A Comparative Usability Study of Physical Multi-touch versus Virtual Desktop-Based Spherical Interfaces

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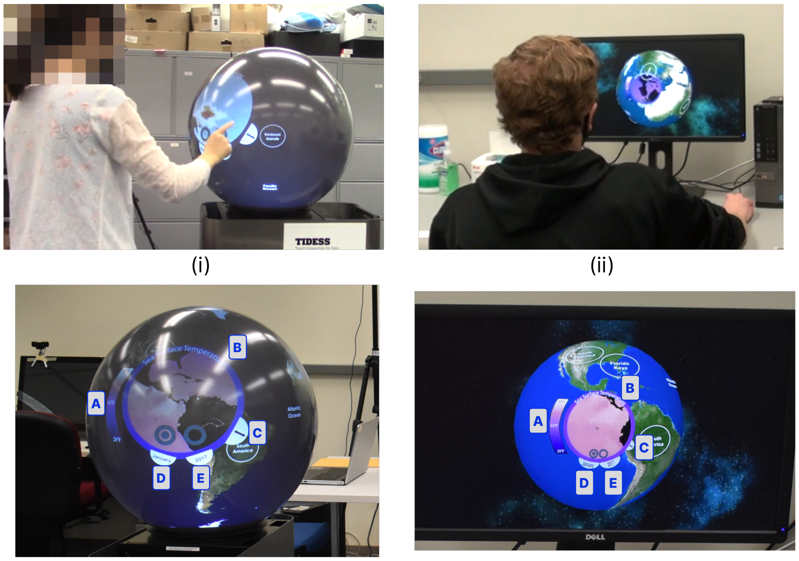

(i) (ii)

(iii) (iv)

Figure 1: Our set-up for (i) physical multi-touch spherical display interface and (ii) virtual desktop-based spherical interface. Zoomed-in view of our Earth's ocean temperature system prototype on the (iii) multi-touch physical and (iv) virtual spherical display (iv) Prototype description: [A] Color Legend to help correlate colors of data visualizations displayed within the maskviewer lens with corresponding temperature values. [B] An interactive maskviewer lens to display data visualizations of sea surface temperature and coral reef thermal stress. [C] Zoom button to adjust the size of the maskviewer lens. [D & E] Month & Year buttons to select a specific month [D] or year [E] for the data being visualized within the maskviewer lens.

ABSTRACT

Physical multi-touch spherical displays can provide a direct, hands-on, embodied interaction experience with global visualization data like ocean temperatures and currents. However, current commercially available displays may be cost-prohibitive for educational institutions and/or non-profits to acquire. Virtual globe-based visualizations like Google Earth are a potential alternative, but it is not clear how well the interactive affordances of physical spheres may transfer to the virtual. We conducted a within-subjects comparative study with 21 participants who completed similar tasks on a physical and a virtual spherical interface platform, which were designed to be as similar as possible, in order to allow us to compare the interaction experiences. Our results overall showed no significant difference between usability or task time on the two platforms. In their qualitative feedback, participants noticed the differences between the physical sphere and virtual sphere in terms of effort and motor demand. Our research implies that, in resource-constrained environments, a virtual globe can be a sufficient substitute for a physical sphere from a usability perspective.

Index Terms: Human-centered computing—Spherical display interfaces—Flatscreen displays—Touchscreens

1 INTRODUCTION

Physical spherical interfaces (Figure 1, i & iii) have emerged in the last 20 years for educational purposes such as in museums and science centers, especially for presenting interactive geoscience data visualizations for Earth science education [28, 45, 50]. For instance, NASA's Space Communication and Navigation Center [28] and Soni et al. [45] publicly deployed a physical multi-touch spherical display to help the general public learn about space exploration and Earth's climate system, respectively. These interfaces allow users to explore different perspectives of global data by physically moving around the sphere and directly manipulating geodata [44, 51]. Prior work suggests that physical spherical interfaces offer

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numerous engagement and educational opportunities for developing geographical thinking within both public and classroom learning environments [40, 45]. However, when considering cost, space, and environment/location, current commercially available physical spherical interfaces are often inaccessible to educational institutions and/or non-profits [20], let alone individuals or K-12 classrooms. Although researchers have developed more affordable options (e.g., for USD $500) for physical spherical interfaces with multi-touch support, significant hardware development efforts in regard to light brightness and resolution are needed before these interfaces can be widely deployed at scale at low-cost options [20].

In contrast to physical spherical interfaces that are distinguished by their spherical form factor and allow users to present and manipulate 3D geodata in its innate form (Figure 1, i & iii), virtual spherical interfaces present 3D geodata on a 2D desktop flatscreen (Figure 1, ii& iv). Virtual spherical interfaces such as NOAA's SOS Explorer [35], Google Earth [24], and NASA World Wind [34] has also been used in museums and classrooms for educational purposes [7]. These interfaces offer potential alternative to physical spherical display interfaces that are not only more cost-effective (e.g., Google Earth is free to access), but are also more mobile and can work on personal devices without the purchase of additional hardware. These factors make them more appropriate for supporting online learning, which has spread widely post-pandemic. The goal of our study is to compare usability differences between physical versus desktop-based virtual spherical interfaces for geodata visualization context. This comparison is important for several reasons. Firstly, despite the known limitations of desktop interfaces, such as a less immersive experience [57] and constrained interaction modalities via mouse and keyboard [54], they are widely used for presenting geodata visualizations due to their affordability, accessibility, and hardware compatibility. This widespread use necessitates a detailed understanding of how these interfaces perform against emerging physical spherical display interfaces for global data context. Secondly, although multiple prior works in IEEE VR and 3D User Interfaces community have compared desktops to VR/AR-based interfaces [23, 27, 36, 57], there is a lack of comprehensive research comparing physical touch-enabled 3D user interfaces such as spherical displays to virtual desktop-based spherical interfaces directly for geoscience data exploration. **Therefore, it remains unclear how the form-factor of spherical interfaces (i.e., physical versus virtual) influences users' interaction experiences during the exploration of geoscience data**. Our study takes a first step toward addressing this research gap. By exploring this comparison, we can assess the trade-offs and user experience differences, enabling researchers and practitioners to make more informed decisions about ways in which the use of these interfaces and the experiences offered by them differ. Understanding usability differences would be especially relevant when practical constraints necessitate substituting physical spherical interfaces with virtual ones and when considering key design questions for porting geodata visualization applications across interfaces. Due to the innate three-dimensional nature of geodata and the opportunities spherical interfaces offer to present this data without map projection compromises [30], geodata visualization offers a unique context for this comparison.

