore the physical space [6]. Consequently, based on prior research on physical travel, this may influence how a person experiences a data story by fostering immersion and attentiveness [67]. We argue that by fusing physical movement and virtual data storytelling, authors can create more engaging and immersive experiences for users who wish to consume and understand data stories by leveraging *animation*, *physical locomotion*, and *the spaces* around us.

3.1 Strollytelling Key Concepts

We define strollytelling experiences by the following key concepts:

- A **"strolly" path** is the physical path the user is expected to follow to advance in the data story. The strolly path is described as a set of connected line segments such that $S = \{\overline{P_0P_1}, \overline{P_1P_2}, ..., \overline{P_{n-1}P_n},\}$. From an authoring perspective, the path must consider the relationship between the physical space and the virtual environment.

- A **data story point** represents some piece of data that must be communicated as part of the data story. Data story points are placed in relation to the strolly path and may be realised through the representation described below.
- **Representations** are the manifestations of data story points and can include charts such as bar charts, line graphs, and, more generally, text, graphics or audio.
- **Animations** such as revealing charts, updating data values, and text guide user attention and facilitate movement within the strollytelling experience. They serve as continuous cues to encourage the user to navigate the data story. An animation is defined as a tuple $A_n = (V_m, K, L_q, f_q, L_r, f_r)$, where V_m is one visualisation within the experience; K is a set of keyframes consisting of a state description for the visualisation and a timestamp; L_q and f_q are the line segment of the strolly path and the normalised distance along that segment respectively where the animation begins; and L_r and f_r are the line segment of the strolly path and normalised distance along that segment respectively where the animation ends.
- A **pause point** is where users are expected to pause their movement. At these designated locations, users can engage with the data, including reading or interacting with data, examining their surroundings, or simply absorbing the immersive experience before progressing further in the story. The corresponding data visualisation animates when the user locomotes from one pause point to another. Upon reaching the pause point, the user can see the visualisation at its peak visibility. Pause points can be integrated using diegetic cues within the environment, such as a pile of leaves on the strollypath in a virtual forest environment or by the natural pauses in the data visualisation animations as the user approaches them.

3.2 Animation Through Locomotion

Animations of the data story points are tweened based on the user's position. Animation tweening is used in animation and computer graphics to create smooth transitions between keyframes. In tweening, intermediate frames are generated automatically by the software to fill the gaps between two keyframes, allowing for fluid motion or transformation of objects or characters [15].

Algorithm 1 illustrates the algorithm for calculating the tween position. The algorithm attempts to project the user's position on the closest line segment of the strolly path, which is then used to determine all animation positions. First, the user's position is projected onto each line segment. The closest line segment determined by that project is selected and that line segment L' as well as the normalised distance along that line segment is returned by the algorithms. With that information, the system selects all animations that the resulting line segment falls into, where $L_q \leq L' \leq L_r$. Each selected animation is set to a specific tween position given its total duration and the line segment normalised position.

Algorithm 1: Find the normalised distance $d' \in [0, 1]$ along the closest line segment L' from the strolly path S to the user's position U

FindClosestPoint (U, S)
- $L', P', d' \leftarrow \infty$;
- **foreach** *line segment* $L \in S$ **do**
  - $\hat{\mathbf{d}} \leftarrow \frac{L_1 - L_0}{|L_1 - L_0|}$; `// get the direction vector of L`
  - $d \leftarrow \vec{UL_0} \cdot \hat{\mathbf{d}}$; `// get the dot product projection of user position U on L`
  - $d \leftarrow min(max(d, 0), 1)$; `// clamp the dot product`
  - $P \leftarrow L_0 + \hat{\mathbf{d}} * d$; `// calculate the projected point on L`
  - **if** $|U - P| < |U - P'|$ **then**
    - $L' \leftarrow L$;
    - $P' \leftarrow P$;
    - $d' \leftarrow d$;
- **return** L', d'; `// return the line segment and the normalised distance along that segment`

4 Designing for strollytelling

In conceptualising strollytelling, we have conducted a design exploration through designing and developing a range of strollytelling experiences. This section provides potential *strollytellers* (i.e. strollytelling designers) guidance by reporting the heuristics that have emerged through our design exploration. We identify key design considerations when designing a strollytelling experience, describe a set of preliminary design layouts, and provide a practical process for curating a strollytelling experience.

4.1 Design Considerations

The design of effective strollytelling experiences requires addressing several design considerations. These considerations draw upon multiple sources: McKenna et al.'s [70] "flow factors" (i.e. navigation input, level of control, navigation progress, story layout, the role of visualisation, story progression, and navigation feedback), current practices in immersive data storytelling [13, 81] as well as our experience in developing strollytelling experiences. To explore various design layouts and considerations, we developed four strollytelling experiences with linear narrative structure. The four data stories were "Deforestation in the Amazon" [30], "The Tale of Two Pandemics'' [63], "Road to Nowhere: China's Belt and Road Initiative at Tipping Point" [1], and "COVID-19 in Africa" [49]. Three of these utilised a linear design layout, while the fourth was an experimental implementation of a circular layout within a physical space featuring a large table in the centre. We outline the following key design considerations for strollytelling as follows.

[DC1] ***The available physical space***. The physical space where the user experiences the virtual content is a primary design constraint. The space informs the strolly path and impacts the number

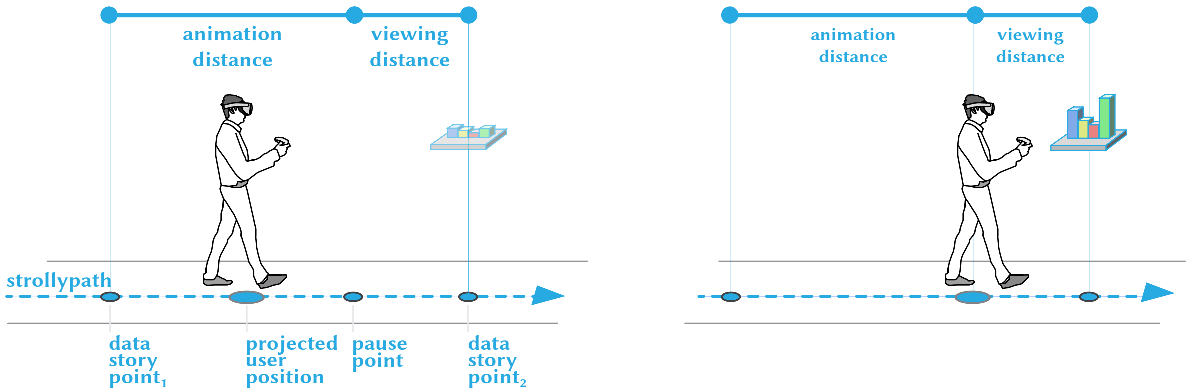

Figure 2: Illustration of strollytelling and key concepts. We show data points and pause points along an example "strolly" path and demonstrate scale as a form of animation tweening between the data story point$_1$ and the pause point.

