Enhancing Geographic Information Visualization: A Comparative Analysis of Digital Maps and Projection Augmented Relief Maps

Changyuanlang Teng
Xi'an Jiaotong-Liverpool University
Suzhou, China
Changyuanlang.Teng22@alumni.xjtlu.edu.cn

Zhiwei Shi
Xi'an Jiaotong-Liverpool University
Suzhou, China
Zhiwei.Shi22@alumni.xjtlu.edu.cn

Lingyun Yu
Xi'an Jiaotong-Liverpool University
Suzhou, China
Lingyun.Yu@xjtlu.edu.cn

Yu Liu
Xi'an Jiaotong-Liverpool University
Suzhou, China
Yu.Liu02@xjtlu.edu.cn

ABSTRACT

This study examined the effectiveness of Projection Augmented Relief Maps (PARM)—an emerging display medium in public education spaces like museums—and traditional Digital Maps (DM) for visualizing geographic information. Our evaluation focused on four key metrcs: effectiveness, efficiency, memory retention and user engagement, on basic map reading and comprehension tasks. The results revealed that neither PARM nor DM consistently outperforms the other across all tasks, highlighting the importance of selecting the appropriate medium based on specific contexts. Moreover, our research identified significant gender differences in how users comprehend these mediums, underscoring the necessity for more inclusive and user-centric design approaches. This study contributes to the field by emphasizing the critical role of task-oriented media selection and the consideration of user diversity in designing or choosing geographic visualization tools.

VLDB Workshop Reference Format:
Changyuanlang Teng, Zhiwei Shi, Lingyun Yu, and Yu Liu. Enhancing Geographic Information Visualization: A Comparative Analysis of Digital Maps and Projection Augmented Relief Maps. VLDB 2024 Workshop: Relational Models.

VLDB Workshop Artifact Availability:
The source code, data, and/or other artifacts have been made available at URL_TO_YOUR_ARTIFACTS.

1 INTRODUCTION

In modern museums or many public education settings, the display of visualized geographic data plays a pivotal role in enhancing visitor experience and education. These technologies are often utilized to illustrate historical military routes, dynastic distributions, and other spatial information. Recently, the mediums for showcasing these data have diversified into two primary categories (see examples in Figure 1): electronic screens, including touch screens, large-scale displays, and interactive panels, and physical models, such as 3D printed landscapes and interactive sandboxes, often enhanced with projections. The novelty offered by physical models with projections, in particular, has garnered significant attention. However, their effectiveness in enhancing information comprehension and engagement within public settings remains unknown.

Much research in recent years has explored the value of physicalization. Ren et al. [28] compared 3D pole visualization in physical and virtual reality(VR) settings, discovering virtual representation and the VR technology significantly inhibit participants' ability to work with the data set. Jansen et al. [13] explored differences between 3D physical models and on-screen 3D bar charts on task completion time and error rates, finding that the ability to touch the physical model supported understanding. Stusak et al. [30] assessed the memorability of physical visualization and on-screen 2D visualizations, noting that the physical bar chart model led to better retention after two weeks. Kirshenbaum et al. [14] evaluated the effectiveness and user engagement of geovisualization data projected on either a flat 2D surface or a 3D terrain representation. They observed a slight increase in engagement with the 3D representations, which were also preferred by participants. Despite these findings, no research to date has compared the effectiveness of Projection Augmented Relief Maps (PARM) with traditional digital screens for the general public.

To address this gap, we have investigated the performance of Digital Maps (DM) with PARM in terms of effectiveness, efficiency, memory retention, and user engagement in 3 types of map reading and comprehension tasks frequently engaged in our daily life. This study contributes to a deep understanding of how different display media influence reading and learning geographic information in public environments. Our findings are intended to assist museums and art galleries make informed decisions about the choice of mediums for presenting geographic data, ultimately aiding curators and staff in optimizing visitor engagement and understanding.

This work is licensed under the Creative Commons BY-NC-ND 4.0 International License. Visit https://creativecommons.org/licenses/by-nc-nd/4.0/ to view a copy of this license. For any use beyond those covered by this license, obtain permission by emailing info@vldb.org. Copyright is held by the owner/author(s). Publication rights licensed to the VLDB Endowment.
Proceedings of the VLDB Endowment. ISSN 2150-8097.

2 RELATED WORK

This section summarizes the key articles in the following three related areas and classifies these studies according to their associated characteristics.

