The Effect of Exploration Mode and Frame of Reference in Immersive Analytics

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Abstract—The design space for user interfaces for Immersive Analytics applications is vast. Designers can combine navigation and manipulation to enable data exploration with ego- or exocentric views, have the user operate at different scales, or use different forms of navigation with varying levels of physical movement. This freedom results in a multitude of different viable approaches. Yet, there is no clear understanding of the advantages and disadvantages of each choice. Our goal is to investigate the affordances of several major design choices, to enable both application designers and users to make better decisions. In this work, we assess two main factors, exploration mode and frame of reference, consequently also varying visualization scale and physical movement demand. To isolate each factor, we implemented nine different conditions in a Space-Time Cube visualization use case and asked 36 participants to perform multiple tasks. We analyzed the results in terms of performance and qualitative measures and correlated them with participants' spatial abilities. While egocentric room-scale exploration significantly reduced mental workload, exocentric exploration improved performance in some tasks. Combining navigation and manipulation made tasks easier by reducing workload, temporal demand, and physical effort.

Index Terms—Navigation techniques, Frame of reference, Immersive analytics, Space-time cube.

1 Introduction

Immersive Virtual Environments (IVEs) are more and more used for data visualization, which led to the formation of the research area of Immersive Analytics (IA) [37]. The combination of stereoscopic displays, head-coupled perspective, and more intuitive controls allows the data analyst to be placed "inside" their data, and facilitates the manipulation and comprehension of three-dimensional representations. However, the vast design space offered by IVEs results in a multitude of different approaches being proposed and used indiscriminately, without a clear understanding of the advantages and disadvantages of each.

Data representations can be rendered at arbitrary scales. Further, they can either remain static in space while the user navigates around them, or have their positions, rotations, and scale manipulated (or a combination of both approaches). When the data scale is sufficiently large and in the absence of physical constraints, the user gains the ability to "dive" and navigate inside the data while observing details with an egocentric view, typically with 6 degrees-of-freedom (DOF) flying [17], [55]. A common alternative is to render the data at a smaller, room-scale size, and allow the user to navigate by physically walking within it. Such a scale also better affords the use of embodied actions to interact with and manipulate the data. Finally, another design option is to render the data at an even smaller scale in front of the user [15], [36] (e.g., above a desk [53]), providing an exocentric or allocentric [32] overview of the data.

A deeper understanding of the affordances of each of these different design choices would enable designers and users to make more well-informed decisions. It would also enable the identification of possible points of improvement for existing techniques and determine potential advantages in the integration of different approaches, with the goal to better support a variety of analysis tasks within an application. While interaction and visualization design also play important roles in IA, we focus our investigation here on the navigational aspects of such 3D environments.

After reviewing previous IA applications and related work (Section 2), we distinguish these approaches through two main variables: exploration mode (navigation or manipulation) and frame of reference (egocentric or exocentric). Here, we study the impact of these variables in terms of different metrics and tasks. To isolate these variables, we prepared three different environments (room-scale exocentric, room-scale egocentric, and large-scale egocentric view), and three different exploration modes for each of them (manipulation, navigation, or both) (Section 3), resulting in 9 different conditions. We conducted a user study with a spatio-temporal visualization use case (Section 4). Results are analyzed and discussed in terms of participants' spatial abilities and task requirements (Sections 5 and 6).

In summary, our main contributions for IA are:

- A comparative user study clearly investigating the effect of ego- and exocentric frames of reference and different exploration modes.
- Discussion on how different reference frames and navigation modes can better support user needs, also considering individual characteristics.
- Design recommendations for future IA systems.

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2 Related work

IA employs novel display and interaction technologies to immerse users in their data, typically through Virtual (VR) and Augmented (AR) Reality systems [11], [37]. Here, we review relevant approaches and other preceding work.

2.1 Approaches for immersive data exploration

One of the most common navigation metaphors in VR-based IA applications is virtual flying with six degrees of freedom (6DOF), normally controlled by a joystick or hand controller. The motivation for this approach is the ability to see yourself "as part of the data" [4], to explore the data "from the inside-out" [13], to navigate in any direction to inspect details, and to get information from datapoints without constraints [23]. For spatial geographic representations, it affords also the ability to easily move around a very large virtual space [29], [40]. Some examples for abstract data visualization include 3D node-link diagrams [17] and scatterplots [16], [55]. However, the main limitation of this approach is a high incidence of participant discomfort. Wagner Filho et al. [55] reported that 40% of users experienced significant simulator sickness while performing tasks. Many potential solutions have been proposed to minimize this issue. They include the use of physical movement cues, such as body leaning [39], the inclusion of spatial references [9], and the dynamic reduction of the field-of-view during flying [21], [29].

Alternatively, many applications allow the user to physically walk around a room-scale environment. This approach greatly diminishes the incidence of simulator sickness [51] and can leverage the spatial orientation abilities of the user [45] for the analysis process. Yet, walking is constrained by the available tracked space, which can be limiting for very large, dense, or complex datasets. Also, extended navigation can become fatiguing, and portions of data located closer to the ground or to the ceiling can be more difficult to inspect.

An exocentric view of the data affording stationary manipulation can be less fatiguing, require less physical space, and be easier to use within existing analyst workspaces. It can also potentially combine some of the benefits of both previously-mentioned options. Examples include *ImAxes*, where data axes can be manipulated and combined to generate different visualizations [15], and *VirtualDesk*, where the data is rendered above a reproduction of the user's desk and directly manipulated by hand gestures while the user stays seated [54]. Bach et al. [2] also studied an AR prototype for seated exploration of small-scale 3D scatterplots.

Some applications also offer more than one navigation metaphor. Notably, in the *IDEA* project, four different modalities were combined [22]. The user was allowed to fly around a large-scaled 3D scatterplot and teleport to any position, always coupled to a flying platform which included a rotating chair. Inside this platform, the user could move around by physically rolling their chair or by standing up and walking, for local inspection tasks. In *Google Earth VR*, two different modes are supported: egocentric flying and exocentric manipulation of the globe [29]. In *FiberClay* [27], users combine physical walking with bimanual view manipulations to quickly change perspectives and data scales for the visualization of 3D trajectories. A small-multiples grid positioned on the floor also allows quick transitions between different data mappings.

Finally, depending on individual characteristics of the data domain, other metaphors may also be advantageous. For example, for node-link diagrams, Kwon et al. proposed a spherical layout for egocentric exploration, which enables exploration based only on physical rotations [35]. However, this option is not applicable to other representations which use spatial position to encode information.

2.2 Effects of frame of reference and movement

The cognitive effects of ego- and exocentric frames of reference in IVEs and visualization have been studied frequently. For scientific visualization, McCormick et al. [38] found that an exocentric view of a 3D scatterplot better supported search and judgment tasks, while an egocentric one improved travel performance. Risch et al. [42] proposed the use of external viewpoints for data overview and internal navigation for local inspection. Hedley et al. [26] also combined different reference frames for geographic visualization: in their system, users interact exocentrically with 3D models in AR, but have the option to fly inside the data in VR to experience the model more immersively.

Fravoyir and Teng [19] studied preferences and performance in virtual navigation, comparing ego- and exocentric strategies in an urban touring system. They found that participants preferred the egocentric method for moving and orientation, observing that women were more likely to navigate allocentrically. In *"Be the data"*, Chen et al. [12] employed an egocentric perspective to engage students in learning data analysis. Using tracked hats, each student assumed the position of a data point and gained an improved understanding of the spatial organization of the dataset.