of data story points that can be presented. For instance, a long hallway would be appropriate for a linear layout, while a room with a large, open area with a sizable table at its centre might be suitable for a circular layout, where story elements are arranged around a central point. The size of the physical space plays a significant role in ensuring that the users can navigate and interact with the data points comfortably. Furthermore, an unobstructed physical space is crucial to minimise disruptions to the user's experience, thereby facilitating a sense of place illusion (PI) [100].

[DC2] ***Placement of data story points*:** Data story point placement depends on proximity to the user and other data story points.

Our current heuristic is to provide a minimum of one metre of physical space before a data story point,ensuring animations are complete and visualisations are fully visible for the pause point.

This prevents overwhelming the users and accidental triggers. Given the average human stride of 0.72 m [38], this spacing allows comfortable navigation. While one-metre gap ensures that users encounter new information at regular, manageable intervals, adding intentionally larger gaps between data points could help build anticipation and momentum, while minimum spacing can highlight connections between related points.

[DC3] ***The virtual environment*:** The virtual environment can be a replication of an existing physical environment or an entirely abstract or fictional space. An analysis of immersive stories [52] found that a virtual environment thematically aligned to the narrative content could foster engagement and immersion. Additionally, the virtual environment must be congruent with the physical space, accurately reflecting the physical space's layout and dimensions, including any boundaries or obstacles.

[DC4] ***Navigation*:** Ensuring that the users can identify the correct strolly path in the virtual environment is crucial. We have found that both *diegetic* (i.e. elements that are part of and contribute to the narrative) and *non-diegetic* (i.e. elements that exist outside of the narrative) cues can guide the users to stay on the strolly path. An example of diegetic cues could be a physical path through a forest, while non-diegetic cues would be arrows overlaid on the environment pointing in the direction to move.

[DC5] ***Accessibility*:** Strollytelling (walking with or without assistance) allows additional data representations to make the experience accessible. Providing subtitles, audio descriptions, and adjustable interaction settings will ensure a wider audience can engage with the strollytelling experience.

4.2 Design Layouts

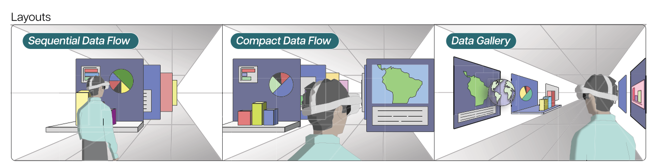

Figure 3: We present three types of layouts for linear strollytelling experiences. 1) Sequential Data Flow; 2) Compact Data Flow; and 3) Data Gallery.

To organise the data story points for our strollytelling experiences, we used *single path* layouts deriving from exhibition design [45], which allows a designer to plan a visitor's route such that they encounter a succession of exhibits in a preconceived fashion along a linear path. Hughes [45] explains single paths as advantageous where "the objective is to build a platform of knowledge in the visitor's mind." However, issues arise, such as "dwell time", where a visitor may dwell on one exhibit for a long period of time, obstructing the path from others and causing traffic management problems within shared spaces. Inspired by exhibition design, we investigated different design layouts for *single path* strollytelling to determine how we could arrange and present data visualisations, shaping how users navigate the narrative and interact with the information. Figure 3. presents three different linear strollytelling design layouts. We omitted the circular layout due to physical space constraints to experiment with the layouts. While the layout in all three examples is linear, the placement of the data points differs, directly influencing the area of the physical space and movement of the user:

[DL1] Sequential Data Flow Layout: This layout places data story points sequentially in the line of view of the user. See Figure 3 left. Sequential data flow layout aims to prevent the overlapping of points and requires no additional head and eye movements. We speculate the sequential data flow is useful where the *strollyteller* wishes to strongly control the user's sight lines, and successive experiences of a narrative. However, the layout introduces issues such as path obstruction within shared spaces (such as *museums* and *galleries*), potentially making it more useful for private dwellings with less foot traffic such as *homes* and *controlled spaces*. For sequential data flow, we suggest that the placement of data points requires at least one metre of physical space per data point to ensure clarity; to illustrate, a data story with eight data points would require a minimum of 8–10 m of physical space.

[DL2] Compact Data Flow Layout: This layout aims to increase the effective space usage over DL1, accommodating more data points in a given physical space. It aims to achieve a denser presentation of information while still enabling the user to make linear traversal of the space. Additionally, This design pattern requires more eye movement than DL1 and requires careful design of cues or animation so that the user knows where to look. We envisage compact data flow to be useful in private dwellings and shared spaces with low foot traffic due to having a division for passersby to navigate while maintaining a clear successive experience for the user.

[DL3] Data Gallery Layout: This layout is a middle-ground between DL1 and DL2 regarding space usage that encourages head and body rotation, Figure 3 right. It aims to present data story points like a museum corridor. This design patterns requires significantly more head and eye movement than DL1 and DL2, however it is potentially easier to convey the navigation pattern for the user. We also envisage data gallery to be suitable for public spaces with high foot traffic (i.e. museums and galleries), where dwell time is vital for comprehending and consuming successive narrative experiences.