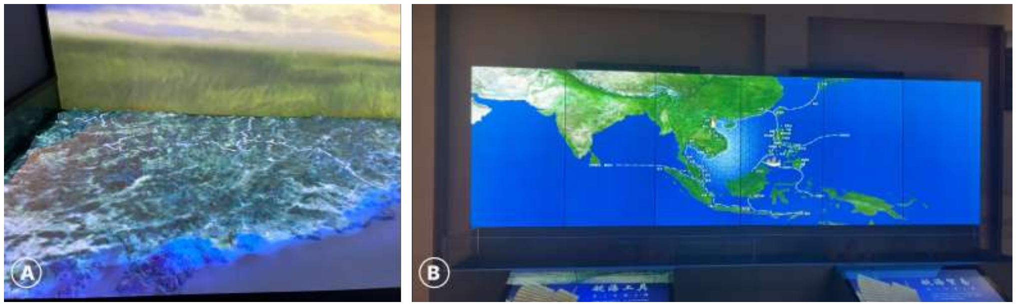

Figure 1: A- The PARM at the museum. B- The DM at the museum. Both photos were shot at the China Grand Canal Museum.

2.1 Evolution in Geodata Physicalization

Geographic datasets are well suited for fabrication since they pertain to a specific stereoscopic configuration or geospatial setting. Many studies explored various physicalization approaches and continuously refined them to depict the topography more effectively. In contrast to initial solid terrain models either static [4] or configured by actuators [7], Illuminating Clay [24] examined real-time manipulable alterations of landscapes using computer-based analysis. The system comprised modifiable clay and laser scanners to monitor and record its form [19]. It was upgraded to TanGeoMS [34] later to better capture surface parameters and reproduce feedback information after calculation. Afterwards, to offer greater convenience and flexibility in simulation and operation, based on PARM [26], a tactile geographic display with projectors reflecting data on CNC-machined or 3D-printed model, AR Sandbox [31] using sand and Tangible Landscape [32] using molds launched a series of richly interactive and dynamic installations. Furthermore, integration of sensing hardware to track faces and gestures [14, 16] facilitated a higher level of interaction with and presentation of geospatial datasets.

2.2 Application of Geodata Physicalization

Benefiting from the affordability and accessibility of fabrication and projection augmentation equipment and techniques, devices above tended to march into various utilization settings to demonstrate their unique allure. In educational contexts, survey results [15, 35, 37] revealed that students from geoscience subjects were overwhelmingly positive in their perception of how AR sandbox improved their understanding of learning objectives compared to traditional printed maps. When there were PARM displays in museums, observations and interviews [25, 27] indicated that visitors were more likely to give their focal attention, show an apparent expectation for direct immersive interaction, and a deeper comprehension in the themes of exhibition. Additionally, in many pragmatic settings such as ecological design [33] and terrain analysis [11] before concrete planning and construction stage, experiments with tangible landscape could encourage different modes of spatial thinking and strategies for ideation, modeling, and rapid iteration. Therefore, it is evident that burgeoning physical displays offered their unique possibilities in enhancing user experience compared to traditional maps.

2.3 Evaluations on Display Media

To assess whether enhanced physical models improve understanding of geographic information, the research employed a mix of qualitative and quantitative methods, including tests, questionnaires, interviews, and simulations, to evaluate user performance. Compared to flat printed maps, physical ones helped users to quickly and accurately interpret the landscape, transfer the experience of exploring new places and learn spatial properties and relations [2, 23]. Physical approach also enabled participants to more effectively interact with the system and each other, positively impacting their task-specific knowledge acquisition and sensations of experience [18]. However, compared to screen-based digital maps, experiments carried out among college students [14] and by Army Futures Command [10] showed that media used did not significantly alter the accuracy in performing normal comprehension tasks, but may have an effect on complete time on some occasions. Nevertheless, students and professionals all performed better in missions with a higher level of creativity and complexity [12]. They indicated that such a physicalization is closer to their interactive experiences and expectations, so they could exploit its natural haptic guidance for further learning.

2.4 Summary

Despite the progress and ongoing research efforts in geodata physicalization, including comparative experiments to evaluate effectiveness, notable gaps persist. Specifically, there is a need for wider adoption among general users in practical daily settings and for systematic studies that quantitatively assess user performance when using these increasingly popular map media (PARM) compared to traditional digital maps on screens (DM).

3 EXPERIMENT

To fill this research gap, we compared geovisualization in which a digital map is presented on a computer with geovisualization in which the map is projected onto a physical model 3D printed. We used within-group test, allowing each participant to experience both geovisualization, and we also designed paired questions to ensure the same level of difficulty between the two mediums. Our study has been reviewed and approved by the school's ethical committee as well. Performance data of users in the study was collected anonymously and strictly kept confidential, and will be deleted permanently after the entire research is published.

3.1 Apparatus & Setting

The models in our system were 3D printed with photosensitive resin and the source terrain files were exported and downloaded from the free service Terrain2STL [3] with box scaling factor of 20, vertical scaling of 4, water drop of 4 mm and base height of 5 mm. A 4K 1700 CVIA projector was placed on a desk of 80 cm height to forward projection onto the model fixed on the wall at the same level. The vertical scale in this study was chosen based on the pilot study results within co-authors. We used the online map application Mapmaker [21] to design settings and tasks in the same area of our physical models (see Figure 2). To match the size of the terrain base and projection area, two 15.6" laptops were selected to operate the digital experiment platform.