Prior research has compared user interactions with virtual spherical interfaces on different forms of large flatscreen displays (i.e. touch table and touch wall) in geodata visualization context, revealing differences in users' gestural interaction patterns across various touchscreen formats [5]. However, deployment of these large flat-screen displays come with their own size and cost challenges; therefore, desktop-based virtual spherical interfaces emerge as a potentially more practical alternative for widespread implementation. While personal mobile or tablet-based virtual spherical interfaces offer broad deployment possibilities, they have limited screen real estate for visualizing global data as compared to personal desktop-based spherical interfaces. Thus, in our study, we focus on **comparing interaction affordances offered by desktop-based virtual spherical interfaces with physical multi-touch spherical interfaces**. This comparison is crucial, especially in geodata visualization context, where the nuances of interface interaction can impact the user experience of data exploration. Spherical interfaces provide a partial field of view from one location based on users' view, which might lead users to more frequently perform navigation interactions using either a mouse or hand gestures to explore the entire interface [51]. Additionally, physical spherical interfaces offer users the option to move around the display during their exploration, as opposed to remaining stationary when interacting with virtual spherical interfaces [45, 51], and moving the virtual sphere itself. These differences may not only influence users' preferences for physical versus virtual spherical interfaces, but might also present distinct usability challenges, necessitating further investigation. Our intention through this comparison is not to argue for the substituting of physical spherical displays. Rather, our goal is to explore a case where the accessibility of physical spherical displays is difficult and what we might be losing or what we might want to consider when porting existing physical spherical display applications for more easily deployable desktop-based virtual globes.

To this end, we conducted a within-subjects comparative study with 21 participants who completed similar tasks on a physical and a virtual spherical interface (Figure 1), which were designed to be as similar as possible, in order to allow us to compare the interaction experiences. We answer the following key research questions:

- **RQ1**: What impact does the form factor of the spherical interface (physical multi-touch versus virtual desktop-based) have on participants' experiences, considering factors such as task completion time, physical and mental demand, and usability?

- **RQ2**: What are users' subjective preferences when interacting with geoscience applications in these two interaction modes? What aspects do they like and dislike about each interface?

Our results overall showed no significant difference between quantitative measures of usability or task time on the two platforms. In their qualitative feedback, participants noticed the differences between the physical sphere and virtual sphere in terms of effort and motor demand. Based on our qualitative and quantitative analyses, we conclude that using virtual spherical interfaces could be a reasonable substitute for physical multi-touch spherical interfaces when the latter is unavailable, e.g., due to cost issues. However, when it is possible to access physical multi-touch interfaces, our findings show that they offer a more engaging and embodied learning experience.

This work makes two key contributions to the IEEE VR and 3D user interactions research community: (1) empirical evidence and a deeper understanding of usability differences and similarities between physical multi-touch and virtual desktop-based spherical interfaces for geodata visualization exploration, and (2) a set of implications for the design of interactive experiences across the two form factors of spherical interfaces. Researchers within IEEE VR or broader HCI community can use our findings to inform future research comparing physical spherical interfaces to mixed reality VR and VR interfaces for geodata exploration. The design implications drawn from our research will be particularly valuable for designers and developers of future spherical interfaces of both types, especially in the context of geoscience data visualizations.

2 RELATED WORK

We survey related work on (1) physical spherical interfaces with multi-touch support, (2) comparisons of multi-touch interfaces with GUI-based interfaces, and (3) virtual spherical interfaces for geodata exploration.

2.1 Multi-touch Physical Spherical Interfaces

Although not specifically focused on multi-touch spherical displays, prior work has explored interaction design for handheld physical spherical displays [15, 32, 53, 55]. For example, Louis et al. [32] explored a suite of interaction techniques such as selection, scaling, and continuous parameter control, in the context of anatomy learning for handheld perspective corrected spherical display. Their user evaluation with 8 students revealed that users often used physical head movements instead of digital rotations when exploring content with handheld spherical displays. Similarly, Yamashita et al. [53] showed the benefits of using tangible (non-touchscreen) globes coupled with a VR interface for supporting astronomy education and spatial perception. However, we do not yet know if similar would be true for large non-handheld spherical displays with multi-touch capabilities.

More specifically in the context of physical multi-touch spherical displays, multiple prior works have explored the interaction design space for individual and collaborative interaction [10, 13, 50, 51]. In 2008, Benko et al. [10] developed the first physical spherical display and introduced a set of user interactions such as dragging and scaling of objects. Bolton et al. [13] conducted a lab-based study exploring competitive and cooperative tasks on spherical displays. They implemented several software-based "peeking" techniques to allow users to view other parts of the display. Through an in-the-wild study by Williamson et al. [50], the authors examined how supporting different types of interactions affected dwell times at the spherical display: offering more interactive options increased dwell times as users explored more of the features. Yip et al. [55] explored the use of direct manipulative spherical displays for presenting geospatial internet data traffic, and discussed the benefits of spherical nature of the display to present global data. Englmeier et al. [22] conducted a study with 26 participants to compare task performance across three different conditions: a fixed physical sphere, a physical sphere that could be rotated, and an entirely VR-based spherical interface. The findings indicated that the physical sphere with rotation capability led to more accurate results and faster completion of tasks. Furthermore, participants noted reduced mental and physical strain, workload, effort, and frustration when using the rotatable physical sphere. Soni et al. [43] compared users' interaction design behaviors and mental models for flatscreen tabletop versus multi-touch spherical displays, with both children and adults. They found that the spherical form factor influenced users' gesture design decisions: users were more likely to perform multi-finger or whole-handed gestures on the sphere than in prior work on tabletop displays [43].

All of the above-mentioned studies were conducted in the context of application-agnostic interactions, such as dragging an object, and did not necessarily require users to perform these interactions in context, such as when interacting with geodata visualization tasks. Vega et al. [47] explored challenges and opportunities for designing geodata visualization applications for physical spherical interfaces, and proposed design considerations including layout, content presentation, color, and font aesthetics. In another study, Soni et al. [45] deployed a large multi-touch spherical display prototype about Earth's climate system in a public science musuem to investigate the natural group collaboration behaviors of multi-generational families when exploring global data visualizations. However, this prior work mainly focused on group collaboration dynamics in informal learning settings, and did not delve into investigating the physical or mental efforts required from users when answering geodata visualization questions on a touchscreen spherical form factor. Our work adds to this body of literature by comparing interaction experiences across physical and virtual spherical interfaces for geodata tasks related to exploring sea temperature and coral reef data across global space and time.