4.3 Strollytelling Design Process

We propose an iterative process composed of four phases (phases 1–4), drawing inspiration from Zhu et al. [118] process they used for designing VR data stories in the health sector. The design process emphasises the selection, arrangement, and refinement of data story, visualisations, and interactive elements. Each phase represents a component of the design workflow defined by its specific focus. Each phase informs the next phase and phases can be revisited on subsequent iterations. Together, these phases contribute to shaping the final strollytelling experience. This iterative process is needed due to the underlying tension between the length of a data story and adapting it to the constraint of the physical space. The iterative strollytelling design process is illustrated in Figure 4.

Following each design phase, we present a callout box describing the application of each design phase to two strollytelling experiences we developed: `AMAZON`, about the deforestation in the Amazon rain forest and `COVID`, about how New Zealand reacted to the COVID pandemic. These two stories were used in the subsequent user study described in Section 5. Figure 5 illustrates the overview of the data stories, incorporating the design considerations and refinements from each design phase.

Phase 1—Data Story Creation/Adaptation: In this phase, the strollyteller identifies the data story to convey. This may be either an existing data story adapted from an existing source or be developed "from scratch". When adapting existing stories, Zhu et al. [118] suggest that data stories designed for scrollytelling (using a mouse) can be readily adapted into immersive data stories. We consider good candidate data stories with a strong and clear narrative structure, which maps to a strollypath to guide the user and creates a sense of progression within the data story. Additionally, data that is naturally connected to physical space (e.g., geographical data) can be particularly effective in a strollytelling format. Furthermore, the strollyteller has the opportunity to identify the data story points, which may be reduced in subsequent phases depending on the availability of the physical space. We argue that data stories should be tailored and complementary to VR, making use of spatial *visual* and *auditory* capabilities of the technology to necessitate their adaptation and creation, in contrast to being presented through traditional screen-based mediums (i.e. webpage, video, and text).

`AMAZON` *and* `COVID` *were both adapted from existing scrollytelling stories, "Deforestation in the Amazon" [30] and "COVID-19 in New Zealand" [63] respectively.* `AMAZON` *(21 data story points) illustrated four decades of deforestation in the Brazilian Amazon, while* `COVID` *(22 data story points) tracked Auckland's pandemic progression, comparing case numbers, lockdowns, and vaccinations nationwide. We envisioned immersing users in a forest with ambient nature sounds to communicate insights regarding deforestation and a desolate hospital hallway with the ambient sound of ill patients (coughing, sneezing) to communicate the impact of COVID-19 in New Zealand.*

Phase 2—Physical and virtual layout of the data story: In this phase, the strollyteller must determine the optimal placement of each data story point ([DC2]) within the virtual environment, taking into consideration the physical environment in which it will be used. The physical environment includes factors spatial layout, accessibility, and the flow of movement, ensuring comfortable navigation, as discussed in [DC1]. When considering the virtual layout, Figure 2 illustrates key elements such as strolly path, data story points, pause points, and viewing distance that must be mapped. The strolly path should be mapped with respect to the physical environment and the data story narrative structure. Design layouts may be applied (Section 4.2), considering factors such as visibility, context, and narrative flow. The available physical space and the number of data story points significantly impact the choice of design layout. For example, the sequential data flow layout is well-suited to larger spaces, while the compact data flow layout is more appropriate for smaller areas. Therefore, identifying a suitable physical space is essential, with the understanding that adjustments can be made in subsequent phases. Additionally, pause points should be considered, where users are encouraged to pause and interact with the visualisations to avoid overwhelming the user and give them time to reflect. This iterative process involves refining the placement and arrangement of visualisations to ensure a logical progression of the data story.

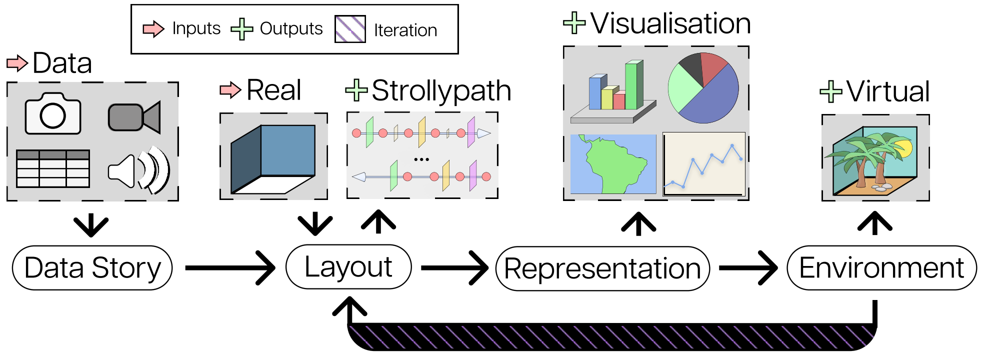

Figure 4: We define the strollyteller's journey as iterative and non-linear through a series of phases, beginning with an strollyteller identifying a data story they wish to *strollify*, then progressing and re-iterating through the different phases to craft the experience.