Our experiment was conducted in an on-campus laboratory. To ensure the clarity of the projected content, the laboratory was darkened throughout the day by closing the blinds, and participants were allowed to freely adjust their viewing angles and positions to observe and read the visualizations.

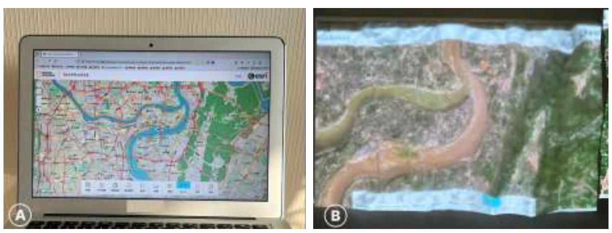

Figure 2: The experimental device of DM (A) and PARM (B).

3.2 Participants

We recruited 20 college students (10 females) from age 21 to 26 (M=23.80, SD=1.72) in our school. 18 of them had a science or engineering education background (but not geoscience or related fields), with the other 2 from art discipline. All participants reported having a basic sense of traditional digital maps (navigation or map applications on mobile devices etc.), but no prior map reading experience in specialized mapping system (such as PARM or other similar innovative geovisualization media). All the participants reported to have normal visual acuity, could perceive stereoscopic objects and were not troubled by color discrimination problems (red-green color blindness etc.). In addition, another two students were invited to conduct a pilot before the formal experiment. Their performance data were to help us refine our experiment and were not included in the final analysis.

3.3 Tasks and Stimuli

For the design of test questions in our experiment, we referred to Roth's empirically based taxonomy in geovisualization [29]. We only employed the first three objectives - Identify, Compare and Rank with the two interaction operands - Space-Alone and Attributes-in-Space, dropping the last two objectives (Associate, Delineate) and the last operand (Space-in-Time) in that they tend to engage more complex interaction with better equipment and somewhat difficult for common users without certain geography knowledge. To ensure that all participants go through an identical test between the two medium, each category of tasks consisted 4 questions in each medium with equivalent difficulties, with a total of 48 (6×4×2) questions for everyone.

To include the most common types and forms of datasets in typical maps [17], we picked two layers: hybrid satellite images and open street maps. They provided all required information, covered general map reading tasks, and satisfied basic demands in our daily lives. As for specific location, we selected Chongqing, a city that features in complex spatial properties both naturally and culturally to support various tasks [9].

3.4 Procedure

Our experiment was divided into five stages, with an average duration of approximately 40 minutes per participant.

- In the first stage, the participants were introduced to the procedure and related details of the experiment, then they checked and signed an informed consent form. Afterwards, in the aid of our researchers, they familiarized themselves with the model, including settings of experimental environment, some symbols and reading skills commonly used in the maps.
- In the second stage, a series of objective questions was raised to test participants' performance in effectiveness and efficiency. Then they were instructed that they need to answer each question sequentially with the provided medium. They were informed that both completion time and accuracy would be recorded so that they were suggested to achieve a balance between speed and precision in their responses. For the 20 participants, the first half started from DM then PARM, and another half reversed. Within each half, 5 started from hybrid satellite layer then open street layer, and another 5 reversed. Therefore, there was an existence of 4 branches in total, so as to eliminate possible ordering effects in a counterbalanced way.
- In the third stage, we aimed to evaluate participants' memory retention. First, they were told that they needed to answer six questions, probably about landform features, street information, and so on, without a specific description. Then the participants were required to pick a model between DM and PARM to facilitate their memorization of the map. After a 90-second glancing period, we intentionally interrupted the progress by chatting with the participants about some questions irrelevant to the experiment, taking a break of around 3 minutes. After the break, we asked the six questions and recorded the correctness and contents of their answers. In the end, we asked them whether they would pick another medium or just confirmed this choice if provided another chance in a similar context.
- In this stage, the participants were required to complete a questionnaire to measure user engagement. According to the refined user engagement scale (UES) [22], the questionnaire was designed and compromised 4 dimensions : aesthetic appeal, focused attention, perceived usability and reward factor. Participants were asked to complete a likert

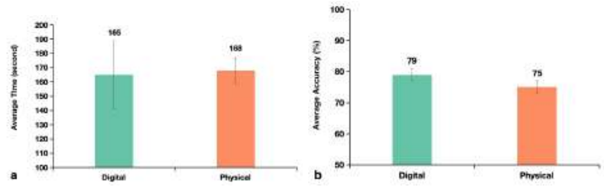

Figure 3: The average time (a) and accuracy (b) in answering all the questions.

scale of 1-5 based on their experience in fulfilling all these tasks.