2.2 Multi-touch Interfaces versus GUI-Based Interfaces

Much prior work has empirically compared direct-manipulation interfaces such as tangibles or touchscreens to indirect-interaction interfaces such as mouse and keyboard [17, 46, 56]. Travis and Murano [46] conducted a within-subjects study with 30 participants to test the effectiveness and user satisfaction of touch-based interaction compared to mouse-based interaction for equivalent tasks (i.e., drag and drop, point and click, and more contextualized bicycle assembly tasks). The analysis included comparing task error, task time, and user satisfaction for both conditions. The results of the study showed that the GUI condition resulted in less error and task time for accuracy-based tasks (e.g., point and click) as compared to the touchscreen condition. Since this work was conducted in the context of small-screen tablet touchscreens, Travis and Murano [46] called for more comparative studies in the context of large touchscreen displays of different ergonomics (e.g., interactive tabletop and wall displays) versus GUIs.

In another study, Yu et al. [56] compared the user experience of online exhibitions in two different interface modes with 18 adults: desktop GUI versus touchscreen tablets for exhibit navigation tasks. Based on their analysis of usability, immersion, and task time, the authors found that task time was higher for tablet touchscreens versus GUIs, whereas usability and immersion were better for the direct-manipulation tablet condition. Similarly, Chandrasekera and Yoon [17] conducted a study with 30 adult users to examine the impact of GUI-based and Tangible User Interfaces (TUI) on cognitive load during the creative design process for an educational task. The authors found that cognitive load was lower in the TUI condition compared to the GUI condition.

In a study more closely related to our context of geodata, Beheshti et al. [9] compared a large flat touchscreen tabletop display to GUI-based interfaces for map exploration and navigation tasks. They found no significant difference in performance between the two conditions. Anthony et al. [5] compared 30 children's and 27 adults' gestural interaction patterns with Google Earth virtual spherical interfaces deployed on a touch table versus a touch wall. In their findings, the authors found that users were more likely to perform two-handed, multi-touch gestures on the touch wall than on the touch table. However, it remained uncertain whether similar results would hold for virtual spherical versus physical spherical interfaces, due to established differences in ergonomics and form factor between flatscreen and spherical interfaces [5, 43].

Although the aforementioned studies provide important insights into how different types of tangible/touchscreen and GUI interfaces can influence user interaction experiences, the majority of this work has focused on comparing flatscreen displays and maps, with little emphasis on novel 3D user interfaces such as physical spherical displays. Our work adds to this body of literature by providing a new understanding of the impact that the form factor of the spherical interface (physical versus virtual desktop-based) has on participants' experiences, using classic validated usability measures in HCI such as task completion time, physical and mental demand, and usability, as well as users' subjective preferences.

2.3 Virtual Spherical Interfaces for GeoData Exploration

In the context of virtual spherical interfaces, multiple studies have investigated the impact of virtual globes such as Google Earth or NASA World Wind on students' spatial thinking [18, 39]. For instance, Clagett [18] conducted a study with 70 sixth-grade students (age 11-12) to understand their learning experiences with Google Earth for spatial thinking. Although the findings of the study did not demonstrate that Google Earth encouraged higher-order spatial thinking better than paper maps, the author found that exercises were more memorable to students who used Google Earth. The paper also called for future work to do "a comparison of what and how students learn from a variety of different geospatial technologies."

Before educational technologies are integrated into learning environments, it is crucial to design the interactions they facilitate to be intuitive and provide an optimal user experience, to ensure that the interface interaction experience does not hinder learning [4,41]. Our study adds to this existing body of literature on virtual and physical spheres by comparing the differences in interaction experiences with spherical interfaces for the specific task context of geodata exploration. This comparison will provide valuable design insights to consider when developing future geodata educational applications for spherical interfaces.

3 METHOD

We present a within-subject study involving a physical sphere and a virtual sphere in a geospatial data context. The main goal of our study was to understand the similarities and differences in usability experiences between a touch-enabled physical spherical interface versus a GUI-driven virtual sphere interface.

3.1 Tasks

We designed two sets of five tasks (one warm-up, and four information-seeking tasks) for use during our study. The tasks were designed to allow us to compare the user experience between the physical and virtual platforms for the same types of interactions. Table 3 lists the exact wording of the tasks in each set that participants were given, and the rationale for each task choice.

3.2 Participants

A series of five pilot participants helped us test and improve our study protocol but were not included in the analysis. A total of 21 participants took part in our full study. They self-identified as female (5), male (15), or non-binary (0), and ranged in age from 19 to 28 years (mean = 21.2 years, SD = 2.17 years). Based on our IRB protocol, each participant in our study was assigned a random identification number or PID, as listed in Table 1 (e.g., 770). Because height may affect participants' experiences with the physical sphere, we also asked for their height in inches. Self-reported heights of our participants ranged from 59 to 72 inches (mean = 66.8 inches, SD = 3.87 inches). Two of our participants were left-handed. No participants identified as colorblind, and all but one had normal or corrected-to-normal vision[1]. The participants in our study were undergraduate and graduate students at our university who earned extra course credit for their participation.

Based on the demographics questionnaires, participants in our study had extensive interaction experience with touchscreen smartphones (e.g., 21 out of 21 rated their touchscreen phone use as "daily/often") and tablets (e.g., 20 participants rated their usage of touchscreen tablets as "sometimes" or "daily/often"). Few participants had such extensive experience with other types of touch interaction devices (e.g., touchscreen laptops (14), touch tables (0), touch walls (0), and touchscreen spherical displays (0)). Most participants (17 out of 21) also rated their usage of non-touchscreen computers in general as "daily/often." Regarding input modalities on computers like the one they used in our study to access the virtual globe, most participants (19 out of 21) rated their usage of trackpad interaction as "daily/often," while only 1 participant regularly used track-point style interaction. Most participants also regularly used external mouse interaction (like the mouse in our study); 12 said they use it "daily or often" and 8 said they use it "sometimes". About half of the participants (12) in our study rated themselves as having "average" familiarity with virtual globes, and nearly all (18) rated themselves as "beginners" with physical spherical displays.

