Visualizing Streaming of Ordinal Big Data

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***Abstract*— Horizontal transitions are used in the Streaming of Big Data when there is the need to change the aggregation level of the data being presented. For example, data in a heat map may be aggregated into a line chart. Although these transitions have already been studied for quantitative streamed big data, ordinal data remains unchecked. In this study, we conducted an empirical study to explore horizontal transitions for ordinal data using Graceful Degradation, a concept that allows an overview of the received data at different periods via different levels of aggregation. We chose four visual idioms (Histogram, Ordinal Scatter Plot, Heat Map, and Line Chart), created several transitions between them, and tested how effectively could people perceive data in each idiom before, during, and after each corresponding transition. Participants had to watch numerous videos showcasing the idioms and transitions, and then they had to answer a questionnaire for us to measure how effective was their perception. All the four idioms tested were effective, and we were able to define numerous design guidelines for the creation of horizontal transitions in Streaming of Ordinal Big Data.**

***Index Terms*—Information Visualization, Big Data Streaming, User Study, Horizontal Transitions**

I. Introduction

Information analysis is essential for data recognition and decision-making in multiple areas of scientific study. The advancement of information technologies, such as smartphones or IoT devices, has originated a growth in the amount of accessible and valuable data created and stored by increasingly more entities. When the dimensions of these datasets defy computationally their representation, it is safe to say that the dataset belongs in Big Data. Then, when data arrives in real-time, it belongs to Data Streaming.

Let us imagine that a company needs to keep track of how many people access their website and how they navigated it. They have stored data since the company started working, and have now millions of records to be visualized. However, visualizing Big Data is an ongoing challenge because it is hard to represent everything simultaneously without producing visual clutter, compromising the overall analysis. This situation means that Big Data visualizations are obliged to find adequate aggregation techniques to effectively represent the whole dataset by reducing the overall complexity of the data. For example, if not enough aggregation is applied, the visualization may be forced to depict too many elements, which most likely affects the system's hardware performance. Besides, the overdrawing of elements will make the visualization impossible to understand. In both cases, the analysis is compromised. However, the solution should not always apply high aggregation levels because the visualization might lose the ability to present valuable information. It should therefore be dependent on the intended detail designers want to convey.

Now let us imagine that, at a certain moment, the company started monitoring in real-time the same data records that they had been storing since the beginning, and they were receiving thousands of records per minute. This time, when information is being received in real-time, regardless of being Big Data, designers are faced with new challenges. Streaming is characterized by the data's moment of creation during the observation of the visualization. The primary concern is the representation of the data as soon as it is received, and without it constantly changing due to the new data. One visualization must be able to process information and show it as it is received simultaneously. Unlike Big Data, visualizations must use adequate visual idioms and internal structures to manage information in real-time.

The company was now facing two different challenges, Big Data and Data Streaming (Big Data Streaming) and new issues need now to be solved. Since the data is streamed, it cannot be processed before the start of the visualization. Then, because it is Big Data, it needs to be aggregated to be perceptible. Therefore, besides processing the data, the data must be grouped in real-time. However, this grouping needs to be handled carefully. If grouped too soon, the system could, again, lose necessary information. If too late, the visualization will hold too many visual elements, thus producing visual clutter. Finally, the data timestamps should be explicit in the visualization. Newer data is usually the focus of Streaming visualizations. However, since Big Data information is aggregated, older data may also contain important information. Therefore, the visualization should allow an overview of how the data evolves by presenting different data periods. The company then decided that it needed a way to visualize the data gathered since the beginning, and how data was evolving in different periods.