- In the last stage, we interviewed the participants about their overall experience with the two models, any confusing problems they encountered while completing the tasks, and some suggestions for refining the apparatus from their perspective.

4 RESULTS

4.1 Effectiveness & Efficiency

To assess the effectiveness and efficiency of participants' performance in the two distinct media, our study calculated completion time and accuracy in three kinds (Identify, Compare and Rank). Through Wilcoxon Signed-Rank Test, selected for abnormal distribution of performance data, we found that the total average time and total average accuracy of DM were not significantly different from PARM, as in Figure 3.

Specifically, in the context of average time efficiency, three categories of tasks demonstrated significant differences (as shown in Figure 4). For identification in space, PARM exhibited a notably shorter completion time compared to DM, with a statistically significant result (Z=-2.377, p=0.017). Conversely, DM outperformed PARM in tasks related to identifying and ranking attributes. This was evident in the identifying category (Z=-2.314, p=0.033) and the ranking category (Z=-2.538, p=0.011), where DM's average time was much shorter. Furthermore, our study also highlighted differences in average accuracy across the three task kinds, where DM demonstrated higher accuracy than PARM. As in Figure 4, this can be observed in identification of attributes (Z=-2.309, p=0.021), comparison in space (Z=-2.121, p=0.034), and ranking of attributes (Z=-2.288, p=0.022).

We also conducted a gender-based analysis, revealing that the average response time among male for digital models was much shorter compared to female, also with a significant difference (Z=-2.599, p=0.009). However, as show in Figure 5, no significant gender difference existed in the average time for physical models and in the average accuracy for both models.

4.2 Memory Retention & User Engagement

As for memory-related tasks, our study observed that among all participants, 13 opted for Digital Maps (DM) and 7 chose Projection Augmented Relief Maps (PARM) to support themselves solving a set of six questions. We employed Mann-Whitney U Test for our statistical analysis, given the disparity in sample sizes and the independent property of samples. When analyzing based on the type of question, we found no statistically significant difference in average accuracy between participants using DM and PARM, as depicted in Figure 6. After finishing the memory test, we asked the participants whether they regretted their choice of media (DM or PARM). 19 participants still confirmed their choice and one participant expressed his willing to change (from DM to PARM next time). He reflected that, *upon getting a fully understanding of the tasks, he would prefer PARM as it offered a more vivid, three-dimensional experience in space, convincing him that PARM would be a better choice for solving similar intuitive problems in the future.*

For the evaluation of user engagement, we employed Wilcoxon Signed-Rank Test to evaluate the discrete rating scores from 1 to 5. As illustrated in Figure 7, our experiment revealed that there was no significant difference in user engagement.

4.3 Interview

During the interview, we investigated the reasons behind participants' choice of the model and their overall experience with the two media. For DM, participants indicated that the advantages include clarity of details, such as distinguishing colors, evident straight distances, clear symbols, obvious contrast and so on. However, DM failed to involve stereoscopic information such as height and other properties of landforms, so users didn't have a clear perception when solving related questions. Some participants said that *they were more familiar with traditional digital maps, and DM already satisfied their basic daily needs, including information for traffic conditions, navigation, traveling etc.*

For physical models, participants indicated that the advantages were obvious features of the terrain, visible distribution of vegetation and buildings above surface, clear positional location, impressive perception of spatial distance and so on. However, PARM usually failed to present detailed information clearly and quickly, and the undulating topography did disturb users in some tasks. Most participants mentioned that DM seemed to be more helpful in a particular context, for example, leading intuitive navigation before hiking, traveling, and exploring in parks or facilitating a better comprehension of processes and characteristics of things happening in a specific area. Some participants indicated that *PARM was more immersive and appealing to them. They may use it to observe or learn something when put in a new place or setting. They also wished that more useful interactive means could be added to the system.*

5 DISCUSSION

The findings from our comparative experiment revealed that the choice of media plays a significant role in users' comprehension effectiveness and efficiency with geographic information, yet this influence varies considerably based on the context and nature of the tasks. Our analysis showed no significant differences in overall effectiveness, efficiency, memory retention and user engagement when participants used either PARM or DM across a range of task categories. This suggests that, at a general level, both media are equally capable of supporting user comprehension of geographic information. This finding is consistent with previous comparison between physicalization with other mediums like VR [10, 28] and comparison of geovisualization data projected on either a flat 2D surface or a 3D representation of the terrain [14]. However, when