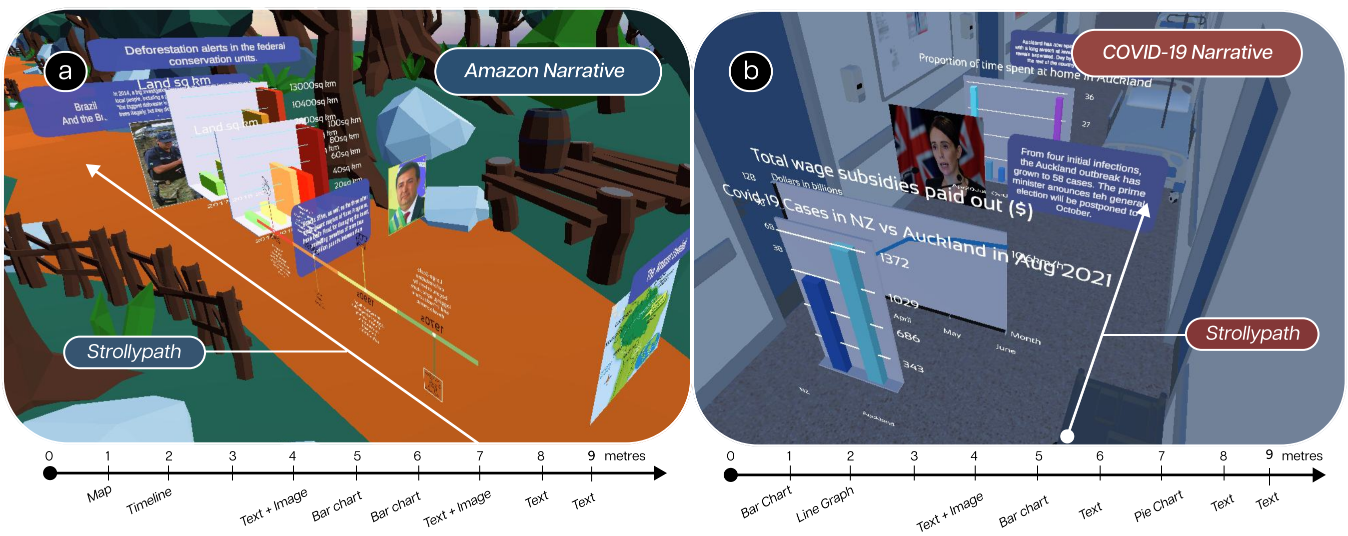

Figure 5: Overview of the narratives developed for the Strollytelling system. We highlight where the data story points are presented physically in metres on the strolly path. The gap at 3 metres indicates a small break from the data representations.

Both AMAZON *and* COVID *primarily used the Sequential Data Flow Layout [DL1], with a single instance of the Data Gallery Layout [DL3] in* AMAZON *for timeline presentation. [DL1] was used due to its ability to provide a clear and guided progression through the data, ease of implementation, and alignment with the chronological nature of the data stories. Initially, we incorporated 10–12 data story points in each story. However, due to the constraint of the chosen physical space (9m), we could only accommodate 8 data story points while maintaining the minimum 1m gap between each data story point. Redundant or combinable data story points were removed to achieve this.*

Phase 3—Representations: Strollytellers ideate representations in this phase. We achieved this through storyboarding but acknowledge other ideating methodologies such as sketching [34], brainstorming [85], and bodystorming [96]. Storyboarding [111] is an iterative process to refine the integration of data visualisations, interactive elements, and spatial navigation. During storyboarding, a strollyteller selects relevant graphs, images, and other data representations to communicate the underlying data effectively while maintaining thematic coherence with the chosen narrative. We used Leitch's [62] storyboard template, specifically designed for VR, to visualise the user's journey through the physical and virtual environments. The ideated representations were then created and adapted for VR to be evaluated and refined and animated. Animation start and end points along the strolly path should be determined in this phase. We explored the following representions but acknowledge there are many potential possibilities: 1) ***Textual elements***, such as concise descriptions, labels, and contextual information, can be incorporated to provide additional context and reinforce key insights from the data; 2) ***Visualisations***, such as bar charts, pie charts, images and line charts; 3) ***Audio***, including voice-over narration, background music, and sound effects to guide the user's attention.

A combination of graphs, maps, and timelines were used to visualise the progression of deforestation over time, the geographic distribution of affected areas, and the relationship between deforestation and various factors (e.g., agriculture,logging) in AMAZON. *Similar representations were used in* COVID *to present daily COVID-19 case numbers and cumulative infection rates in Auckland compared to other regions in New Zealand.*

Phase 4—Virtual Environment: This phase entails choosing an environment for the data story. While designing spaces that resonate with users' real-world expectations may help establish a comfortable and understandable virtual environment, it could be beneficial to leverage the capabilities of virtual reality to add elements that transcend the limitations of the real world to make the strollytelling experience more exciting for the users [DC3]. For instance, exploring data insights related to COVID-19 in a familiar hospital virtual environment is an interaction that's not feasible in the real world but could be engaging for the users. Research shows that by choosing and designing virtual environments, storytellers can create effective data stories that resonate with the users [52].

The physical space for both AMAZON *and* COVID *was a large room with a straight, unobstructed 9m long path that could accommodate the linear layout of the data stories.* AMAZON *was presented using a virtual forest with ambient nature sounds, and* COVID *was set in a virtual hospital environment. We aimed to connect the virtual environments to the respective data story.*

5 User study

We sought to understand the benefits and limitations of strollytelling by comparing it to a non-Physical Locomotion using an exploratory comparison study. Our user study addresses the following research questions.

RQ1: *How do physical and virtual locomotion affect the narrative immersion in an immersive data storytelling environment?*

RQ2: *What is the impact of strollytelling on users' information recall in an immersive data story compared to Virtual Locomotion method?*

RQ3: *How does strollytelling affect users' sense of agency within an immersive data storytelling environment compared to Virtual Locomotion?*

Strollytelling intrinsically links *Physical Locomotion* to data visualisation animation. Considering this, we separate locomotion as factor in our study, comparing *Physical Locomotion* to *Virtual Locomotion* to help understand the broader effects of strollytelling. For a *Virtual Locomotion* method to compare with, we use *continuous movement with a joystick* as it provides continuous movement that can be mapped to visualisation animation, and it is the most prevalent commercial continuous virtual locomotion technique [5]. The user study received approval from the relevant institutional ethics committee.

The study had 26 participants (17 male and 9 female) who volunteered to participate. Participants were sampled from the university population. Participants were aged from 19 to 45 (M = 28.38, SD = 6.22). All participants were undergraduate and postgraduate students at the University. (3/26) participants had never tried VR before, (6/26) participants had tried VR once before, and (17/26) participants used VR either monthly, weekly or daily. All participants were right-handed, and thirteen participants had corrected vision. Participants received a $20 gift card for their participation.

5.1 Independent Variables

The study employed a 2×2 within-subjects design with one independent variable of *technique* and *data story* as a controlled variable. Each participant experienced both locomotion techniques, with two distinct data stories having the same number of data points and level of narrative complexity and presented in a linear layout to reduce content-specific biases. To minimise potential order and learning effects, the presentation order of the locomotion techniques and data stories was counterbalanced using a Latin square design.