Research has also investigated the effects of physical movement. For VR, Usoh et al. [51] compared walking, walking-in-place, and flying approaches, finding that presence correlates highly with the user's degree of association with the virtual body. Their evidence suggested that presence was higher for real walkers. The match between presence and proprioception in real walking was shown to avoid oculomotor discomfort and result in a more compelling experience. Chance et al. [10] compared real and joystick-controlled walking. After navigating through a virtual maze, real walkers were better at identifying the direction to target objects, suggesting that spatial orientation tasks could benefit from real rotations and translations.

Ruddle and Lessels [44], [45] investigated a navigational search task, where participants had to find all target objects hidden under identical boxes in a room-scale environment. While participants who navigated the scene by physically walking were nearly perfect, others who used only unnatural navigation or only rotational physical movements often searched boxes repeatedly. Riecke et al. [41] repeated this study under more controlled conditions and did not find differences between body rotations and full physical motion. This result was also recently confirmed by Nguyen-Vo et al. [39], who performed an experiment comparing unnatural navigation, full translation, and rotations combined with body-leaning techniques for translation.

Walking has also been shown to benefit data exploration outside of VR. Ball et al. [3] found that increased physical navigation results in improved performance when working on large displays. Büschel et al. [8] compared two forms of interaction with a 3D visualization on a touchscreen tablet:

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touch-based orbiting or physical movement around a desk. Even though performance was similar, users preferred the latter, finding it to be more supportive and comfortable.

2.3 Previous evaluations of IA metaphors

Prior work on navigation in IA includes Bellgardt et al. [4], who outlined three distinct approaches derived from everyday usage scenarios: sitting at a desk, standing, and room-sized walking. In a position paper, they discussed example applications that could benefit from each approach and the tradeoffs involved, such as level of immersion, comfort, and workspace integration. No studies were conducted.

In a series of work targeting 3D scatterplots, Wagner Filho et al. [53], [54], [55] compared large-scale flying and desk-scaled manipulation metaphors. Although both resulted in similar error rates, the latter exhibited smaller completion times and less simulator sickness symptoms. With flying, 40% of participants reported significant sickness, but none with the desk-based version. Yang et al. [59] investigated suitable metaphors to present maps and globes in IVEs, comparing ego- and exocentric alternatives. The traditional exocentric globe turned out to be more accurate and faster to use in most tasks. For graphs, Drogemuller et al. [17] compared flying (steered with one or two hands), teleportation, and world-in-miniature (WIM) techniques for large-scale navigation. Two-handed flying was fastest and preferred by participants for search tasks, while WIM was less physically demanding and preferred for overview tasks.

Below, we discuss the four studies most closely related to our work. Simpson et al. [48] assessed the effect of physical movement on memory by questioning participants about 3D scatterplots they had explored for two minutes. They used a between-subjects design with 10 participants with two conditions: walking around the data or rotating it around its vertical axis. For 3 out of 15 dataset-task pairs, interactions were found between condition and spatial ability. In these cases, walking increased and rotations reduced user performance for the low ability group.

Lages and Bowman [36] also investigated the effects of walking, comparing its time performance to grabbing and rotating the data around its center in a demanding counting task on a complex biological structure. Findings of the within-subjects study with 32 participants indicate that the participants' spatial abilities and gaming experiences affect the outcomes: walking was beneficial only for users who had low spatial abilities and no gaming experience.

Kraus et al. [33] compared two desktop-based (2D scatterplot matrix and 3D interactive scatterplot) and two VR-based (scatterplot above a virtual desk and room-scale scatterplot) environments. All 3D environments were similar in terms of errors and completion times for a single cluster identification task. The "less immersive" desk environment was identified by 50% of participants as their favorite, compared to 17% for the "fully immersive" room-scale one. The latter required more physical activity, did not afford an overview of the data—important for cluster identification—and suffered from blind spots, suggesting a restricted area to be more adequate.

Yang et al. [58] adapted two standard 2D navigation techniques, overview+detail and zooming, to 3D scatterplots in VR. They compared a static room-scale environment to a table-sized fully manipulatable one, both of them with and without the support of a 3D *minipap* view. Participants preferred the manipulation mode with no overview, which was also fastest in the most difficult task (comparison of large distances). However, the room-scale navigation mode was the fastest in the counting task, and also the most accurate in the comparison of short distances when supported by the *minimap*. The authors suggest that different navigation modes may favor different tasks depending on their requirements.

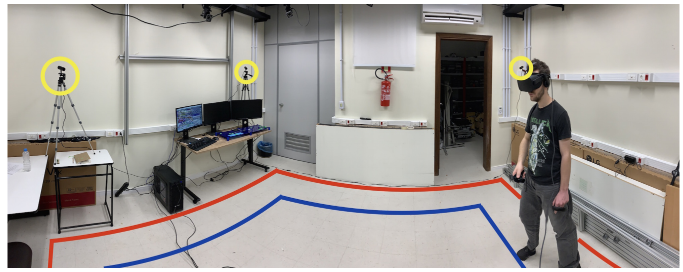

Fig. 1. Panoramic image of the user study setup. The 2.5m × 2.5m red square indicates the walking area used for the *Ego* mode, tracked by 3 Oculus sensors (highlighted in yellow). The 1.5m × 1.5m blue square represents the position of the virtual table in the *Exo* mode.

Despite focusing on different representations and tasks, the conditions considered in all of the above-mentioned studies largely correspond to a subset of our nine conditions. The first two studies focused on manipulation and movement in an exocentric room-scale environment, the third one compared ego- and exocentric environments, and the last one compared egocentric navigation to data manipulation (also offering an overview mode). Here, we use a larger experiment in order to better identify the effect of the relevant variables.

3 Interactive Visualization Design

Immersive Analytics has been applied to a wide range of data domains, including spatial and abstract information [37]. For our IA navigation study, we selected the Space-Time Cube (STC), an inherently three-dimensional spatio-temporal data representation with previously demonstrated benefits in immersive exploration [50], [56].

The STC combines spatial (x,y) and temporal (z) information, supporting a variety of tasks that require their integrated understanding. Examples include identifying meeting points, stopping locations, comparing different events [56], and correlating different trajectory datasets [50]. These tasks are often cognitively demanding, which increases the potential impact of different interaction approaches. This supports our investigation of navigation design factors.

We implemented three immersive STC environments for our evaluation, each affording different levels of immersion and using different scales (Subsection 3.1). In each, three forms of data exploration are possible, requiring different amounts of physical and virtual navigation: manipulation, navigation, or a combination of both (Subsection 3.2). The combination of our three environments and three exploration modes results in nine different conditions to be evaluated in our user study (Section 4). Our goal was to fully isolate the exploration mode and frame of reference factors.

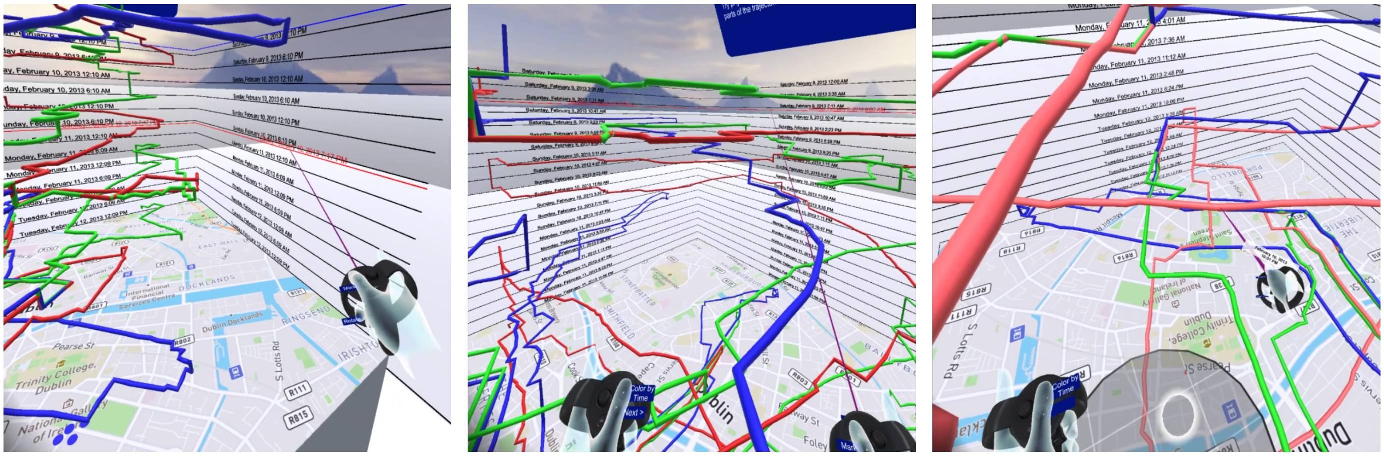

Fig. 2. Exocentric (left) or egocentric walking (center) and egocentric flying (right) are common alternatives for navigating in IA, which also allow users to manipulate the position of the data. How do these different frames of reference and exploration modes affect task efficiency and workload?