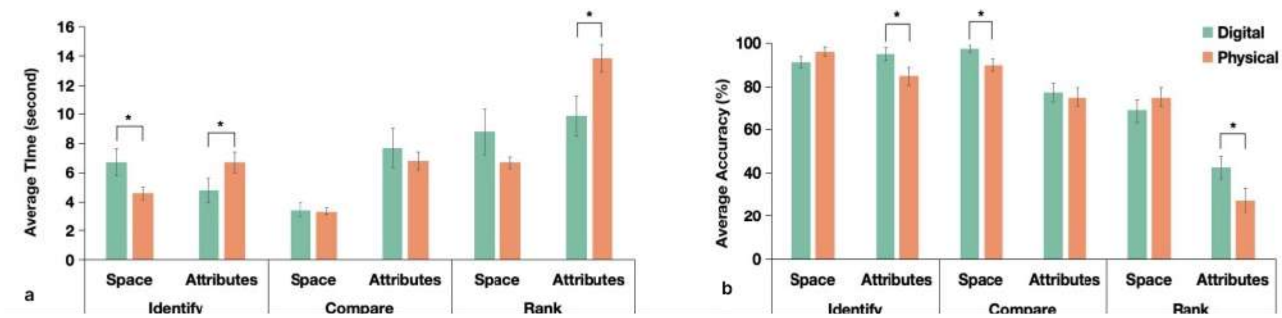

Figure 4: a- The average time to answer each category of questions. b- The accuracy for each category of questions.(*:p<0.05)

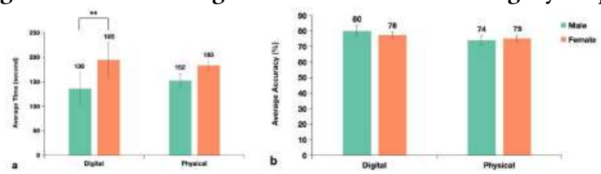

Figure 5: a- The average time to answer all questions among gender. b- The average accuracy for all questions among genders. (*:p<0.05, **:p<0.01)

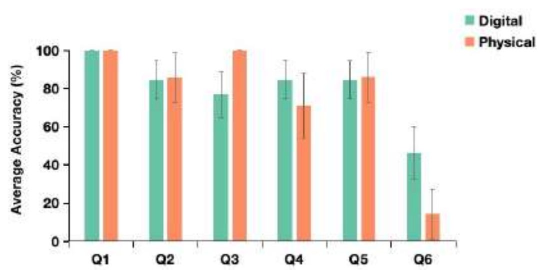

Figure 6: The average accuracy for memory questions.

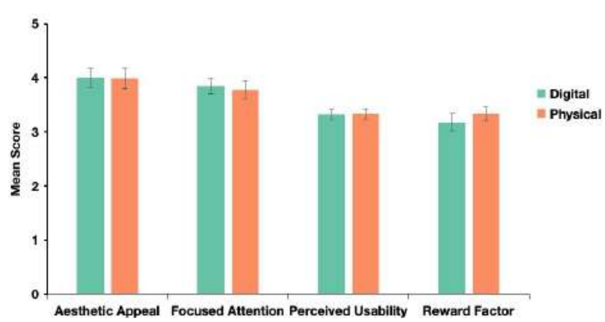

Figure 7: The rating scores for user engagement.

delving into specific types of tasks, like identifying, comparing, and ranking, the choice of medium becomes critical. PARM was found to be more effective for intuitive tasks that required spatial recognition, highlighting its utility in enhancing spatial understanding. Conversely, DM excelled in tasks that demanded quick identification and ranking of attributes, demonstrating its efficiency in handling attribute-based information.

Furthermore, our study explored the impact of these media on short-term memory retention, where we found no significant difference between PARM and DM. This finding aligns with what was indicated before [30] in terms of memory retention. The medium does not drastically influence the user's recall of geographic information over short periods. A notable aspect of our research was the observation of gender-specific differences. When using DM, male participants completed tasks more quickly than female participants, despite similar accuracy levels. This gender-based disparity in interaction time suggests that user interface design in geographic information systems should consider these potential differences to enhance efficiency and inclusiveness. This result is consistent with previous exploration in map-related tasks across genders [20, 36].

In the exploration of projectors and physical 3D maps as visual media, we found that the direction of projection and lighting conditions emerge as two pivotal factors for effective visual communication. The following analysis will delve into these aspects, discussing their impact.

5.1 Options and Impact of Projection Direction

In our study, we utilized horizontal projection, a prevalent method that projects content onto a 3D map's surface horizontally. This technique ensures a viewing experience akin to watching electronic screens, maintaining a consistent perspective. However, it also restricts direct frontal observation of the overlaid information and the physical map due to the positioning of the projector. As for vertical projection, it directs content downward onto a map (usually larger in size) laid on a surface such as a floor or tabletop. This approach offers flexible perspectives and immersive experience but poses challenges in viewer positioning and angle, where movement around the map is necessary. Moreover, when projecting on non-flat surfaces with height differences of more than 6 cm, it is often necessary to apply some form of projection mapping [8] to avoid visible distortions of the projected content, which is discussed in TanGeoMS system [34]. Therefore, when choosing ways of projection, we should consider viewer habits, presentation content, hardware conditions etc. to ensure an optimal visual experience.