5.1.1 Technique. Two locomotion techniques were compared. **1) Strollytelling**, where participants navigated by physically walking in the physical world; and **2) Virtual Locomotion**, where participants navigated continuously within the immersive environment using the joystick on the Meta Quest 2 controller[1] while remaining stationary in the physical world. The acceleration was set to 0.05 m/s^2, and the participants were instructed to use the joystick on the left controller to move forward and backwards and the right controller for rotation in the data story. *Virtual locomotion* through joystick navigation was chosen as the baseline condition because it shares similar qualities to walking (i.e., continuous motion and adaptation, as required by the animation aspect of strollytelling) and is currently the most widely used continuous virtual locomotion technique in commercial VR applications [5].

5.1.2 Data story. The study used two adapted web-based data stories, **Amazon** and **COVID-19**, the designs of which are described in subsection 4.3. Both stories contained an equal number of data story points (eight each), were of similar complexity, and were designed to avoid targeting any specific culture or political group.

5.2 Dependent Variables

We collected both quantitative and qualitative data. Quantitative data included subjective measures such as immersion, recall, sense of agency, simulator sickness, and perceived workload. Qualitative data gathered through a post-study questionnaire provided insights into user preferences and reasons for those preferences.

Immersion: Immersion was measured using a modified version of Georgiou and Kyza's immersion questionnaire [36]. The questionnaire encompasses three levels of immersion: *engagement*, *engrossment*, and *total immersion*. Georgiou and Kyza describe immersion as the "participant's suspension of disbelief that she or he is 'inside' a digitally enhanced setting" and a "form of cognitive and emotional absorption". This aligns with narrative immersion [79], which focuses on the psychological process of becoming deeply involved in an experience, both cognitively and emotionally, aspects integral to storytelling. The questionnaire was adapted to focus on VR in

[1]https://www.meta.com/en-gb/help/quest/articles/getting-started/getting-started-with-quest-2/using-touch-controllers-quest/(lastaccessed27November2024)

contrast to Augmented Reality (AR) and reduced to 12 questions on a five-point Likert scale.

Recall: A signal detection theory (SDT) method [2] was used to test the narrative recall for each task [14]. It is a framework used to measure the ability to distinguish between signal (previously encountered information) and noise (new information). We sought to use SDT to evaluate how well participants can recall the elements of the data story inspired by the following works using SDT for narrative recall [31, 106]. Each questionnaire had 15 questions with two options; "I remember encountering this in the experience" and "This is new to me; I haven't seen it before". Sensitivity (d') was calculated to evaluate the impact of each condition on the recall.

Sense of Agency: The Sense of Agency Scale [107] was used to measure participants' perceived control over their actions in the VR environment. The questionnaire consists of 13 questions, of which 6 questions capture the sense of positive agency and 7 questions capture the sense of negative agency on a 7-point Likert Scale.

Simulator Sickness: Simulator Sickness was assessed using Simulator Sickness Questionnaire (SSQ) [54]. Scores for the sub-scales of nausea, ocular disturbances, and disorientation were calculated along with the total SSQ score.

Perceived Workload: We used NASA TLX questionnaire [42] to measure the cognitive, temporal and physical demands placed on the users in the immersive data storytelling environment.

Post Study Feedback: After completing both conditions, participants completed a post-study questionnaire consisting of 10 questions. This questionnaire aimed to gather additional insights into their experience, including their preferred condition and the reasons for their choice.

5.3 Experimental Apparatus

We developed the immersive data stories with the Unity Game Engine[2] version 2022.3.20f1 and presented them on a Meta Quest 2[3] headset. Additional assets and 3D models were purchased from the Unity Asset Store and SketchFab[4]. A high-performance computer (Intel Core i7) with 16 GB RAM was used to develop the strollytelling experiences. The user study was conducted in a large room with an area of 82.6 m^2. The room had a 9 m long unobstructed path to accommodate the linear layout of both the data stories. We covered the ground with ten 1 m × 1 m square gym mats to provide a physical cue for the beginning and end of the strollytelling experience. The user study took place in a quiet room to reduce any potential confounds of ambient noise hindering participants' experience.

5.4 Procedure

Participants went through the same protocol as follows: (1) Introduction, (2) Screening, (3) Training, (4) Main Tasks, and (5) Survey. For Step 1, the experiment was explained to the participants, and afterwards, they completed the consent form. During Step 2, participants completed a brief survey to survey their experience with VR, as well as gender, age, and their knowledge regarding both the data strollytelling topics used in the study. In Step 3 of the experiment, participants were trained to familiarise themselves with the immersive data storytelling environment and with both locomotion techniques. The participants were allowed to experience both *Virtual Locomotion* and *Physical Locomotion*. Before data collection began, participants were given time to get comfortable walking with the VR headset, ensuring they understood the guardian boundary of the safe play area. We closely monitored the experiment to prevent participants from colliding with physical obstacles. During Step 4, participants were guided through the main tasks. After completing each condition, they answered the following questionnaires: Sense of Agency, NASA TLX, Simulator Sickness, Immersion Questionnaire, and Signal Detection Theory Questionnaire. For Step 5, participants completed a final qualitative survey, asking which condition they preferred and the reason behind their choice. The experiment took approximately 1 hour, and each participant received a $20 gift card for their time.

6 Results

In this section, we discuss the results of our experiment, based on statistical and qualitative analysis, regarding immersion, preferred conditions, recall, sense of agency, and simulator sickness. All the data were statistically analysed using Python and Jupyter Notebook[5]. The authors studied participants' post-condition feedback in a Miro[6] board to identify common themes and derive key insights using thematic analysis [95]. Our analysis and supplemental material are shared via the Open Science Framework (OSF)[7].

6.1 Quantitative Results

6.1.1 Immersion. To address RQ1, which explored the influences of locomotion type on subjective immersion in an immersive data storytelling environment, the Wilcoxon test was conducted to compare participants' self-reported immersion between strollytelling (M = 4.2, SD = 0.52) and *Virtual Locomotion* (M = 4, SD = 0.7) conditions since the data was not normally distributed. The results revealed a statistically significant difference in immersion scores between the two conditions ($W(25)$ = 65.500, $\boldsymbol{p}$ **= 0.016**), indicating that strollytelling led to higher levels of immersion. See Figure 6.

6.1.2 Preference. Evaluation of the self-reported preference revealed that (17/26) participants preferred *Physical Locomotion* i.e. strollytelling whereas (9/26) participants preferred *Virtual locomotion*. See Figure 6.