All IVEs were built using the Unity3D engine, visualized in an Oculus Rift CV1 HMD, and manipulated by Oculus Touch hand controllers. Following Oculus' recommendations, a room-scale setup using 3 sensors was configured in our laboratory, as shown in Figure 1. Adequate computing hardware was employed to ensure a frame rate above 80 FPS and to minimize user discomfort.

3.1 Prototype environments

In this section we describe the three prototype environments we implemented (see Figure 2): **exocentric room-scale** (*Exo*), **egocentric room-scale** (*Ego*) and **egocentric large-scale** (*Huge*). They represent different frames of reference and visualization scales. *Huge* is unconstrained by space availability and tracking range, and consequently much larger than *Ego*. *Exo* uses the same space as *Ego*, but to offer an exocentric view, its visualization space is even smaller.

Each environment has different potential advantages and disadvantages. Being outside of the data in *Exo* affords a full overview. Meanwhile, being inside the data in *Ego* allows the observation of details, the use of the sense of proprioception for estimations and comparisons, and stimulates more data exploration. The use of large-scale flying in *Huge* affords the same level of access to data at all heights and further emphasizes the observation of details, as if the user was "part of the data". *Huge* is also potentially less fatiguing by not demanding physical movement. Since the environments are intended to vary only in our studied factors, they all share the same visualization and interaction design.

3.1.1 Visualization design

Colored 3D tube meshes were used to represent individual trajectories in the STC (see Figures 2 and 3). Following design choices from Kapler and Wright [28], Amini et al. [1] and Wagner Filho et al. [56], time starts at the top and advances downwards. The map display stays fixed in the same position, affording a constant viewing angle. When manipulation is allowed, trajectories can be moved across the map. Maps were obtained from the Mapbox Unity SDK. We also provide an option to change the color encoding to represent different day periods [24], [56].

Visualization scales correspond to two different situations. For the walking conditions, the available physical space and tracking range are important constraints and, after extensive testing, a **2.5m × 2.5m × 2m** area was deemed to be a reasonable and realistic limit, while still being large enough to require movement for data exploration. A larger height would compromise the observation of details in the upper portion of the data when manipulation was not available. For the exocentric mode, the STC occupies 60% of the volume of the room (**1.5m × 1.5m × 1.2m**) and is placed on top of a 70cm-tall base. On the other hand, for the large-scale *Huge* unconstrained mode, the STC volume was increased a thousand times (**25m × 25m × 20m**), a scale which we empirically selected to achieve the expected immersive effect, without being excessively large and hard to explore. All environments therefore share the same 3D aspect ratio.

3.1.2 Interaction design

In all conditions, remote interaction through ray pointing was implemented for data manipulation. Even though prior work on immersive STCs prioritized local virtual-hand-based interactions [56], this decision was necessary to minimize confounding factors and isolate the navigation variable. Local manipulation would not be viable in *Huge* due to large distances nor in *Exo* due to reachability issues.

To maximize the intuitiveness of such remote manipulation, multiple interaction methods were implemented, and controller mappings were inspired by the popular *Google Earth VR* application [29]. A single pointer ray originates from the user's dominant hand controller. This maximizes mapped actions since the controllers do not need to be symmetric, and reduces confusion and visual clutter by avoiding potentially contradictory commands and unintended highlights when using two rays. Labels are permanently positioned next to each button/trigger to remind users of what features they represent (see Figure 2).

When data manipulation is available, users can move either the map (horizontally), the time grids (vertically), or trajectories (in all directions) by pointing the ray and grabbing with the index-finger trigger. *Raycast-with-reeling* [5] with the joystick is enabled while grabbing trajectories, allowing the user to move the focus point along the selection

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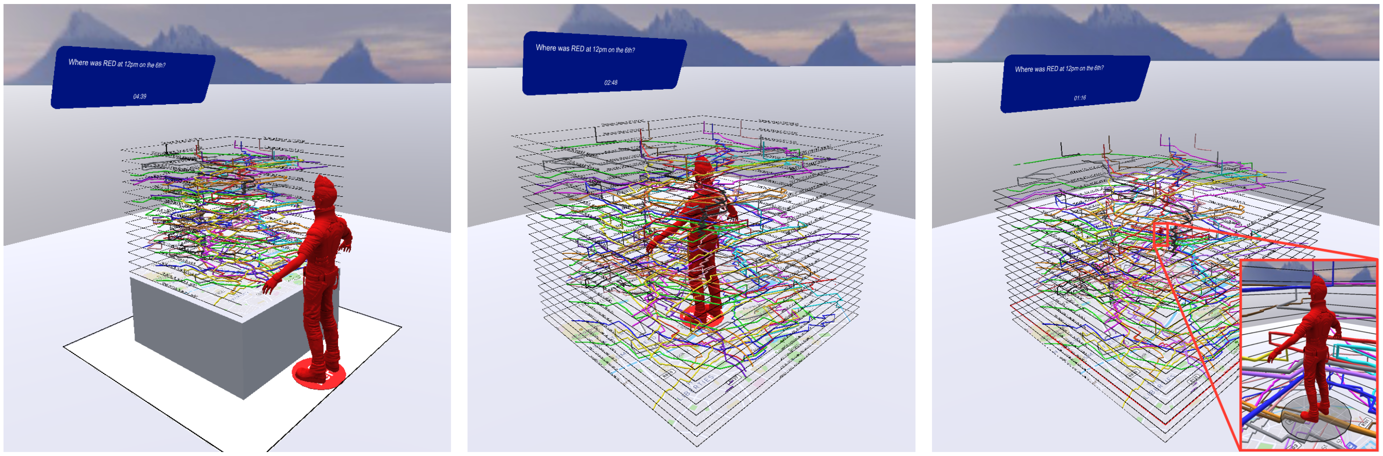

Fig. 3. While in *Exo* (left) the STC is placed on top of a central table and explored exocentrically, in both *Ego* (center) and *Huge* (right) the user is placed inside the representation—the only differences being the scale of the environment and navigation methods used. All visualization and interaction design choices are shared among all three environments. 6-feet (1.82m) tall avatar added only for scale illustration.

ray. It is also possible to rotate the map around its center by grabbing it with the middle-finger trigger.

Given that we focus on investigating specific variables, we did not enable data scaling, i.e., changing the resolution of axes. Even though this is a common form of interaction, users cannot replicate its behavior exclusively through navigation. Data filtering was also disallowed since it greatly reduces the need for manipulation and movement in most tasks, and we wanted to investigate exactly these actions.