PID	#	Gen	Age	Height	Hand	Vision	Pref
770	1	F	21	64	R	NOR	PHY
588	2	M	20	72	R	NOR	VIR
621	4	F	19	67	R	NOR	PHY
779	3	M	22	71	R	COR	VIR
7	1	F	28	62	R	NOR	VIR
639	2	F	20	62	R	NOR	VIR
16	3	M	20	-	R	NOR	VIR
452	4	M	21	70	R	NOR	VIR
53	1	M	23	68	R	NOR	PHY
189	2	M	20	68	R	NOR	PHY
504	3	M	24	68	R	NOR	PHY
262	4	F	22	59	R	NOR	PHY
813	1	M	21	67	L	NOR	PHY
626	2	M	20	71	L	NOR	PHY
431	3	F	19	63	R	NOR	VIR
479	4	M	19	60	R	NOR	PHY
537	1	M	19	66	R	NOR	VIR
138	2	M	21	70	R	NOR	PHY
943	3	M	22	70	R	NOR	-
925	4	M	23	68	R	NOR	VIR
596	1	M	20	70	R	NOR	PHY

Table 1: Summary of Participant's demographic data. The data points from L-R include: participant ID, Task group number (from Table 2), reported gender identity [Male (M), Female (F)], age, height (in inches), dominant hand [Left (L), Right (R)], vision class[Normal (NOR), Corrected (COR)], and preferred sphere type [Physical (PHY), Virtual (VIR)]

3.3 Apparatus: Equipment and Data Collection

In this section, we describe the apparatus (i.e., physical sphere, desktop computer), our prototype applications, and data collection methods used in the study.

Physical Multi-touch Spherical Interface: The physical sphere used in this study is a PufferSphere from Pufferfish Ltd. [37]. It is 24 inches in diameter, placed on a base pedestal approximately 34 inches in height, and operated in a standing position, as seen in Figure 1 (i & iii). This display employs internal cameras to detect touches on the sphere's exterior interface, allowing for multi-user, multi-touch interactions to occur simultaneously [1]. The touch data is made accessible through TUIO (tangible user interface) protocol events [29]. Our prototype application is designed to listen for these events and interpret them as individual touches on GUI elements. It can also combine them into more complex gesture interactions from one or more users as needed, enabling it to respond appropriately to user interactions. The physical sphere supported the following interactions: move earth (drag), select dataset/open timeslider (tap), and change months on timeslider (drag a finger along the timeslider).

Virtual Spherical Interface: Our implementation of the virtual sphere involved running a 3D globe simulation via a Unity prototype. The software was run on a Windows 10 desktop with a keyboard and mouse for interaction. The participants interacted with our virtual spherical interface prototype while seated in front of a 24-inch monitor. The possible interactions for the virtual sphere included: move earth (hold the left mouse button and move the mouse), select dataset/open timeslider (left click), and change months on timeslider (hold the left mouse button and drag the mouse along the timeslider).

Prototype Applications: Both the physical and spherical interface prototypes were designed to be as similar as possible. Our prototype applications provided users with the opportunity to explore two visualization datasets of Earth's ocean temperature system: baseline ocean temperatures and coral reef heat stress, from NOAA's SOS Dataset [2]. To facilitate user exploration of the temperature data, our application incorporated an interface element known as a "maskviewer" lens (Figure 1, iii, [B]). The maskviewer lens displays a portion of one of the two ocean map view datasets that would be

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[1] This participant indicated they were not wearing their glasses, but that they didn't feel this impacted their interaction with the prototypes.

Task Group No.	**Block 1**	**Block 2**
Group 1	Task Set 1-Physical	Task Set 2-Virtual
Group 2	Task Set 1-Virtual	Task Set 2-Physical
Group 3	Task Set 2-Physical	Task Set 1-Virtual
Group 4	Task Set 2-Virtual	Task Set 1-Physical

Table 2: Participants completed both task sets in two blocks: one on the physical sphere and one on the virtual sphere. Order was counterbalanced across both platforms (condition) and task sets. See Table 1 for group assignments for each participant.

visible beneath it. Previous research has found that such maskviewer lenses can help users to focus on part of the data visualization at a time so that users can build their understanding piece by piece across space [42]. The interactive maskviewer could be dragged and resized. Users could switch between datasets by clicking on the toggle buttons on the lens. Additionally, our applications included a time slider that allowed users to interactively explore continuous temperature changes for different geographic locations over different months for a specified number of years. Users could activate or deactivate the time slider for months or years by clicking on a "Month" or "Year" label on the maskviewer lens. Once the time slider was activated, users could drag across the slider to adjust the month or year as required. To assist users in distinguishing between the two datasets, the lenses included appropriate labels and legends. The base earth map also featured six continent hotspots that, when tapped, reveal an information box about each continent. The prototype also allowed users to rotate the sphere in all three directions, similar to the movement of a physical model of the Earth. This could be accomplished either by dragging on the physical sphere or using a mouse on the virtual sphere.

Both physical and virtual spherical interface prototypes captured detailed touch logs including touch coordinate sequences, which interface elements users were interacting with, and related timestamps. All study sessions were video and audio recorded with two external cameras. We also used the Open Broadcaster Software (OBS) [3] to screen-record each participant's interaction with the virtual sphere in a video format (.mp4). No screen capture software was available for the physical sphere. Qualtrics XM [38] was used as a survey tool to collect participant demographics, SUS, NASA TLX, open-ended voluntary question responses, and session debrief information.

3.4 Procedure

At the beginning of each study session, a researcher explained the study procedure to the participant and sought informed consent before starting. During the study, participants interacted with both platforms to complete several assigned tasks. We had two task sets designed to be isomorphic in complexity to each other. Each task set included one open-ended warm-up task, lasting about 5 minutes, and four information-seeking tasks, lasting about 10 to 15 minutes total. Participants were given small slips of paper with each task printed on them to refer to during the study. Participants first interacted with either the physical sphere or the virtual sphere to complete one task set, and then interacted with the other platform to complete the other task set. The order of task sets and platforms was counterbalanced as shown in Table 2. After each task set/platform, we asked participants to complete several questionnaires to rate their experience with that platform, including the NASA-TLX questionnaire [26], the System Usability Scale (SUS) [6], and two open-ended questions asking about their likes and dislikes of the interface. At the end of the study, the participants filled out a demographics survey which also included questions about their experience with various interactive technologies related to this study. Finally, the participants were asked about their preferences between the two platforms. Our study protocol was approved by our Institutional Review Board (IRB).