6.1.3 Recall. To address RQ2, which explored the impact of strollytelling on users' recall in an immersive data story, a paired sample t-test to compare the recall sensitivity between *Physical* and *Virtual Locomotion* was conducted. It revealed no statistical significance between the sensitivity scores in both conditions ($t(23)$ = 0.802, p = 0.431). See Figure 7. Additionally, we found no statistically significant relationship between SDT scores and participants' pre-screening responses regarding their prior knowledge of the data story topics.

[2]https://unity.com/releases/editor/whats-new/2022.3.20notes(last accessed 27 November 2024)
[3]https://www.meta.com/au/quest/products/quest-2/(last accessed 27 November 2024)
[4]https://sketchfab.com/feed(last accessed 27 November 2024)
[5]https://jupyter.org/(last accessed 27 November 2024)
[6]https://miro.com/(last accessed 27 November 2024)
[7]https://osf.io/bavzg/?view_only=a1a3efa712bd4786b945b7f9bf4dff1f(last accessed 27 November 2024)

6.1.4 *Sense of Agency.*

To address RQ3, which explored the impact of strollytelling on user's sense of agency, a paired-sample t-test was conducted. We did not find a statistical significance in SoA between strollytelling (M = 78.55, SD = 12.5) and *Virtual Locomotion* (M = 74.85, SD = 15.3), ($t(25)$ = 1.35, p = 0.188). See Figure 6.

6.1.5 *Simulator Sickness.*

A paired-sample t-test was conducted to compare participants' self-reported simulator sickness (SSQ) scores between the strollytelling (M = 7.91, SD = 14.04) and *Virtual Locomotion* (M = 8.77, SD = 14.76) conditions. The results did not reveal a statistically significant difference in SSQ scores between the two conditions ($t(25)$ = -0.47, p = 0.642), See Figure 7.

6.1.6 *NASA TLX Score.*

A paired sample t-test showed that participants rated strollytelling as significantly more physically demanding than *Virtual Locomotion* ($t(25)$ = -4.34, $\boldsymbol{p}$< **.001**). The results revealed no significance for other subscales. The average physical demand score for strollytelling was 4.2, while the average for *Virtual Locomotion* was 1.8. See Figure 7.

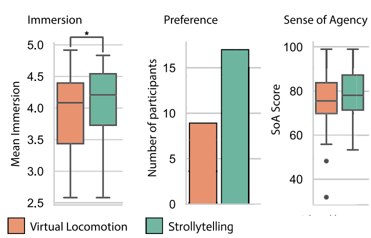

Figure 6: Immersion, preference, and sense of agency results fromwted *Strollytelling* as being significantly more immersive compared to *Virtual Locomotion*. Symbol explanation: * p < 0.05

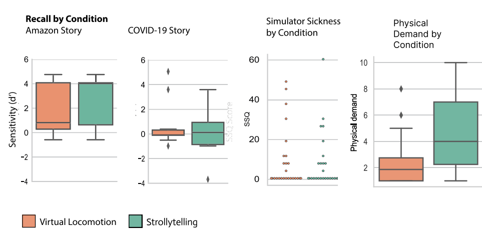

Figure 7: Recall, Simulator Sickness (SSQ) and Physical Demand (subscale of perceived workload) comparing *Strollytelling* and *Virtual Locomotion*.

6.2 Qualitative Feedback

Participants were asked post-study open-ended questions about preference, visualisations, mapping between physical movement and animation, auditory thoughts, the impact of the physical and virtual environment, and general thoughts. The authors applied deductive thematic analysis, a qualitative research method that identifies patterns or themes within data based on pre-existing themes or research questions, to draw insights from the responses [95]. This section summarises responses to each question, highlighting key themes and patterns.

Participants preferred strollytelling: The majority of the participants (17/26) preferred *Strollytelling* over *Virtual Locomotion* (see Figure 6), with P3 describing strollytelling as "more enjoyable," while P13 found it "more natural." P7, to contrast, found *Virtual Locomotion* "uncomfortable" and quoted that it "gave me a slight headache." While some participants acknowledged the potential benefits of *Virtual Locomotion*, such as precise scrolling (P3) and convenience in certain scenarios (P10), concerns were also raised. P15 reported having motion sickness with *Virtual Locomotion*, while P22 expressed a lack of agency and difficulty with the embodiment in *Virtual Locomotion*. P19 observed that audio and story elements could be easily skipped in *Virtual Locomotion*, highlighting a potential drawback compared to the controlled, more deliberate steps in strollytelling.

Participants described strollytelling as more immersive: P3 described strollytelling as "extremely immersive." P6 and P7 reported feeling physically "present" in the environment, with P6 stating that it "made it seem like I was walking in that hospital myself" and P7 describing it as "closer to reality." P21 explored the environment, stating, "walking to the forest and discovering the history." P23 felt that strollytelling was "less mentally straining." In contrast, for *Virtual Locomotion*, P13 stated that while it was still enjoyable, it felt less natural than walking and could potentially cause motion sickness. P22 found the Virtual Locomotion experience "plain and basic" and "unimaginative."

The mapping between physical movement and the animations: The mapping between the physical movement and the animations of the visualisations was well-received (21/26). P3 praised the "awesome" animated graphs and felt it "worked quite well overall" but suggested a small gap between the animations to prevent accidental triggering. P2 described the mapping as "very accurate," while P4 enjoyed the experience as a refreshing change. P10 and P11 liked the control physical movement offered to them. However, P10 suggested customisable data positioning. P14 liked the smoothness of the animations, while P6 and P17 suggested clearer initial calibration. In summary, the mapping successfully created an immersive and interactive experience for the participants.

Participants preferred a combination of Sequential [DL1] and Data Gallery Design [DL3] Layout: Participants expressed diverse preferences regarding the placement of the visualisations. P1 quoted, "I prefer putting in front of me. but the timeline is still a good one." While some preferred visualisations placed directly in front (P1, P4, P10), others preferred a combination of front and side placements (P6, P17, P14). P10 and P13 raised concerns regarding potential frustration and difficulties with navigation if all visualisations were placed on the side. Conversely, P7 would have appreciated "if the information was on different places in the environment as this would allow me to explore the virtual environment more." In summary, varied placements of the visualisations could be beneficial, catering to different preferences and enhancing the immersive experience.