3.2 Exploration modes

In all environments described in Subsection 3.1, three different forms of exploration are possible: **manipulation** (M), i.e., moving the data, **navigation** (N), i.e., moving yourself inside or around the data, and **combinations of both** (C). While manipulation is consistent across all environments, as described in Subsection 3.1.2, movement introduces two variables: navigation form and movement demand. For the room-scale environments (*Ego* and *Exo*), all navigation is performed by physical walking. Physical demand is higher for the *Exo* mode, since users need to walk around the visualization, while in *Ego* they start at the center and walk inside it.

In *Huge*, navigation by flying is needed to reach all points in the STC. Steering is implemented based on the hand orientation, i.e., forwards or backwards relatively to the direction of the pointing ray when pressing the controller joystick. This approach, first proposed by Robinett and Holloway [43] and also employed by *Google Earth VR* [29], allows the user to turn and look in any direction while moving, and always preserves the virtual world orientation.

We adopted a series of design choices to minimize simulator sickness across all environments. In *Huge*, a transparent grounding platform is placed under the camera and operates as a magic carpet [9] (see Fig. 3–right). Also, the index-finger triggers decrease (left) or increase (right) the movement speed [29], which by default is 3m/s. In all environments, any manipulation or non-physical movement deploys an automatic dynamic reduction of the field-of-view, through a black vignette around the center of the image [21], [29].

In all scenarios, a skyline composed of distant mountains provides visual landmarks to help the user stay oriented during movements [52], while being subtle enough to avoid diverting attention or affecting readability (see Figure 2–center). Moreover, we always required users to stand to minimize differences, even if no movement was allowed. Based on Riecke et al.'s observation that physical full-body rotations alone are sufficient to increase navigation performance [41] and considering that they can be easily implemented in any space, we decided to allow them in all conditions, even when walking or flying is constrained.

In all conditions, the data immediately disappeared when the user tried to execute any of the following actions: going inside the *Exo* table, going outside the cube area in the egocentric environments, walking in *Huge*, or moving above a small threshold during Manipulation-only conditions.

4 User Study

We evaluated our studied factors in a controlled fashion through a comparative user study.

4.1 Hypotheses

H1. We expect Combined to be the most efficient mode for *Ego*. Walking navigation is an intuitive method of exploration, but access to lower or higher areas is difficult and accessing data points across the room takes longer.

H2. We expect Manipulation to be the most efficient mode for *Exo*, since walking around the table can be slow.

H3. We expect *Exo*-Manipulation to be at least as efficient as *Ego*-Combined. The combination of multiple manipulation forms enables easy access to any data point, and exocentric environments afford better data overview.

H4. We expect *Huge* to be less efficient and less comfortable. Its large scale will require a larger amount of navigation or manipulation, and flying techniques are known to cause more simulator sickness [55].

H5. We expect spatial ability and gaming frequency to correlate with participants' performance (as observed in prior work [36], [48]) and exploration choices.

TABLE 1
Selected tasks demand movement and manipulation for data exploration and information extraction, requiring participants to find and compare different spatio-temporal features in the STC. With the exception of T3, tasks are performed in a dense environment with 12 simultaneous trajectories displayed. To avoid an excessively long experiment, T1, the simplest task, is the only one with multiple trials per condition.

Task	Description	Example	Trajs.	Trials
T1	Information seeking	*Where was RED at 8pm on the 6th?*	12	3
T2	Data inspection	*Where did GREEN meet with others for an extended period (i.e. vertical lines together) for the first time on the 6th?*	12	1
T3	Comparative overview	*Who travelled the longest distance from home to his/her first morning appointment on the 7th?*	3	1
T4	Interaction demanding	*Mark YELLOW's home location and the 3 different locations where he/she had lunch during the 3 days. Then mark again the place where YELLOW had lunch closest to his/her home.*	12	1

4.2 Tasks and Data

We defined four different STC tasks (see Table 1), aiming to stimulate different forms of data exploration. These tasks were inspired by previous STC evaluations [1], [34], [56] and require the user to either move themselves or move the dataset while using the map plane and grid walls as reference to find the required information. T1 and T2 require information seeking and data inspection to identify answers, which can be then easily and objectively determined. Tasks 3 and 4 require distance comparisons, adding another level of difficulty. T4 was designed to demand an even higher amount of interaction, requiring the extraction of multiple pieces of information before the comparison.

We adopted the 3-day simulated trajectory dataset from Amini et al. [1], extracting three different subsets. The first subset was composed of 12 trajectories, resulting in a high level of visual clutter and demanding a high amount of navigation and manipulation to extract the required information in tasks T1, T2, and T4 (as mentioned above, we disabled data filtering on purpose). The second one was composed of 3 trajectories and used for T3, since traveled distance comparisons between more trajectories in a cluttered environment would be extremely difficult. Finally, a third subset with 3 trajectories was used for training purposes in the system tutorial. Three different task stimuli were extracted for each task trial, one in each day in the dataset, i.e., at different heights in the STC. We rotated all combinations of conditions and stimuli across participants, thus always counterbalancing task difficulty.

4.3 Participants

Thirty-six students were recruited from the university campus (32 male/4 female, mean age 24.4, sd 3.4). Twelve of them had corrected-to-normal vision. Most were familiar with 3D computer games (1 no familiarity, 3 low, 4 average, 13 high, 15 very high) and gamepads (4, 1, 4, 15, 12). However, only a minority was experienced with VR HMDs (5, 10, 14, 6, 1) or motion controllers (6, 9, 11, 7, 3), and very few with the Oculus controllers (12, 14, 9, 1, 0).

4.4 Experiment design

Given the high number of studied conditions, it would be excessively demanding for any participant to complete tasks in all of them. Therefore, we adopted a **mixed experimental design**, with the 3 environments as a *between-subjects* factor and the 3 exploration modes being *within-subjects*. Each participant performed 3 trials of T1 and 1 trial of T2, T3, and T4 for each of 3 exploration modes, totaling $6 \times 3 = 18$ trials per participant.

Participants started the experiment by filling a consent form and providing demographic information. They filled a pre-exposure Simulator Sickness Questionnaire (SSQ) [31] and performed the VZ-2 Paper Folding spatial ability test [18]. This test, also used in Lages and Bowman's study [36], consists of two 3-minute rounds, each with 10 exercises, where participants are given illustrations of a sequence of paper folds followed by a puncture and must correctly identify, among 5 alternatives, the positions of holes after the paper is unfolded. The score obtained in this test was dynamically used to approximately balance new participants across the three between-subjects groups depending on the scores of earlier ones. The order of the three within-subjects conditions was always fully counterbalanced and only started after a tutorial, which introduced all forms of navigation and manipulation. We asked participants to answer the tasks "accurately but also as quickly as possible".

Tasks were always presented in the same order and users could read the instructions and ask questions before starting each one. As in the tutorial, instructions were displayed in a blue panel at the top of one side of the STC. After marking the location selected as the answer, users would press a button on the controller to submit it and then answer a Single Ease Question (SEQ) [46] inside the IVE.

After completing the 6 tasks in one mode, participants were asked to remove the HMD and fill questionnaires on a computer, also to enable them to take a small break. These included a post-exposure SSQ, a Raw NASA TLX Workload questionnaire [25], and the single general item from the Igroup Presence Questionnaire (IPQ) [47], the sense of "being there" [49]. Finally, after completing the three rounds of tasks and beyond general preference questions, users were also asked to answer the System Usability Scale (SUS) [7] and the full IPQ questionnaires, for the entire system.

5 RESULTS

Here, we report results obtained for all tasks, frames, and modes. We compute statistical significance through repeated-measures ANOVA tests with $\alpha = .05$ (main effects of frame, mode, and interactions are marked in plots with $*$). A post-hoc power analysis with G*Power [20] yielded .998, assuming a large effect size for differences between many means (effect size $f = .4$ [14]). As skewness and kurtosis exceeded the ± 1 range for most groups and variables, we adopted the Aligned Rank Transform (ART) method for nonparametric factorial analysis [57] followed by Tukey-corrected pairwise comparisons of estimated marginal means (EMMs).