3.5 Measures

We collected several sources of quantitative data during and after participant interactions with our prototypes.

Time on Task. To identify how long each participant spent performing each of the five tasks (including the warm-up task) for each platform, we reviewed the video recordings we collected. We annotated the START and END of each of the tasks relative to the start of the video file for each participant and computed the total duration of each task as the difference between END and START. We also computed the total time for each participant on each platform by summing the time duration for all tasks. Video recordings for 1 participant were unavailable due to technical issues with the recording process, and one remaining participant's video unexpectedly ended after the start of Task 3 for the virtual sphere, so this analysis is based on 19 or 20 participants only.

NASA-TLX. After completing the four tasks in a set, the participants completed the NASA-TLX questionnaire to rate their subjective workload. The questionnaire consisted of 15 pairwise combinations to assess which factor had the most effect on the workload. It also included 5 questions in which the user rated the factor's presence in the study on a scale of 0 to 100. Some participants did not answer all the questions, so analysis for Temporal Demand and Performance are based on 20 participants total; the other four dimensions include all 21 participants.

System Usability Scale (SUS). Our survey further incorporated 10 items from the standard System Usability Scale (SUS) questionnaire to evaluate the usability of our prototypes. The participants ranked their preference of the system on a scale of "Strongly Disagree" to "Strongly Agree", which we converted to a 1 to 5 scale for analysis. Data for all 21 participants was complete for this analysis.

Demographics and User Preferences. After the session, the participants completed a demographics questionnaire, which included questions about gender identity, age, education level, occupation, major, height, vision, color blindness, and handedness. They were also asked which interface they preferred, if they noticed any differences between the platforms, and if they had anything in particular that they liked or disliked about their interactions with the sphere. They were asked to rate the frequency of their use of a variety of touch- and non-touch-enabled devices and platforms (e.g., "I have never heard of it", "I have never used one", "I have tried it once or twice", "I use it sometimes", and "I use it daily/often"). Finally, the participants were asked to self-rate their own familiarity with touch interaction, mouse interaction, virtual spheres, and spherical displays (e.g., "beginner," "average," or "expert"). Data for all 21 participants was complete for this analysis.

3.6 Qualitative Data Analysis Method

To analyze the questionnaire responses addressing user preferences for physical versus virtual spherical interface, we conducted a qualitative data analysis using standard data coding and thematic analysis techniques [14]. Due to the brevity and objective nature of the responses, a single researcher handled the qualitative analysis [33]. The first step involved the researcher creating a syntax guide by going through the responses to identify relevant codes as well as dimensions to group them by. An additional researcher helped in spot-checking the main codes to ensure they mapped sufficiently to our quantitative measures. Finally, the researcher qualitatively coded the responses for each participant according to the syntax guide and performed 2 additional iterations to synthesize the results until they provided sufficient details at a minimal length.

4 RESULTS

Next, we discuss the results of our quantitative and qualitative data analyses.

Task	Task Set 1	Task Set 2
Warm-Up	Exploration and think-aloud: the user rotates the globe and moves the default lens (sea surface temperature).	
	”This is a warm-up activity. It is time for you to explore and think aloud as you use the globe. In particular, determine the sea surface temperature of the water near the northeast coast of Australia (e.g., Cairns). Let me know when you have completed this activity and feel ready to move on.”	”This is a warm- up activity. It is time for you to explore and think aloud as you use the globe. In particular, determine the sea surface temperature of the water near the south-west coast of Europe (e.g., Spain). Let me know when you have completed this activity and feel ready to move on.”
Task 1	Information box: (a) the user rotates the globe, (b) the user clicks a button, (c) the user reads and understands the information box.	
	”Rotate or move around the globe so you can see Asia. Click on the word that says “Asia” so that the information box appears. State the region that is drier than average during El Niño.”	”Rotate or move around the globe so you can see South America. Click on the words that say “South America” so that the information box appears. State the region that is drier than average during El Niño.”
Task 2	Dataset understanding: (a) the user uses the lens to access a different dataset, (b) the user reads several pieces of information from the lens.	
	”Locate the coral bleaching lens. According to the legend, what color indicates the lowest heat stress depicted in the lens? Please also state what month and year are currently displayed in the lens.”	”Locate the coral bleaching lens. According to the legend, what color indicates the highest heat stress depicted in the lens? Please also state what month and year are currently displayed in the lens.”
Task 3	Global navigation: (a) the user rotates the globe and moves the lens, (b) the user changes the information timeline, (c) the user interprets a dataset.	
	”Bring the sea surface temperature lens to the Gulf of Mexico (the area between Florida and Texas/Mexico). After you’ve done so, change the lens view to show March 2018. Which area has the warmest temperatures?”	”Bring the coral bleaching lens to the Indian Ocean (the area off the coast of Asia). After you’ve done so, change the lens view to show June 2019. Which area has the highest heat stress?”
Task 4	Comparing multiple datasets: (a) the user looks at multiple datasets (months) and compares the information.	
	”Compare sea surface temperatures for January, February, March, April, May, and June in 2017 in the Gulf of Mexico. What did you observe?”	”Compare sea surface temperatures for January, February, March, April, May, and June in 2018 in the Indian Ocean. What did you observe?”

Table 3: Our two task sets progressing from a warm-up task to more complex tasks requiring interaction with specific parts of the interface.

4.1 Time-on-Task Results

We compared the overall time on task that participants spent using the virtual sphere versus the physical sphere, as measured from the videos. A paired-samples t-test of the cumulative time across all four tasks showed a marginal significant effect of platform (t(18) = 2.03, $p < .055$). The average time spent completing the tasks with the virtual sphere was 7.5 minutes [SD = 4.0], and in the physical sphere it was 9.3 minutes [SD = 3.4]. Table 4 displays the mean and standard deviation of each task in minutes (N=20 for warm-up, Task 1, and Task 2; N=19 for Task 3 and Task 4 Paired-sample t-tests showed that there was a significant difference in time on task for Task 3 (t(18) = 4.53, $p < .001$), and Task 4 (t(18) = 3.80, $p < .001$), but not the other tasks.