Currently, there is yet no final solution to this issue. However, one system in development called VisMillion (fig. 1) has been taking the first steps in Big Data Streaming Visualizations, in hopes of allowing people to have an overview of data at different periods. However, all the work conducted in VisMillion has assumed that data is quantitative. We question how well would people perceive data depicted using this prototype if ordinal data was applied instead. Therefore, our goal was to **choose visual idioms for streaming of ordinal big data**, we designed **horizontal transitions** between those idioms, and then we conducted a **user study** to measure how accurately would people perceive both the information

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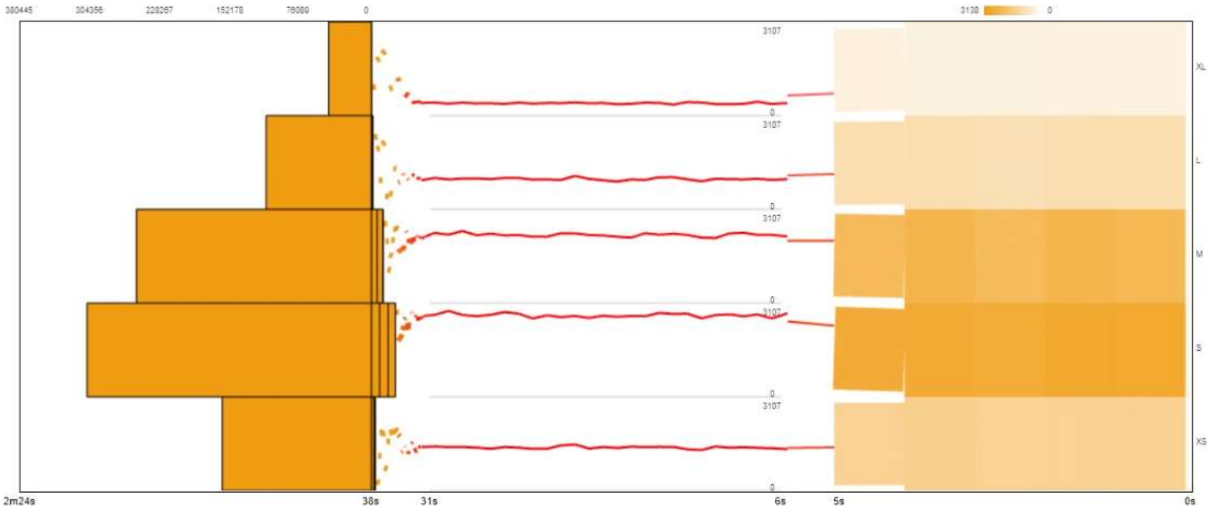

Fig. 1. Our prototype of VisMillion depicting the concept of Graceful Degradation from right to left. In this example, the streamed data arrives at the Heat Map, then it goes to the Line Chart via a horizontal transition, and then it goes to the Histogram with another horizontal transition. Each visual idiom corresponds to a different aggregation level, which represents different periods.

depicted in the idioms and transitions between them. Our major contribution is **design guidelines for choosing visual idioms and horizontal transitions for streaming of ordinal big data**.

II. Related Work

Big Data Streaming imposes several challenges in different domains [15], [16], [21] such as the social networks [23], industry [13], educational sector, healthcare system [1], [20], financial transaction, national security [18], oil and gas industries, and transportation [27], [32]. The datasets are often dynamic and characterized by high variety and volatility [5], [7], [21], [28], and their processing usually involves five steps: cleaning, aggregation, encoding, storage, and access [5], [7], [13], [15], [21], [28]. However, additional V's such as Visualization and Value have also been used to improve the definition of big data [24]. For visualization, systems must be designed to support real-time interaction, quick data processing, visual scalability, user assistance, and personalization [5], [13], [17], [29]. Machine learning, for example, is used to process vasts amounts of data to feed systems who output structures that help to predict and analysis trends and patters via visualization techniques [13], [21], [29], [31]. These insights can then be used for effective decision-making and reporting [13]. However, people must be able to have an effective overview of the data depicted, and must be allowed to filter any detail if needed [13], [29].