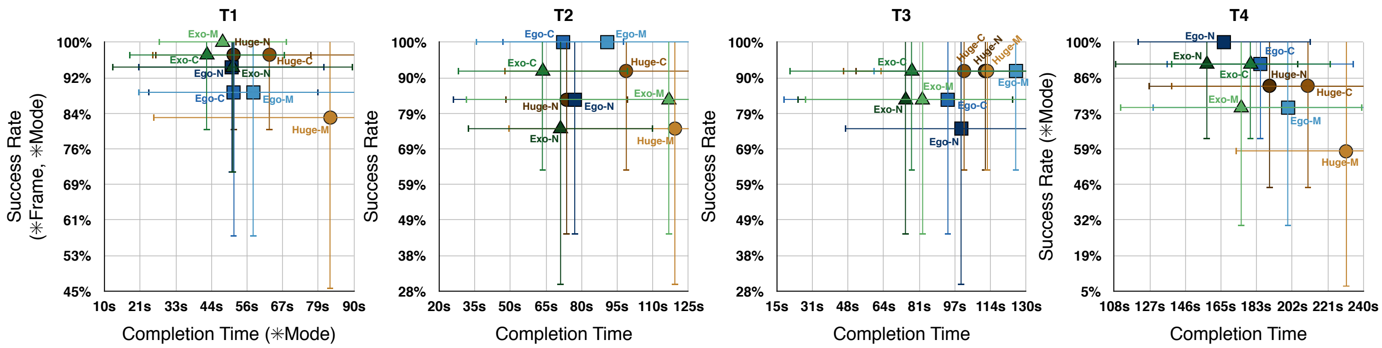

Fig. 4. Averages and standard deviations for task completion times and success rates. Performance is best closest to the upper left corner and worst closest to the bottom right. Manipulation (light shades) was *overall* significantly slower in T1 and led to more errors in T1 and T4. Still in T1, *Exo* (△) was significantly more accurate than *Huge* (□), and both were better than *Ego* (◯).

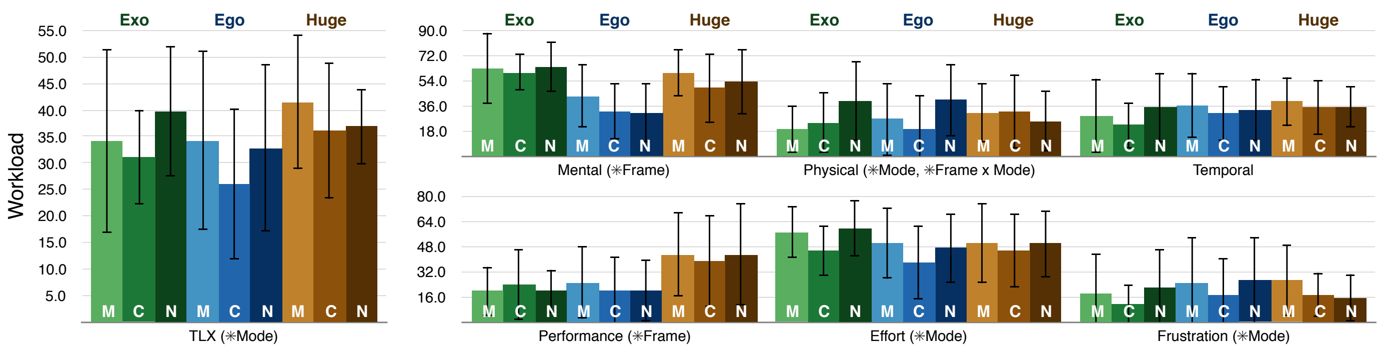

Fig. 5. Average scores and standard deviations for the NASA Raw Task Load Index (TLX) and its six sub-components (lower is better). Combining Navigation and Manipulation modes significantly reduced the overall score, temporal, and physical demands. Main effects of frame of reference indicated that *Ego* was less mentally demanding than both other environments and that *Huge* negatively affected the perception of performance.

5.1 Task performance

Figure 4 shows completion times and success rates for all tasks and conditions. We only found one main effect on completion times, by exploration mode in T1 ($F(2,282) = 5.19, p = .006$). In this task, **Manipulation was significantly slower** (avg = 62.7s) than both Navigation (51.1s, $p = .009$) and Combined (52.4s, $p = .028$). Additionally, we found marginally significant effects of exploration mode in T4 ($F(2,66) = 2.78, p = .069$, *Manip>Nav* $p = .069$) and of frame of reference in T1 ($F(2,33) = 3.08, p = .059$, *Exo<Huge* $p = .051$) and T3 ($F(2,33) = 2.94, p = .066$, *Exo<Huge* $p = .072$).

In terms of success rates, we found main effects of exploration mode in tasks T1 ($F(2,282) = 9.41, p < .001$) and T4 ($F(2,66) = 6.82, p = .002$), as well as of frame of reference in T1 ($F(2,33) = 39.96, p < .001$). In T1, **Navigation (avg = 95.4%) was better** than Combined (94.4%, $p = .001$), which was better than Manipulation (90.7%, $p < .001$). ***Exo* (97.2%) was better** than *Huge* (92.6%, $p < .001$), and both were better than *Ego* (90.7%, $p = .017$ and $p < .001$). In T4, Manipulation (avg = 69.4%) once again led to worse performance than Combined (88.9%, $p = .003$) and Navigation (91.7%, $p = .011$). In this task, we also found a marginally significant effect of frame ($F(2,33) = 3.11, P = .057$, *Exo>Huge* $p = .060$).

5.2 Workload

We found multiple significant differences in terms of workload as measured by the NASA Raw TLX questionnaire (see Figure 5). The overall score presented a main effect of exploration mode ($F(2,66) = 4.2, p = .018$), but no effect of frame ($F(2,33) = 0.9, p = .401$), nor interactions between both ($F(4,66) = 2.1, p = .090$). The **Combined mode had lower workload** (avg = 31) than both Manipulation (36.7, $p = .035$) and Navigation (36.5, $p = .037$).

Considering the TLX sub-components, we found two main effects of frame of reference. The first one was in terms of mental workload ($F(2,33) = 8.0, p = .001$), indicating that ***Ego* was significantly less mentally demanding** (avg = 35.2) than both *Exo* (62.0, $p = .001$) and *Huge* (53.7, $p = .029$). In terms of perceived performance ($F(2,33) = 3.5, p = .043$), *Huge* obtained a non-significantly worse score (41.7) than both *Ego* (21.3, $p = .093$) and *Exo* (20.9, $p = .058$).

Three sub-components also presented effects of exploration mode. **Combined was significantly better** rated (29.2) than Navigation (34.3, $p = .034$) **for temporal demand** ($F(2,66) = 3.3, p = .041$), and non-significantly better rated (43.1) than both Navigation (52.3, $p = .076$) and Manipulation (52.3, $p = .058$) for perceived effort ($F(2,66) = 3.4, p = .037$). Matching intuition, **Navigation** (34.7) **resulted in significantly higher physical demand** ($F(2,66) = 3.9, p = .024$) than Combined (25.0, $p = .003$) or Manipulation (25.5, $p = .043$). This component also presented a significant interaction between factor and mode ($F(4,66) = 3.1, p = .020$). A difference-of-differences analysis indicated that this did not apply to the artificially-navigated *Huge* (see Figure 5).