4.2 NASA-TLX Results

We used the NASA-TLX analysis spreadsheet tool from Virtanen et al. [48], which computes raw and weighted scores for each of the six workload dimensions: mental demand, physical demand, temporal demand, performance, effort, and frustration. As those authors recommend, we use the raw TLX scores rather than the weighted scores because there is a high correlation between the two indices. We used paired-samples t-tests to compare the overall within-subjects means of the workload scores between platforms (physical versus virtual sphere), shown in Table 5. We found a significant difference for Mental Demand by platform: the physical sphere was rated as imposing a higher mental demand than the virtual (t(20) = 2.98, $p < .01$). Participant ratings were also significantly higher for the physical sphere than the virtual sphere for Physical Demand (t(20) = 4.53, $p < .0001$). Participants also rated their Effort slightly higher for the physical sphere than the virtual sphere and the t-test showed a marginal difference (t(20) = 2.03, $p = .056$). The other three dimensions showed no significant difference by platform.

	Physical Sphere	Virtual Sphere
Warm-Up	02:02 [01:12]	02:16 [02:04]
Task 1	01:11 [00:33]	00:59 [00:28]
Task 2	01:16 [00:40]	01:10 [00:52]
Task 3*	02:11 [00:47]	01:27 [00:33]
Task 4*	02:32 [01:43]	01:32 [01:11]
Overall	09:19 [03:21]	07:29 [03:59]

Table 4: Time-on-task measurements overall and per task by condition. Rows marked with a * are significantly different at the $p < .01$ level. SD in square brackets.

	Physical Sphere	Virtual Sphere
Mental Demand*	67.86 [21.13]	56.19 [19.68]
Physical Demand*	42.62 [25.67]	16.43 [23.30]
Temporal Demand	28.25 [25.41]	26.00 [20.04]
Performance	74.75 [16.02]	80.00 [19.67]
Effort	55.48 [24.08]	46.43 [19.95]
Frustration	45.71 [30.47]	39.29 [27.99]

Table 5: NASA-TLX scores by condition. Rows marked with a * are significantly different at the $p < .05$ level. N is 21 for all measures except Temporal Demand and Performance, for which one participant each declined to answer (N = 20).

4.3 System Usability Scale (SUS) Results

We first converted the System Usability Scale (SUS) scores to the same direction (e.g., question #1 was positive so 1 was subtracted from each value, whereas question #2 was negative so the value was subtracted from 5). A rating of 5 corresponded to “Strongly Agree”. Then, all normalized scores were summed up across all 10 questions, and multiplied by 2.5 to scale the values out of 100. A paired-samples t-test between the within-subjects overall SUS scores by platform showed no significant difference (t(21) = 0.46, *n.s.*). The average SUS score for the physical sphere was 60.48 [SD = 14.97] and for the virtual sphere it was 62.74 [SD = 18.04]. Table 6 shows the raw average ratings across participants on each statement of the SUS, compared by platform. Overall, participants rated both platforms as having similar usability for most statements, though some trends show that the physical sphere was rated a bit lower than the virtual (e.g., see statements 1, 4, and 8).

SUS Question	Physical	Virtual
+1. I think that I would like to use this system frequently.	2.95 [1.07]	3.24 [1.09]
-2. I found the system unnecessarily complex.	2.67 [0.91]	2.57 [1.16]
+3. I thought the system was easy to use.	3.57 [0.98]	3.24 [1.18]
-4. I think that I would need the support of a technical person	2.19 [0.98]	1.81 [0.81]
+5. I found the various functions in this system were well integrated.	3.29 [0.85]	3.33 [1.02]
-6. I thought there was too much inconsistency in this system.	2.67 [1.11]	2.43 [1.03]
+7. I imagine that most people would learn to use this system	3.76 [0.94]	3.71 [1.01]
-8. I found the system very cumbersome to use.	3.10 [0.89]	2.95 [1.02]
+9. I felt very confident using the system.	3.43 [0.93]	3.52 [0.93]
-10. I needed to learn a lot of things before I could get going with this system.	2.19 [0.87]	2.19 [1.03]

Table 6: System Usability Scale (SUS) scores averaged across participants. Participants rated each statement on a scale of 1 to 5, with 5 being the highest, as to how much they agreed with each statement. Statements 1, 3, 5, 7, and 9 are interpreted as *higher* scores being better for usability; whereas statements 2, 4, 6, 8, and 10 are interpreted as *lower* scores being better for usability.

4.4 Qualitative Questionnaire Findings

Next, we present qualitative analysis of the participants' questionnaire responses.

4.4.1 Self-reported Preferences for Physical or Virtual Sphere

After interacting with both spheres, each participant was asked to specify which platform they preferred in a close-ended question. The majority of our participants (12, 57.1%) stated they preferred the physical sphere over the virtual sphere (8, 38.1%), while a single participant (1, 4.8%) was indifferent in their response. Next, we delve into possible reasons for this preference based on participants' subjective responses.

4.4.2 Identified themes from qualitative responses

1. **Hands-on experience interacting with both spheres:** Approximately half (57%) of the participants expressed a key emotional impression while interacting with each sphere type. They were particularly excited by the **novelty** (71%) and **tangible** (76%) nature of the physical sphere: P452 said, *"all of [my] senses were...attracted towards it, in a way, because...it's in the physical form."* The participants expressed **content** with the virtual sphere (71%): P626 said, *"the virtual one was fine, like it would get the job done..., [the physical sphere] would just be really cool to have...it's a very interesting and very real way to interact with the globe."*. More specifically, the participants generally considered the hands-on experience offered by the physical sphere to be a positive element that increases the perceived level of engagement with the system. As said by P588, *"[even] if you're not interested in sea temps, being able to interact with the globe might draw you in."*.

When interacting with the physical sphere, participants commented on its **physical size** (14%), **touch sensitivity** (24%), and discussed **leveraging prior experience and a possible learning curve** (10%). In terms of size, some participants commented liking the size of the spherical display, which they perceived to be large. In the words of P639, *"it was just...nice to...see everything, it was very...large visually, easy to navigate."* This feedback was provided without any prompts. In addition, some participants discussed the high touch sensitivity of the physical sphere's interface, leading to accidental touches (24%). P431 said, *"With the physical globe, I had more accidental" interactions, or more so unintentional [interactions] where I was clicking, trying, experimenting to do things."*. When interacting with the desktop-based virtual spherical interface, our participants found it to be familiar (38%), For example, P596 said"the flat display...[was] very similar to programs that already exist such as Google Earth...[which] we're already kind of used to.". On the other hand, when interacting with the physical spherical interface, participants had a stronger learning curve and sometimes felt they were unfamiliar with the way interactions might work on the physical sphere.