5.2 Requirements of Projection Equipment and Environment

The requirements of projection equipment mainly concerns better quality of resolution and luminance. High-resolution graphics aim to clearly provide identical details on digital screens, especially when the physical model is large. Higher luminance aim to enhance the readability of colors, shapes etc. on PARM especially when the system is placed in a bright indoor setting. In this study, to ensure optimal projection quality, curtains were used to block out light in a secluded classroom setting. This suggests that DM might be superior in multifunctional settings or environments where light conditions cannot be precisely controlled, while PARM typically need a darker environment to prevent interference from strong light, which could diminish the visual clarity.

6 LIMITATIONS & FUTURE WORK

6.1 Sample Limitations and Impact Evaluation

Our study predominantly involved student participants, which potentially restricts the generalizability of our findings. The student demographic typically exhibits higher adaptability and receptiveness to technology, potentially skewing performance favorably with DM. However, the implications of this demographic bias on the use and experience of PARM remain unclear. Acknowledging and assessing the impact of this limitation is crucial. Relevant literature supported the variability in technology acceptance among different demographics, highlighting background and culture as significant factors [1], and some experiments explored possible influence of background information on geospatial ability [5, 6]. To enhance the generalizability of future research, participants should include a broader range of demographic characteristics and explore cross-national comparisons to examine how geographic information visualization tools perform across different cultural settings. Although our sample is limited, our findings offer valuable preliminary insights into the application of PARM and DM in geographic information tasks, laying a foundation for further, more inclusive research.

6.2 Impact of Scale and Interactivity

Our study is currently limited by the use of devices solely as non-interactive display units at a uniform size of 15.6 inches. The small size usually failed to provide enough presentation details and immersive experience as those huge screens or PARM applied in museums [25, 26] etc. Moreover, this setup restricts our understanding of how interactive means and techniques might influence the effectiveness, efficiency, user preference for media types etc. Incorporating interactive elements into the displays could significantly alter how users engage with the information, potentially enhancing learning outcomes and user satisfaction. Moreover, as tasks become more complex with the introduction of interactivity, effectiveness and other measurements of different media types could vary, necessitating a more nuanced structure and approach [29] to evaluating their impact. Analyzing these aspects more thoroughly could provide deeper insights into optimizing media for various tasks and user experiences.

Furthermore, our study did not explore the long-term memory retention of geographic information with different media. The extent to which physical and digital models impact long-term memory retention is an interesting and unexplored area. Future research in this direction could significantly contribute to understanding how different forms of geodata visualization aid in the long-term retention, to facilitate depiction of geographic information details, to acquire a structured comprehension etc., which are usually crucial in educational, academic, and engineering related settings.

7 CONCLUSION

Our research aimed to compare Projection Augmented Relief Maps (PARM) with traditional Digital Maps on screens (DM) in basic map reading and comprehension tasks. Although our experiment did not conclusively prove the overall superiority of either medium, we observed that the efficacy of each varies significantly depending on the specific tasks at hand. In particular, PARM demonstrated advantages in spatial identification tasks, while digital screens excelled in detailed attribute-based comparison and ranking tasks. This finding emphasizes the importance of task specificity in selecting the appropriate medium for geographic information visualization. Moreover, during our study, we noted that PARM requires more strict hardware and environmental conditions, suggesting that real-world application decisions should consider multiple factors beyond mere efficiency and effectiveness under ideal conditions. Additionally, our exploration of gender differences in map-related tasks highlights the need for a more nuanced approach when choosing a medium, aiming for inclusiveness and user-centric design.

ACKNOWLEDGMENTS

This work was supported by a grant from RDF-22-01-092. We also thank all participants involved in our user study.