Analyzing the answers to the Single Ease Question (SEQ) posed immediately after each task (see Figure 6), we found main effects of Mode in T1 ($F(2,66) = 7.8, p < .001$), T2

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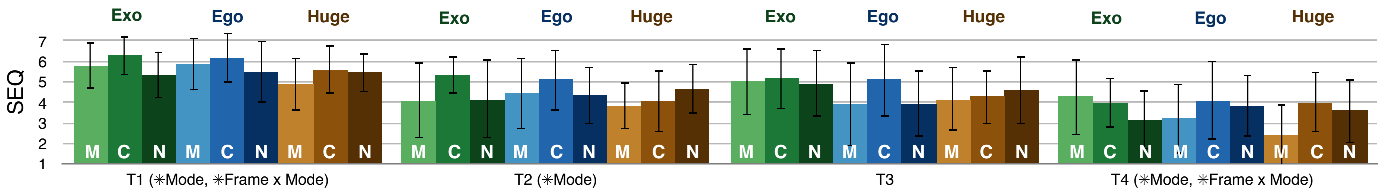

Fig. 6. Averages and standard deviations for the Single Ease Question ratings (7 represents *very easy*). As expected, the ratings decrease as task complexity increases. Combined navigation and manipulation significantly increased ease scores in three out of the four tasks.

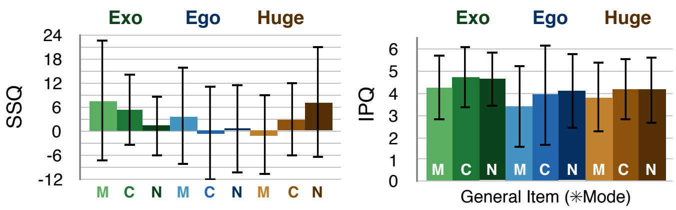

Fig. 7. User feedback for simulator sickness (left) and the sense of "being there" (right). All conditions obtained negligible or minimal sickness scores. Exploration through Navigation or Combined resulted in significantly higher presence than using only Manipulation.

(*F(2,66) = 3.2, p = .045*), and T4 (*F(2,66) = 3.8, p = .027*). In all cases, **Combined significantly increased the ease-of-use score** over Manipulation (*p < .001, p = .037, p = .040*). In T1, it was also significantly higher than Navigation (*p < .001*).

Finally, the SUS questionnaires filled at the end of each session indicated that participants rated *Huge* (mean 68.3, sd 16.9) as less usable than both *Ego* (mean 80.6, sd 11.4) and *Exo* (mean 78.9, sd 9.4). However, this difference was not statistically significant (*F(2,33) = 1.9, p = .155*).

5.3 Simulator sickness

We **did not find significant differences** for the SSQ scores, neither in terms of frame of reference (*F(2,33) = 0.2, p = .801*), nor of mode of exploration (*F(2,66) = .1, p = .896*). All combinations were within the negligible (<5) or minimal (5-10) symptoms ranges [30] (see Figure 7–left). Interestingly, we observed this **despite long VR exposure periods**, which averaged 37.6 minutes (sd 6) in *Exo*, 39.3 (sd 7.5) in *Ego*, and 48.2 (sd 9.4) in *Huge*. The maximum was 58.8 in *Huge*.

Flying navigation, a cause of concern in prior work [55], resulted in higher sickness scores in the *Huge* environment (7.1 compared to -0.9 of Manipulation and 2.8 of Combined), but still within the minimal range, likely due to the measures we adopted to minimize sickness (see Subsection 3.2).

5.4 Presence

We found a main effect of exploration mode on the "sense of being there" ratings (*F(2,66) = 7.1, p = .001*), with lower scores for Manipulation than for Combined (*p = .010*) and Navigation (*p = .002*) (see Figure 7–right). This shows that **navigation, either physical or artificial, resulted in increased presence**. A between-subjects comparison of the full IPQ questionnaires failed to indicate significant differences.

An analysis of Spearman's correlations indicated that presence correlated negatively with the TLX (-.31 for *Exo*, -.35 *Ego*, -.29 *Huge*) and positively with SUS (.30, .20, .24). People who reported feeling present also tended to walk more (.36 for *Ego*, .17 for *Ego*) and manipulate less (-.47, -.35, .03, considering data translations) in the room-scale environments. However, in none of these cases is *p < .05*. A significant correlation was only found with mental workload in *Exo* (-.73, *p = .007*) and a marginally significant one with frustration in *Huge* (-.54, *p = .067*).

5.5 Usage patterns

Figure 8 presents the average distribution of the total time spent by each user in tasks T1-T4 in terms of different manipulation and navigation interactions. With the exception of trajectory inspections, all components presented significant effects of exploration mode. Compared to Manipulation, Combined decreased map (*p < .001*) and time translations (*p = .084*), as well as map rotations (*.019*) and trajectory translations (*.028*). Compared to Navigation, it decreased head/body movement (*p < .001*).

Except for trajectory translations and inspections, all components also presented significant effects on frame. ***Exo* had a much larger amount of map rotations** than *Ego* (*p = .006*) and *Huge* (*p < .001*). Even when participants were not allowed to walk, there was still time spent with small head/body movements, probably in an attempt to avoid occlusion and get a better view into the data.

In both **egocentric frames, we observed more vertical time translations**, probably due to the larger height of the STC and the intention of moving points of interest closer to eye level — difference only significant for *Huge* (p = .002). Horizontal **map translations were less used** in *Ego*-Combined and *Huge*-Combined, since it was more intuitive to egocentrically navigate towards the desired location. Additionally, fewer data rotations were executed since participants could physically rotate their view instead. Due to the ability and ease of walking, *Ego* had more body movement than both *Exo* (*p = .007*) and *Huge* (*p = .021*).

In *Huge*, its noticeable that only a **small portion of time is dedicated to flying** the platform. However, part of the navigation time is hidden in the head movement time, since both activities could be performed at the same time due to the pointing-based steering method. Yet, our observations indicate that most users indeed preferred to move for short distances to avoid occlusions and then used trajectory inspections with the pointer, probably due to a perception that distances were very large to travel and to avoid discomfort. This is also reflected in an increase of head rotation time over both *Ego* (*p = .064*) and *Exo* (*p = .041*).

5.6 Effects of spatial ability and gaming frequency

Considering previous reports [36], [48], we investigated how spatial ability (SA) and gaming frequency (GF) affected user

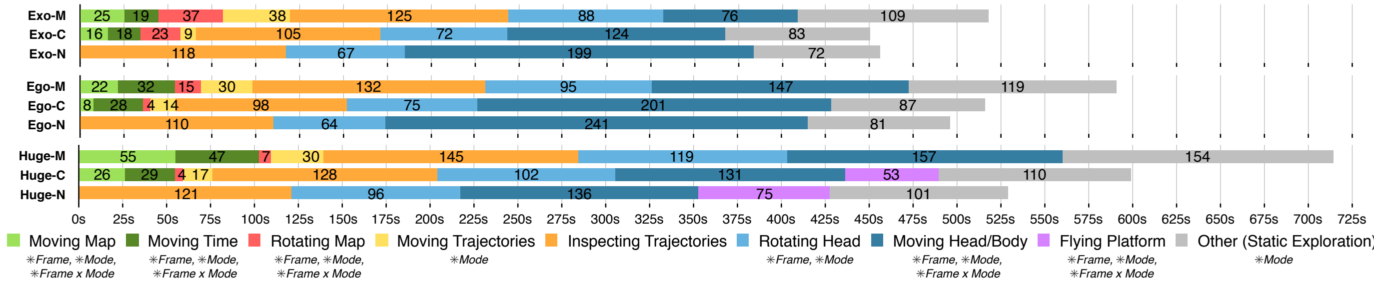

Fig. 8. An analysis of the average distribution of aggregate task times across different navigation and manipulation activities offers insights on user preferences when they have the option to combine both modes in the different environments. Exocentric rotations and egocentric map translations were used less when navigation was available. In *Huge*, only a minor part of the time was dedicated to flying.