Another unique aspect of interacting with the physical sphere versus virtual was the physical sphere's affordance of supporting **physical movements** around it. Multiple participants (76%) liked being able to move around and explore. P626 says, *"you could just walk around and it was a more a positive experience"*. However, a few (19%) commented on feelings of disorientation on the map, as P007 said: *"I need[ed] to move around, and try to...locate the different place[s]...so sometimes I lost track."* No participant commented about disorientation for the virtual sphere. This could be related to more degrees of freedom offered by the physical sphere (being able to rotate and move around) versus by virtual sphere (being stationary and scrolling).

Overall, the above feedback illustrates that participants had a positive first impression of the physical sphere's form factor in terms of tangibility and physical movement involved while highlighting some limitations related to high touch sensitivity and losing track of map locations.

2. **Comparing Perceived Efficiency:** We saw participants comment on the nature of physical demands needed to interact with the physical and virtual spheres. Although physical sphere allowed participants to explore the entire application while standing in one place, many participants liked walking around (76%), which could have contributed to more **exploration time and physical demand**: P621 noted, "[I] like[d] being able to walk around things.", while the virtual sphere was seen by some (33%) as requiring a lower degree of physical demand: P138 said, "using the mouse and just scrolling, I feel like we're so used to using the mouse." In contrast to liking the interactions afforded by the physical sphere for being more realistic for 3D rotation, several participants (33%) discussed the input method of interacting with the virtual sphere as being less realistic for 3D rotation. For example, P053 says: *"It [physical] felt more fluid here, because you could [move] the sphere and not take your hand off of it. Whereas here [virtual], if you wanted to move the lens and turn the globe you had to move it [the lens], turn the globe, and move it [the lens again]. It just felt broken apart and just cumbersome to use."* They mentioned feeling limited by having to use a keyboard and mouse combination to interact with a round and rotatable object such as a sphere, because they do not easily allow motion in the style of 3D rotation. P504 criticized the navigation of the virtual sphere, saying, *"I didn't know how to move it in three [dimensions] using just left and right [with the mouse]."*

We also found some participants (24%) discussing perceived differences in task completion times across physical versus virtual spheres. They mentioned finding it faster to complete tasks on the virtual sphere as compared to the physical sphere. For example, P007 said, *"[the] virtual sphere was...very handy, and you can just try to find the different place[s]...just use the mouse easily and quickly."*.

In summary, while the quantitative results do not show a significant difference in the task completion time of both spheres, the participants' self-reported feedback indicates a difference in the perceived speed and perceived task-completion time of both spheres; where participants found the virtual sphere to be faster.

5 DISCUSSION

Prior work discusses how tangible interactions could provide benefits compared to other interaction styles [22], including mouse and keyboard-based. Englmeier et al. [22] compared interaction differences between VR and TangibleSphere, a trackable low-cost physical sphere, in terms of accuracy and task completion times. The authors found that being able to physically rotate a spherical interface significantly improves task time and accuracy [22]. In contrast to Englmeier et al. [22] where the authors asked participants to complete application-agnostic precision tasks involving target selection and alignment, our results with exploratory geodata visualization showed no significant difference in quantitative usability measures or overall task time between physical and virtual spherical interfaces. Note, however, that the mean task times for Tasks 3 and 4 (Table 4) were statistically significant (with paired t-test p-values of 0.0001 and 0.0009, respectively), and warrant further discussion. For both tasks, participants took longer to complete the task with the physical sphere than with the virtual sphere. Task 3 involved rotating the globe, moving the lens, changing the information timeline, and interpreting the dataset. During this task, we observed that some participants physically moved around the sphere to evaluate temperature patterns across the Gulf of Mexico or the Indian Ocean. This behavior could have impacted participants' task completion times, but not necessarily their ability to complete the tasks. Task 4 required the user to examine multiple datasets (across months) and compare the temperature patterns. Feedback responses and videos both indicate that participants sometimes struggled to quickly locate and manipulate the time slider to display the datasets across months or years, thereby impacting their task. One reason for the longer time taken by users for Task 4 on the physical sphere compared to the virtual sphere could be touch sensitivity issues on the physical sphere: due to the use of camera-based technology to detect touch input, the physical sphere interface sometimes reacted to hovers when a user's hand got close enough to the surface. A similar issue has been noted in prior work on large touchscreen tabletop displays [52], which frustrates users who are trying to point at the interface without activating it. Next, we discuss important design implications to keep in mind when designing future physical spherical interfaces or when porting applications across form factors.

5.1 Users' Subjective Preferences for Physical Multi-touch versus Virtual Spherical Interface

Multiple previous research comparing graphical user interface (GUI) and flat touchscreen tablet interfaces have indicated a user preference for touch-based displays, largely due to the hands-on, tactile experience that touchscreens provide [17,46,56]. Our findings extend this prior work in the context of the spherical form factor by confirming participants' subjective preference for physical spherical interfaces as compared to virtual spherical interfaces, especially in the context of geodata visualizations. Despite our quantitative and qualitative analyses showing that the physical spherical interface imposes more physical and mental demands (Table 5), our qualitative analysis showed that the majority of our participants still preferred physical over virtual spherical interfaces for geodata exploration. As evident from their quotes, this preference was primarily driven by the hands-on touch experience and the ability to physically navigate around the sphere during exploration. Physical spherical interfaces, as compared to GUI-based virtual spherical interfaces, allow a higher degree of interactive freedom, both in terms of touch input and physical movement around the sphere. However, the degree of this physical interactivity can sometimes place additional mental and physical demands on users if not properly considered during application design. Especially in the context of educational applications, the designers should aim to minimize the physical and mental efforts needed by the users so that they can focus on the learning task at hand [4,41]. For instance, in our study, some participants appreciated the ability to move around the sphere, but they also mentioned occasional disorientation and difficulty in locating their position on the map and resetting it to their desired location (e.g., the quote in which P007 said, *"[I] had to move around, so [I] sometimes lost track."* Which might have led participants to need to perform more motor interactions or gestures to re-orient the map according to their needs, hence leading to their perceptions of increased physical effort. Taken together, these observations suggest the need for **more intentional design practices for physical spherical interfaces that include providing continuous feedback about the spherical interface's orientation and the user's position on the map**, in order to enhance the user experience and reduce the physical and mental load. For example, designers might consider adding an orientation axis that users can toggle on or off as per their needs, or implement an explicit method for resetting sphere rotation through gestural input.