Virtual environments positively impacted participant's overall experience: Participants felt that the diegetic virtual environments (Hospital and Amazon forest) positively impacted their experience of the data story. P7 described the environments as making them "feel part of the actual real environment." P10 found the virtual environments and sound effects to be "realistic and dramatic," helping them "get along with the story and forget about the real outside environment." Participants reported that audio elements enhanced the immersive experience. P7 stated that the voice-over "helped to make the virtual environment more real," while P18 felt that the ambient sounds "made me feel a bit like I am walking in the real world." P5 suggested adding subtitles to support the visuals.

Impact of guardian awareness for strollytelling in the physical environment: Participants generally felt comfortable walking in the physical environment. P5 said the study was "very well programmed and made the experience enjoyable and safe." The guardian boundary provided a sense of security, with P14 stating it helped them "know the border" and feel less scared of bumping into objects. However, some participants expressed mild concern, with P7 admitting to being "slightly afraid of running into a wall." P10 highlighted the challenges of navigating physical environments, emphasizing the potential for distraction and the need for awareness of surroundings. Overall, the physical environment was perceived as safe and comfortable, with P24 suggesting a "more aggressive guardian" for added safety.

7 Discussion

In this section, we discuss insights and observations from the study and conclude with our vision for practical applications of strollytelling.

Strollytelling fosters immersion: The apparent preference for strollytelling suggests that physical involvement is crucial in shaping the overall user experience within the immersive data storytelling environments. It enables participants to explore the data visualisations actively, transforming the experience from passive observation to active involvement in VR. We observed a statistically significant difference in immersion between both conditions, with strollytelling demonstrating a higher mean immersion score than *Virtual Locomotion*. We believe that strollytelling fosters the feeling of being connected to the data storytelling experience, making participants feel like active contributors to the data story. We argue that the heightened sense of involvement naturally piques their curiosity and sustains their interest. Additionally, this aligns with the previous research emphasising the impact of *Physical Locomotion* on engagement [64]. While we used self-reported immersion to measure the impact of strollytelling on immersion, strollytellers may explore alternate methods, such as EEG and eye tracking, to measure immersion.

Strollytelling is preferred over *Virtual Locomotion*. Our findings highlight the advantages of strollytelling. The results found that strollytelling is more engaging and that participants preferred strollytelling over *Virtual Locomotion* as the primary mode of interaction. This preference aligns with previous research emphasising the positive impact of physical activity on cognition [6, 65, 90, 112, 117]. We believe this preference stems from strollytelling's unique ability to give users control over the pace of the data story which aligns with Dooley's [25] emphasis on maintaining viewer agency in VR storytelling. It also enables embodied interaction with the data story points. With the rise of spatial computing, we believe that strollytelling presents an engaging method for people to experience data stories in both private and public settings, compared to traditional virtual locomotion (navigating stories using a joystick). Imagine starting your day by immersing yourself in a data story while enjoying your morning coffee or witnessing the historic events of Apollo 11 unfold within a public museum. Additionally, we think that strollytelling opens possibilities for further research within this domain, where it can contribute to greater immersion (and therefore engagement) and extend the application of strollytelling to other fields, such as education, rehabilitation, and therapy, where active involvement and cognitive benefits are desired.

Strollytelling tradeoffs: It is important to acknowledge that while strollytelling demonstrated clear advantages in terms of user preference and immersion, the analysis of recall, sense of agency, perceived workload (mental, effort, frustration, temporal), and simulator sickness did not reveal statistically significant differences compared to *Virtual Locomotion*. This suggests that strollytelling's impact on information retention and other factors may be comparable to existing continuous virtual locomotion techniques. This raises important considerations for when strollytelling might not be a good choice. For instance, if the primary goal of the data story is to maximise information recall or if the available physical space is severely constrained, strollytelling might not offer significant advantages over virtual locomotion. Furthermore, perceived workload for physical demand showed a statistically significant difference, indicating that strollytelling is slightly more physically demanding than *Virtual Locomotion*. In such cases, the practical limitations might outweigh the potential benefits of enhanced immersion and user preference.

Positive interaction between the physical and virtual environment: The choice of the physical and virtual environments complemented each other. Participant feedback indicated that the majority found it safe and convenient to locomote in the physical space compared to virtual locomotion, aligning with [DC1]. A mismatch between the virtual and physical space, such as presenting an extensive data story within a confined physical area, could result in a sub-optimal and potentially frustrating strollytelling experience. The diegetic cues in the experiences, such as the forest path and hospital hallway, helped participants remain on the strolly path in both virtual and physical environments, aligning with [DC4]. It also aligns with Dooley 's [25] emphasis on effective cueing for directing attention in VR storytelling. Furthermore, participants reported that the virtual environment enhanced their immersion, potentially leading to deeper engagement, supporting [DC3]. Additionally, we observed that the virtual elements, such as the trees and birds (Amazon data story) and the hospital bed (COVID-19 data story), strengthened the themes of each data story, providing a cohesive experience. This is evidenced by participants' comments indicating that the virtual elements helped them connect with the data story and understand the context of the data. For example, one participant stated that "*the virtual elements made the story more interesting as it gave a feeling that we are part of the actual real environment.*"

Possible solutions for spatial constraint: One of the crucial findings of this study is the inherent requirement of physical space for strollytelling. As discussed earlier, a comfortable and engaging experience typically requires at least one meter of space per data visualisation in a linear layout. Non-linear layouts may demand more space. For instance, a branching data story might necessitate a larger, wider physical area with increased intervals between data story points. This can pose challenges in environments with limited space for movement. While there was a slight trend towards higher discomfort with *Virtual Locomotion*, specifically for nausea and disorientation-related symptoms, the differences were not statistically significant. This suggests that *Virtual Locomotion* may be viable when physical space is constrained. However, several other options, such as treadmills, allow us to implement strollytelling without needing a large space. By eliminating the need for extensive movement, these options enable immersive data storytelling in confined spaces, such as small rooms or crowded environments.Additionally, strollytelling can use adaptive storytelling techniques to adjust the story based on available space. Respectively, setting rules, such as the minimum distance between data points or the overall size of the space, and then using computer programs to find the most effective and optimal approach to situate those data points [87].