REFERENCES

[1] Akram Afsay, Arash Tahriri, and Zabihollah Rezaee. 2023. A meta-analysis of factors affecting acceptance of information technology in auditing. *International Journal of Accounting Information Systems* 49 (2023), 100608.
[2] Nachnoer Arss. 2022. Exploring Human Interaction with Projected Augmented Relief Model (PARM). University of Nottingham.
[3] Thatcher Chamberlin. 2023. Terrain2STL. https://jthatch.com/Terrain2STL/
[4] Pierre Dragicevic and Yvonne Jansen. 2003. Solid Terrain Model with Airplane Trajectory. http://dataphys.org/list/solid-terrain-model-with-airplane-trajectory/
[5] Lia Duarte, Ana Cláudia Teodoro, and Hernâni Gonçalves. 2022. Evaluation of spatial thinking ability based on exposure to Geographical Information Systems (GIS) concepts in the context of higher education. *ISPRS International Journal of Geo-Information* 11, 8 (2022), 417.
[6] Michael A Erskine and Karimi Jahangir Gregg, Dawn G. 2022. Individual characteristics and geospatial reasoning ability: A multigroup analysis of age, culture, and gender. *Journal of Decision Systems* 31, 4 (2022), 451–473.
[7] Sean Follmer, Daniel Leithinger, Alex Olwal, Akimitsu Hogge, and Hiroshi Ishii. 2013. inFORM: dynamic physical affordances and constraints through shape and object actuation. In *Proceedings of the 26th annual ACM symposium on User interface software and technology (UIST '13)*. ACM, NY, USA, 417–426. https://doi.org/10.1145/2501988.2502032
[8] A. Grundhöfer and D. Iwai. 2018. Recent Advances in Projection Mapping Algorithms, Hardware and Applications. *Computer Graphics Forum* 37, 2 (2018), 653–675. https://doi.org/10.1111/cgf.13387
[9] Jianming Guo, Guifeng Han, Yusi Xie, and Zhao Yifan Cai, Zhi. [n.d.]. Exploring the relationships between urban spatial form factors and land surface temperature in mountainous area: A case study in Chongqing city, China. *Sustainable Cities and Society* 61 ([n. d.]). https://doi.org/10.1016/j.scs.2020.102286
[10] Kelly S. Hale, Gwen Campbell, Jennifer Riley, Michael Boyce, and Charles Amburn. 2019. Augmented Reality Sandtable (ARES) Impacts on Learning. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* 63, 1 (2019), 2149–2153. https://doi.org/10.1177/1071181319631369
[11] Brendan Alexander Harmon. 2016. Embodied Spatial Thinking in Tangible Computing. In *Proceedings of Tenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '16)*. ACM, NY, USA, 693–696. https://doi.org/10.1145/2839462.2854103
[12] Brendan A. ; Anna Petrasova Harmon. 2018. Tangible topographic modeling for landscape architects. In *International Journal of Architectural Computing vol. 16 - no. 1, 4-21*. CUMINCAD, London, UK, 4–21. https://papers.cumincad.org/cgi-bin/works/paper/ijac201816102

[13] Yvonne Jansen, Pierre Dragicevic, and Jean-Daniel Fekete. 2013. Evaluating the efficiency of physical visualizations. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '13)*. ACM, NY, USA, 2593–2602. https://doi.org/10.1145/2470654.2481359

[14] Nurit Kirshenbaum, James Hutchison, Ryan Theriot, Dylan Kobayashi, and Jason Leigh. 2020. Data in Context: Engaging Audiences with 3D Physical Geo-Visualization. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems (CHI EA '20)*. ACM, NY, USA, 1–9. https://doi.org/10.1145/3334480.3382968

[15] Sandeep N Kundu, Nawaz Muhammad, and Fraha Sattar. 2017. Using the augmented reality sandbox for advanced learning in geoscience education. In *2017 IEEE 6th International Conference on Teaching, Assessment, and Learning for Engineering (TALE)*. 13–17. https://doi.org/10.1109/TALE.2017.8252296

[16] Samuel Luescher. 2013. *Beyond visualization : designing interfaces to contextualize geospatial data*. Thesis. Massachusetts Institute of Technology. https://dspace.mit.edu/handle/1721.1/82428

[17] Ali Mahdavi-Amiri, Troy Alderson, and Faramarz Samavati. 2015. A Survey of Digital Earth. *Computers & Graphics* 53 (Dec. 2015), 95–117. https://doi.org/10.1016/j.cag.2015.08.005

[18] Garrett C. Millar, Payam Tabrizian, Anna Petrasova, Vaclav Petras, Brendan Harmon, Helena Mitasova, and Ross K. Meentemeyer. 2018. Tangible Landscape: A Hands-on Method for Teaching Terrain Analysis. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems (CHI '18)*. ACM, NY, USA, 1–12. https://doi.org/10.1145/3173574.3173954

[19] H. Mitasova, L. Mitas, C. Ratti, H. Ishii, J. Alonso, and R.S. Harmon. 2006. Real-time landscape model interaction using a tangible geospatial modeling environment. *IEEE Computer Graphics and Applications* 26, 4 (July 2006), 55–63. https://doi.org/10.1109/MCG.2006.87

[20] Daniel R Montello, Kristin L Lovelace, Reginald G Golledge, and Carole M Self. 1999. Sex-related differences and similarities in geographic and environmental spatial abilities. *Annals of the Association of American geographers* 89, 3 (1999), 515–534.