TABLE 2
Spearman correlations between spatial abilities (VZ-2 test), reported gaming frequency, and different measures. Significant correlations ($p < .05$) marked with ∗. Both factors often correlated positively (blue) with navigation and negatively (red) with completion times and manipulation.

	Spatial Ability						Gaming Frequency					
Condition	**Time**	**Navig.**	**Manip.**	**Succ.**	**SEQ**	**TLX**	**Time**	**Navig.**	**Manip.**	**Succ.**	**SEQ**	**TLX**
Exo-Manip	.36	—	.31	.32	.04	.22	-.26	—	-.16	.53	.01	-.45
Exo-Comb	.24	.20	-.38	.10	.13	.40	.20	-.34	.16	-.01	-.11	-.16
Exo-Nav	-.20	.37	—	.11	.13	.36	-.55	-.20	—	.56	-.08	.31
Ego-Manip	-.08	—	.08	.28	.51	-.09	-.13	—	-.29	-.03	.24	-.15
Ego-Comb	-.32	.41	-.47	.24	.39	-.17	-.42	**.70** ∗	**-.65** ∗	**.62** ∗	.24	-.44
Ego-Nav	.07	.43	—	-.13	.54	-.57	-.43	.13	—	.35	**.77** ∗	**-.61** ∗
Huge-Manip	.45	—	.10	-.56	-.40	.57	**-.61** ∗	—	-.05	-.03	.16	.08
Huge-Comb	-.08	-.17	.02	-.05	.05	.37	.10	**.72** ∗	-.05	.15	-.52	.57
Huge-Nav	-.13	-.11	—	-.18	-.30	**.73** ∗	-.12	**.59** ∗	—	.19	-.45	.27

performance. As a measure of SA, we asked participants to perform the VZ-2 Paper Folding test. The average score, with a maximum of 20, was 14.22 (median 14, min 9, max 20, sd 2.36) — 14.8 for *Exo*, 13.9 *Ego*, 13.9 *Huge*. This test was applied in the beginning of the experiment and used to balance participants across between-subjects groups. For GF, participants rated on a 7-point scale how often they played video games on computers or consoles. The global average was of 4.2 (median 4, min 1, max 7, sd 1.6) — 4.4 for *Exo*, 4.2 *Ego*, 4.1 *Huge*. Both measures had a global non-significant Spearman correlation of 0.17.

To assess possible interactions between SA and GF, we replicated the robust linear regression approach adopted by Lages and Bowman [36], focusing on the total time differences between navigation and manipulation modes. The contour plots in Figure 9 [6] show the result of this analysis for each frame of reference. The *Exo* model presented a marginally significant effect of SA (p = .054) and a significant interaction between SA and GF (p = .044), while *Huge* presented significant effects of both SA (.003) and GF (.004), as well as a significant interaction (.020).

Interestingly, our model for ***Ego***, although without significant effects, seems to follow the **same patterns found by Lages and Bowman** with an exocentric setup and a different data domain: walking was quicker especially for participants with low levels of both SA and GF, while manipulation was quicker for users with high levels in only one category. In our **exocentric mode**, however, a **different pattern** emerged: participants with a high SA or GF were quicker when walking, while low or high levels of both combined favored manipulation. This difference may be linked to the different environment sizes in both studies. Since our virtual table had

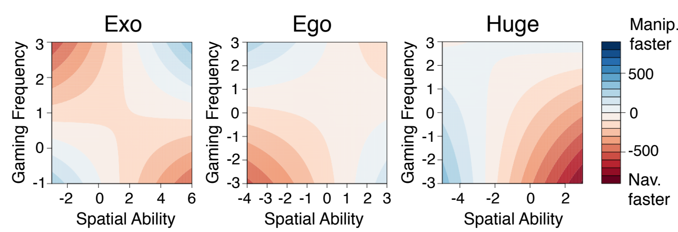

Fig. 9. Time difference between Navigation and Manipulation modes as a function of participants' spatial abilities and gaming frequencies (centered on global medians). Red and blue shades indicate when Navigation was quicker or slower, respectively. Effects varied depending on frame.

a side of 1.5m, compared to a 60cm diameter circle in Lages and Bowman's study, participants with both skills were able to efficiently manipulate, while walking around the desk required more time. Finally, the ***Huge* model also presented a different pattern**: participants with low-to-medium GF were much faster with flying when they had high SA and faster by manipulating otherwise. Users with high GF performed similarly in both modes.

We also assessed whether the aggregate values of other quantitative and subjective measures per participant had monotonic relationships with SA or GF. As seen in Table 2, correlations with both factors were broadly similar, though we found more significant moderate-to-strong correlations for GF. In most cases, both **negatively correlated with completion times and manipulations** (accumulated data translations), while **positively correlating to navigation** (accumulated translations of the avatar base or flying platform). GF positively correlated to success rates, particularly in *Ego*-Combined. **Both factors also correlated positively to**

judgments of task ease and negatively to reported mental workloads in *Ego*, while in some cases these patterns were reversed for *Exo* and *Huge*. One hypothesis is that more skilled participants may have felt more limited by these environments, negatively affecting their feedback.

5.7 User comments

After the experiment, 27 participants elected Combined as their favorite mode. 4 would rather only move themselves (1 *Exo*/1 *Ego*/2 *Huge*) and 5 only the data (1/2/2).

Participants could also offer suggestions through open comments. Three users suggested modifications on the pointing ray, such as a snapping mechanism to make remote inspections easier. The users also proposed additional STC features, such as trajectory filtering and cutting planes, claiming they would make tasks easier. We deliberately had omitted such features in our apparatus to stimulate navigation and manipulation and to increase internal experimental validity. Using a terrain model instead of a 2D map was also suggested as a way of increasing presence. Since some tasks required comparisons of locations and distances, some also suggested adding a *"virtual ruler"* or the *"option to choose marked locations and show the distance between them"*.

6 Discussion

In this section, we discuss the key findings and limitations of this study and how they inform future work, both in terms of design recommendations and research directions.

6.1 Findings

Combined and Navigation required similar amounts of time. We initially expected the Combined mode to be the most efficient in *Ego* (H1), and that *Exo*-Manipulation would be at least as efficient as this combination (H3). However, contradicting H1 and part of H3, we did not find such interaction effects, and, overall, we did not find time differences between these two modes. In terms of accuracy, Combined surpassed Manipulation in T1 and T4, but lost to Navigation in the former. Our results also partly differ from Yang. et al.'s work on scatterplots [58], where different tasks favored either mode in terms of time, possibly because their design allowed teleportation. Yet, similarly to their work, Navigation led to significantly more successes in one of our tasks (T1)—here, without the help of an overview.

Using only manipulation led to worse performance. Contradicting H2, where we expected Manipulation to be the most efficient mode for *Exo*, we did not find significant interaction effects in terms of performance, and, overall, this exploration mode led to significantly more failures in T1 and T4, and took significantly longer in T1. This could be linked to the remote manipulation techniques we employed, a theory that should be investigated in a follow-up study (see Sec. 6.3).

The exocentric environment sometimes led to better performance. Confirming part of H3 and prior work by Kraus et al. [33], *Exo* had a significantly higher success rate than both *Ego* and *Huge* in T1. With marginal significance, it was also more successful than *Huge* in T4 and led to lower completion times than *Huge* in T1 and T3. By providing an overview of the data, *Exo* possibly prevented simple information-seeking mistakes such as missing relevant segments or focusing on wrong portions of the dataset.

All frames of reference can be comfortable with appropriate implementation choices. Contradicting H4, where we expected *Huge* to be less efficient and less comfortable, and also contradicting prior work [51], [55], a large-scale environment with flying navigation was successfully employed with at most minimal sickness symptoms with 41 minutes of exposure. This is likely due to our design decisions, such as restricting the field of view during artificial movements and data manipulation, providing a grounding plane, flight platform, and landmarks. Participants spent only a small part of the time flying, prioritizing remote data inspection, which may also have contributed. This finding is interesting since large-scale virtual environments do not suffer from space availability requirements and could potentially allow the representation of larger volumes of data.