Improvement in the placement of data points: The qualitative feedback suggests that most participants appreciated the placement and the use of a variety (text, images, graphs) of data story points and the animations (scaling and fading) attached to them. However, participant P3 provided constructive feedback, noting that a slightly larger gap between a few consecutive data points would help avoid unintentional triggering of animations. This feedback contradicts [DC2] (The placement of data points), which suggests a minimum of $1m$ distance between the data story points. However, due to the physical space constraint and to maintain uniformity, all the data story points were placed $1m$ apart. Strollytellers could explore different gap intervals within various physical spaces.

Potential for incorporating accessibility: Although the user study was conducted with a sighted population, participants valued the integration of voice-overs and audio descriptions for images and data visualisations. This relates to Butcher's [12] point about using sound strategically in VR storytelling. Additionally, this feedback supports [DC5] (Accessibility), which advocates using diverse modalities to enhance accessibility and inclusivity within the experience. The study's focus on ambulant participants limits its generalisability. However, we believe that strollytelling could benefit non-ambulant individuals. Future research should explore strollytelling's impact on immersion, recall, and sense of agency within the non-ambulant population. Several works highlight virtual reality's positive impact on assisted work, such as Moullec et al.'s work [75] on assisted walking-in-place, allowing participants to navigate the virtual environment. Fu et al. [33] combined virtual reality with robot-assisted gait training to improve the walking ability of children with cerebral palsy, which resulted in 30% weight loss and improved gross motor function, highlighting the positive impact of physical locomotion.

7.1 Potential Use Cases of Strollytelling

We consider strollytelling to have potential applications across several domains. An immediate application domain would be **museums and exhibitions**, where the content can be carefully curated for the physical space. Strollytelling could transform museums and exhibitions into dynamic and interactive spaces; by designing the strolly path and placing the data and pause points, the museum can repurpose the underutilised spaces and prevent visitors from colliding with each other. **Teaching and learning** is a second application domain we consider, though it requires suitable spaces within the teaching environment to be identified. Immersion and engagement are critical factors in effective education [11, 39, 104], and are enabled by strollytelling. Conventional teaching methods could be supplemented with virtual data-rich field trips. Finally, we envision strollytelling as something that could support **journalism**, allowing an audience to consume news stories and enable immersive news reporting. This would require some form of "adaptive" strollytelling (as we describe in future work) to adapt to the variety of physical spaces where journalism is consumed. It could allow the readers to navigate the data stories and engage with them physically. For example, an investigative piece on climate change could be transformed into a virtual tour through affected regions, where readers locomote through deforested areas or melting glaciers, enhancing their understanding and emotionally connecting with the issue.

7.2 Limitations and Future Scope

Our study had several limitations. Firstly, the available space, though large, physically constrained the study, which may have influenced participants' experiences and preferences. Our study employed a nine-meter walking distance. Longer walks, such as in a larger art exhibition, may impact the study results. Future work could investigate using walk-in-place technologies, e.g. Disney Holotile Floor [103], Omnifinity [82], which allow users to locomote within a defined area to mitigate space limitations. Another potential solution to limited space would be *adaptive* strollytelling, where the data story dynamically adjusts based on the available physical space. Using techniques like the optimization-based adaptation policies (e.g. [32]), the virtual environment could adapt its scale, path, and placement of data visualisations to suit various physical environments, ensuring user comfort and an optimal experience regardless of space constraints.

Furthermore, both data stories in our study followed a linear progression. Future research should explore non-linear story progression to determine how it impacts user decision-making, data comprehension, and overall experience. Investigating alternative narrative structures, such as branching paths, could provide valuable insights into how the format and flow of information influence users' immersion, recall, and sense of agency. We predominantly used sequential data flow layout; thus, future investigations should examine the efficacy of compact data flow and data gallery layouts. In the qualitative feedback, participants who preferred *Virtual Locomotion* raised safety concerns regarding strollytelling since they could not see the surrounding physical space. Future research could address this by incorporating passthrough technology or by exploring similar experiences in Augmented Reality (AR), akin to outdoor data tour [37], to ensure participants are aware of their physical surroundings while engaging in strollytelling. It is important to note that this study was conducted with a university population. Results may differ when generalised to the broader public.

We acknowledge that the results of the Simulator Sickness Questionnaire are exploratory and not robust enough to draw definitive conclusions about cybersickness. Further investigation with a more extensive and diverse sample where SSQ responses are collected before and after each condition is necessary to draw definitive conclusions regarding cybersickness. Additionally, our study was conducted with young adults, some of whom had prior VR experience. Future studies should include a more diverse group of participants, such as people from different age groups and non-ambulant individuals, to understand the broader applicability and impact of strollytelling.

8 Conclusion

Our study advances the scrollytelling technique, widely used in web-based data storytelling, into immersive environments. We explore how this storytelling method translates into immersive data storytelling and propose "strollytelling", which combines *Physical Locomotion*, data representations, and animation tweening with virtual reality. We developed a framework for crafting engaging and effective strollytelling experiences by integrating design principles from diverse fields such as museum architecture and scrollytelling. Our study investigated design considerations, including narrative structure, navigation, placement of data visualisations, and layout choices, to understand their impact on user immersion, recall, and sense of agency. Through an experiment comparing *Physical* and *Virtual Locomotion*, we found that strollytelling significantly enhances user immersion compared to *Virtual Locomotion*. While participants generally reported a preference for strollytelling, recall sensitivity varied depending on the specific data story, and the differences observed in recall between strollytelling and *Virtual Locomotion* were not statistically significant. This suggests that while strollytelling may enhance the overall experience and sense of agency, its impact on information retention may depend on factors such as the complexity and presentation of the data story itself. In conclusion, we believe strollytelling presents a powerful and engaging method for immersive data storytelling, offering new opportunities to enhance user interaction and understanding through immersive, movement-driven experiences, paving the way for future innovations in communicating immersive data stories.

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