[21] Esri National Geographic. 2023. Mapmaker. https://www.arcgis.com/apps/instant/atlas/index.html?appid=0cd1cdee853c413a84bfe4b9a6931f0d

[22] Heather L. O'Brien, Paul Cairns, and Mark Hall. 2018. A practical approach to measuring user engagement with the refined user engagement scale (UES) and new UES short form. *International Journal of Human-Computer Studies* 112 (April 2018), 28–39. https://doi.org/10.1016/j.ijhcs.2018.01.004

[23] George Palaigeorgiou, Anastasios Karakostas, and Kyriaki Skenteridou. 2018. Touching and traveling on 3D augmented tangible maps for learning geography: The FingerTrips approach. *Interactive Technology and Smart Education* 15, 3 (2018), 279–290. https://doi.org/10.1108/ITSE-12-2017-0066

[24] Ben Piper, Carlo Ratti, and Hiroshi Ishii. 2002. Illuminating clay: a 3-D tangible interface for landscape analysis. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '02)*. ACM, NY, USA, 355–362. https://doi.org/10.1145/503376.503439

[25] Cheverst Keith Priestnall, Gary. 2022. Understanding visitor interaction with a projection augmented relief model display: insights from an in-the-wild study in the English Lake District. *Personal and Ubiquitous Computing* 26, 3 (2022), 593–607. https://doi.org/10.1007/s00779-019-01320-2

[26] G. Priestnall, J. Gardiner, J. Durrant, and J. Goulding. 2012. Projection augmented relief models (PARM): tangible displays for geographic information. *Electronic Workshops in Computing* 65 (2012), 180–187. https://doi.org/10.14236/ewic/eva2012.28

[27] Gary Priestnall, James Goulding, Alastair Smith, and Nachnoer Arss. 2017. Exploring the capabilities of Projection Augmented Relief Models (PARM). *Geographical Information Science Research UK* 24, 16 (April 2017), 53–58. https://nottingham-repository.worktribe.com/output/856339

[28] He Ren and Eva Hornecker. 2021. Comparing Understanding and Memorization in Physicalization and VR Visualization. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction (TEI '21)*. ACM, NY, USA, 1–7. https://doi.org/10.1145/3430524.3442446

[29] Robert E. Roth. 2013. An Empirically-Derived Taxonomy of Interaction Primitives for Interactive Cartography and Geovisualization. *IEEE Transactions on Visualization and Computer Graphics* 19, 12 (Dec. 2013), 2356–2365. https://doi.org/10.1109/TVCG.2013.130

[30] Simon Stusak, Jeannette Schwarz, and Andreas Butz. 2015. Evaluating the Memorability of Physical Visualizations. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems* (Seoul, Republic of Korea) *(CHI '15)*. ACM, NY, USA, 3247–3250. https://doi.org/10.1145/2702123.2702248

[31] Sergio Álvarez Sánchez, Laura Delgado Martín, Miguel Ángel Gimeno-González, Teresa Martín-Garcia, Fernando Almaraz-Menéndez, and Camilo Ruiz. 2016. Augmented reality sandbox: a platform for educative experiences. In *Proceedings of the Fourth International Conference on Technological Ecosystems for Enhancing Multiculturality (TEEM '16)*. ACM, NY, USA, 599–602. https://doi.org/10.1145/3012430.3012580

[32] Payam Tabrizian, Anna Petrasova, Brendan Harmon, Vaclav Petras, Helena Mitasova, and Ross Meentemeyer. 2016. Immersive tangible geospatial modeling. In *Proceedings of the 24th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems (SIGSPACIAL '16)*. ACM, NY, USA, 1–4. https://doi.org/10.1145/2996913.2996950

[33] Payam; Harmon Tabrizian. 2017. Tangible Immersion for Ecological Design. In *Proceedings of the 37th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA)*. Cambridge, MA, 600–609. https://papers.cumincad.org/cgi-bin/works/paper/acadia17_600

[34] Laura Tateosian, Helena Mitasova, Brendan Harmon, Brent Fogleman, Katherine Weaver, and Russel Harmon. 2010. TanGeoMS: Tangible Geospatial Modeling System. *IEEE Transactions on Visualization and Computer Graphics* 16, 6 (Nov. 2010), 1605–1612. https://doi.org/10.1109/TVCG.2010.202

[35] Robert E. Vaughan, Karen L. Vaughan and Janel M. Seeley. 2017. Experiential Learning in Soil Science: Use of an Augmented Reality Sandbox. *Natural Sciences Education* 46, 1 (2017), 160031. https://doi.org/10.4195/nse2016.11.0031

[36] Jan Wilkening and Sara I Fabrikant. 2011. The effect of gender and spatial abilities on map use preferences and performance in road selection tasks. (2011).

[37] Terri L. Woods, Sarah Reed, Sherry Hsi, John A. Woods, and Michael R. Woods. 2016. Pilot Study Using the Augmented Reality Sandbox to Teach Topographic Maps and Surficial Processes in Introductory Geology Labs. *Journal of Geoscience Education* 64 (2016), 199–214. https://doi.org/10.5408/15-135.1