Individual factors such as spatial ability and gaming frequency directly affect performance and preferences in data exploration. Confirming H5, we found moderate-to-strong correlations between both spatial ability and, particularly, gaming frequency with measures of navigation and manipulation, completion times, and questionnaire scores. Moreover, we observed significant interactions between both factors in a linear regression analysis of time differences between navigation and manipulation. Notably, different frames and environments resulted in opposite effects.

Combining manipulation and navigation made tasks easier and reduced workload. The Combined mode significantly increased SEQ scores for 3 out of 4 tasks. It also significantly reduced the overall TLX score, and temporal and physical demand in the walking environments. This indicates that, in this mode, participants were able to execute system interactions in the way they were most comfortable or confident with.

Egocentric room-scale exploration significantly reduced mental workload and did not increase physical effort when combined with manipulation. In this mode, participants did not need to learn new navigation commands or worry about movement constraints, which may have simplified task execution. Even though exclusively walking led to a significantly higher physical workload, our results indicate that it is comparable to Manipulation and Flying navigation when using the Combined mode.

Navigation increases the sense of presence. Considering the 7-point rating given by users after experiencing each mode, Navigation and Combined significantly increased the sense of "being there" over using only Manipulation. We did not find significant differences in terms of the frame of reference, despite the expected variance of immersion between exocentric, room-scale egocentric, and large-scale egocentric.

Interaction patterns show how participants balance navigation and manipulation to increase efficiency. When given the option, participants performed fewer rotations in *Exo*, opting to sometimes move around the desk. In *Ego* and *Huge*, they performed fewer egocentric map translations, opting to move towards the location of interest. However, in all cases, participants preferred vertical translations over navigation. They also employed remote data inspection to minimize navigation, especially in *Huge*. This may explain the positive results for workload and performance when using the Combined modes.

6.2 Design Recommendations

Here, we derive some general recommendations from our work to support the design of novel IA environments.

How to choose an adequate frame of reference? Our findings suggest that different approaches result in different benefits. Therefore, application designers should carefully consider the trade-offs depending on their specific priorities. *Exo* was the best frame in terms of task accuracy, significantly exceeding both *Huge* and *Ego* in T1. Meanwhile, *Ego* significantly reduced mental workload compared to both other conditions. Although without statistical significance, *Huge* was rated lower in terms of system usability. In general, we believe room-scale environments should be favored when space is available and that, if possible, they should support both ego- and exocentric perspectives (scaling manipulations could be used to switch between the two modes).

What to do when physical movement is not an option? Not all users can execute physical movements to navigate the immersive environment, e.g., due to space constraints in their workspace, and some could prefer to stay seated when spending longer periods of time in VR. In this case, we should consider the trade-off between *Ego*-Manipulation, *Exo*-Manipulation, and *Huge*-Combined. Notably, in our study, relying exclusively on manipulation led to slower and less accurate answers, higher workload, and lower presence ratings. Based on these results, designers should consider supporting virtual navigation in their systems. However, we note that additional studies are needed to determine the effects of different design choices, such as different navigation metaphors, different interaction metaphors, and seated usage (see Sec. 6.3).

How to choose an adequate exploration mode? We believe IA systems should always support both navigation and manipulation. Although, in a single task forcing navigation resulted in larger accuracy, the Combined mode was overall preferred by 75% of the participants, significantly increased task ease, and significantly decreased workload scores. Furthermore, our study confirms prior results [36], [48] that users benefit differently from each mode depending on their spatial abilities and gaming habits, emphasizing the need for multiple modes to better support a diverse population.

How to minimize sickness in large-scale immersive environments? Our results confirm that features such as dynamic FOV reduction [21] and a "magic carpet" platform [9] are effective in minimizing sickness symptoms to levels similar to room-scale environments. The presence of a ground reference, visual landmarks, and the ability to control flight speed may have also contributed to this end. Data manipulation in these environments reduced the sickness scores even more and should thus be always supported in such environments.

6.3 Limitations and Research Directions

Here, we also identify many directions for future expansions of this work, specifically by focusing on variables that we kept fixed in our research.

Investigating the effect of alternative visual representations. When interpreting our findings, two limitations inherent to our study must be considered. The first one is the adoption of a specific data representation, the STC. Since different visual representations might support different analytical tasks to different degrees, due to different needs for data overview or detailed inspection, they may benefit differently from different approaches, which is a subject for future work. However, we claim that the STC is a representative choice for this study due to the way it integrates all three dimensions requiring their simultaneous understanding to accomplish tasks. Moreover, the STC has been recently used with success in different IA environments [50], [56]. We also applied four different tasks to diversify task requirements and stimulated different forms of exploration.

Investigating the effect of alternative interaction metaphors. The second limitation concerns the use of ray-based interaction. Other recent IA work employed local manipulation with a virtual hand [15], [54]. As discussed above, ray-casting reduces the need for navigation, increases reachability, and was employed in our work to fairly compare the different environments. To ensure that participants were familiar with the interaction methods, they all initially performed a tutorial, which lasted on average 12.1 minutes (sd 3.1) and involved simpler versions of the tasks. Yet, most ignored *raycast-with-reeling* and performed relatively few trajectory translations, manipulating the data mostly by decomposing spatial and temporal translations. This probably contributed to the lower Manipulation performance in some tasks. However, despite the lower performance for manipulation alone, our data shows that participants successfully combined ray-based interaction with navigation to reduce workload and make tasks easier.

We acknowledge that each environment individually may benefit in different ways from alternative interactions. For example, using gestures in a small-scale egocentric environment could be more efficient. We believe this is a relevant topic for a follow-up study. One possibility is to provide different modes of interaction so that users can combine them depending on the circumstances, in the same way as they did with exploration modes in this study.

Investigating the effect of alternative environment sizes. It is reasonable to believe that different environment sizes could affect the patterns observed here, as larger environments could make navigation more difficult and smaller ones easier. This should be quantified in future work. However, we hypothesize that the Combined mode will always be a good compromise between manipulation and navigation regardless of environment size.

Investigating differences between standing and seated usage. While in our study users were always standing, another option is to permit the user to remain seated at their work desk [54]. This approach can be more comfortable during long usage periods or when physical movement is not possible. In this case, additional controls and filters on the desk surface could improve manipulation performance, options that could be investigated in future work.

Revisiting cybersickness results. Based on our findings, it is possible that early IA studies might have been overly affected by cybersickness, especially when using large-scale environments. As our results indicate that sickness can be avoided with adequate design choices, revisiting such studies could be a promising direction.

Investigating the effect of presence in IA applications. Our results show that navigation, either physical or artificial, increased the feeling of "being there" in the virtual environment. Additionally, moderate correlations were observed between presence ratings and multiple performance and questionnaire-based metrics. The relevance of the feeling of presence for IA should thus be studied in future work.

7 Conclusion

In this work, we performed a controlled evaluation of two important variables in Immersive Analytics application design: the frame of reference and the exploration mode. Our goal was to derive relevant insights for designers and practitioners in this growing field.

We found that both variables have significant effects on user experience and performance. While an egocentric room-scale environment was less mentally demanding, its exocentric counterpart led to better performance in some cases. Performance and workload were also affected by exploration mode, being improved by the simultaneous availability of navigation and manipulation. User performance was also found to correlate with individual characteristics, such as spatial ability and gaming frequency, confirming prior work [36], [48]. Moreover, all setups avoided simulator sickness, demonstrating the maturity of the adopted techniques and suggesting that previous work which had their results affected by cybersickness might need to be revisited.

Acknowledgments

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