5.2 Ergonomic Needs of Physical Spherical Interfaces

Ergonomics in HCI focuses on the design and arrangement of computing interfaces with the goal of maximizing productivity by reducing fatigue and discomfort [21]. Over time as technology evolved, the focus within HCI shifted towards designing interfaces that are both more user-friendly as well as less physically and mentally taxing [16,25]. Principles of human ergonomics can significantly influence the types of interactions that users find comfortable and intuitive across different touchscreen platforms [5]. For instance, prolonged horizontal extension of one's arm can result in an uncomfortable sensation often referred to as "gorilla arm," noted in several studies of touch-enabled wall displays [31,49]. Wang and Ren [49] have pointed out that arm fatigue is a significant drawback of multi-touch interaction, with the issue becoming more pronounced as the size of the display increases. Given the prevalent issue of arm fatigue, along with the increasing use of larger touch display interfaces such as physical multi-touch spherical displays, it becomes crucial to investigate how interface design can be optimized to reduce user fatigue and accommodate a wide range of ergonomic adjustments, including for wheelchair users or for those who are blind or have low vision [19]. In the context of our study comparing physical and virtual spherical interfaces, all participants were seated during their interaction with the virtual spherical interface, and all stood while interacting with the physical spherical display. The height of our spherical display was 34 inches. Although none of the participants in our study specifically mentioned arm fatigue, we did observe interaction methods with the sphere that could potentially lead to body fatigue. For instance, some taller participants experienced difficulty interacting with the sphere, as they had to bend down to use gestures for moving the lens, information boxes, or for general interaction with the sphere (Figure 2). Hence, when designing physical spherical interfaces, these notes suggest that **the gestural input space must aim to support the physical ergonomic needs of users of all heights and abilities**. For example, the visual layout of the interface could be adjusted to accommodate users of different heights. Additionally, designers can also consider providing alternative input methods, such as using a combination of voice and gestural input could lessen the dependence on physical gestures alone and take into account potential arm and body fatigue during extended interactions. Prior work on multi-modal speech and gesture interactions on large flatscreen displays could be leveraged to inform future work on designing multi-modal interactions for physical spherical displays [11].

5.3 Are Virtual Spherical Interfaces a Viable Alternative?

Taking everything together, **we suggest that virtual spherical interfaces may function as a viable alternative to physical multi-touch spherical interfaces when the latter is not accessible due to cost, space, environment, and other constraints. We make this**

Figure 2: One of our study participants (height: 5 feet 11 inches) bending and arching their back while interacting with the maskviewer lens on the physical sphere.

claim based on our findings on usability and user preferences for exploratory geodata visualization tasks which required participants to retrieve data patterns and make interpretations across space and time. When physical spherical interfaces are available, however, our qualitative findings show that they offer a more engaging and embodied experience. Engagement and embodiment might be important to consider in an educational context [12, 42]. This perspective aligns with Baumer and Silberman's [8] argument in their paper, in which they urge HCI researchers and practitioners to critically evaluate the suitability of technology in a given context. They propose a shift from a "problem-solution" paradigm to a "situation-intervention" approach for technology application, emphasizing the importance of context and appropriateness in technology use. Thus, we recommend that the choice between virtual and physical interfaces should be guided by this situation-intervention framing, considering all relevant factors such as availability, cost, and the nature of the learning experience.

6 FUTURE WORK AND LIMITATIONS

Our findings highlight how virtual desktop-based spherical interfaces can provide a usability experience similar to that of physical multi-touch spherical interfaces. However, in their subjective responses, participants generally preferred the embodied touch and physical movement experience offered by the physical spherical display.

Desktop-based virtual spherical interfaces, such as Google Earth, first launched in 2005 [24], have also been around for much longer when compared to multi-touch spherical displays, which have only recently become commercially available and deployed in public spaces [28, 45]. As a result, participants in our study had no prior experience with physical multi-touch spherical interfaces. Although we asked all participants to complete a trial task on both the virtual and physical interfaces before the start of the main study to level the field, participants' greater prior experience with desktop-based interfaces could have influenced their task time and effort. In future work, researchers could conduct a comparative longitudinal study to provide a more comprehensive comparison of the interaction experiences during geodata exploration between the virtual and physical spherical interfaces. Another limitation in this study is the observed variables (based on user preferences and time on task), we recommend future work to go beyond those variables and consider exploring the quality and correctness of the completed tasks to confirm if our findings hold. Additionally, In our study, the physical spherical interface utilized camera-based technology to detect touch input. This occasionally caused the interface to react to hovers when a user's hand came close enough to the surface, and could have influenced their perceptions of the usability and effort required. Finally, the spherical display used in our study was large, with 24 inches in diameter and 34 inches in height. Different sphere sizes and adjustable heights could also impact the way users conceptualize interactions. In this paper, we compare the interaction experiences of adults (ages 19 to 28) with physical and virtual spherical interfaces. Future work can explore and compare how different user groups, such as children or families, people with motor impairments, or older adults, interact with these interfaces in geodata exploration tasks. Furthermore, we acknowledge the potential of mixed reality AR/VR educational technologies for geodata visualizations. Future work within the IEEE VR/HCI community can build upon our findings to compare 3D physical user interfaces to AR/VR interfaces for geodata exploration.

7 CONCLUSION

We conducted a within-subjects comparative study with 21 participants on a physical and a virtual spherical interface platform to compare the interaction experiences across different form factors. Our results overall showed no significant difference between usability or task time on the two platforms. However, in their qualitative feedback, participants noticed the differences between the physical sphere and the virtual sphere in terms of effort and motor demand. We provide design recommendations valuable for designers and developers of future spherical interfaces of both types, especially in the context of geoscience data visualizations. From the current data presented, we posit that the virtual sphere may act as a viable alternative to the physical sphere, when the latter is not accessible due to cost, space, environment, and other constraints.

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