A. Challenges

There are a lot of popular visualization tools [21], [29], but the majority of visualizations systems cannot handle the size of Big Data datasets [5], [13], [15], [29] because of limited computational and memory resources [5], which often lead to overloading issues [5], [17], [21], [28]. Therefore, data reduction techniques are usually applied. However, these must be carefully applied. On one hand, interesting data patterns may be lost due to careless aggregations. On the other, if not enough aggregations are applied, the visualization may become too dense or cluttered [7]. Regarding streaming, systems need to allow real-time data exploration [5], [13], [17], which may not be easy to accomplish due to the variability of streamed datasets structures [5].

B. Solutions

Depending on the data structure, different visual idioms may be used [8], [9], [12]. Dimension reductions techniques are often designed with hierarchical visual idioms like the Tree Map or Circle packing [5], [10]. Still, other solutions also deal with the high data volume, variety, and dynamics, like the Parallel Coordinates, or any Stacked Graph. The last type in particular works better for temporal data [7] because they allow to see data over time [14]. Then, designers may also employ specialized software to deal with data storage, managing, and analyzes [15], such as the MapReduce, Haddop, or specialized techniques just as the PASS (Preserving Anomaly and Semantics Sampling) [2].

Particularly in streaming, designers focus on having data seen in separate timespans, each for a specific analysis [15], [19]. If possible, people should be able to see data as it arrives [4], [17], [33], for example, to detect anomalies in real-time [10], [30]. Furthermore, the data must be processed without burdening the system's memory too much [7], [13]. Moreover, if different timespan windows exist, designers should employ techniques to preserve a viewer's mental map of incremental results [11]. To ensure this preservation, designers may choose to use animation techniques to help users track how the data evolves. [34]. For example, grouping objects by predefined trending directions and by clustering their moving trends.

C. Graceful Degradation

Recently, the concept of Graceful Degradation [3] has been applied to Big Data Streaming in an innovative system called VisMillion [26]. It was designed to depict time-series big data streamed datasets in different modules, each using a different visual idiom. With this concept, as data gets older, it gets aggregated into different visual idioms. The core idea is that recent data might need more detail than older data. In VisMillion, each module presents data with a different aggregation level. The data flows from right (most recent data) to left (older data), where the left-most module depicts information since the visualization started working.

However, the initial proposal had abrupt cuts between modules, meaning that data got aggregation between visual idioms, but there were no visual cues to preserve the viewer's mental map of what was happening. Therefore, to enhance VisMillion, horizontal animated transitions were implemented [25]. Horizontal transitions are used between two modules to depict how information gets aggregated. For example, between a heat map that shows data distribution and a histogram that aggregates data into categories. Then, vertical transitions were also added to VisMillion [6], [22] to allow one module to change its own visual idiom. Vertical transitions are used in one module to change how the information is displayed. For example, using a heat map, a trend shift might not be detected. Therefore, a line chart would better emphasize this anomaly.

D. Discussion

As we have seen, Big Data Stream is an ongoing challenge due to its datasets properties. There are ongoing attempts to deal with variety and volatility [10], [15], [17], [21], and to deal with Visualization, and Value [5], [13]. Then, in some cases, viewers might be able to see information in different periods [15]. From our literature review, VisMillion was the system that has been actively trying to provide a complete solution to big data stream regarding the visualization phase. It receives Streams of Big Data that can be visualized with different aggregations levels [26] using graceful degradation [3], and it supports animation when data shifts between modules [25] or when viewers need to see information differently [6], [22]. However, the studies conducted until now assumed only quantitative data, and it is known that datasets in Big Data Streams can vary significantly, and there is the need to choose appropriate visualizations [12]. Therefore, we decided to improve VisMillion by adding support to ordinal big data.

III. VISMILLION

VisMillion was conceived to support the Streaming of Big Data. Pereira et al. [26] created a functional web-based prototype. Our solution uses the three.js library to create, manipulate, and display 3D or 2D elements. It is built on top of WebGL, a JavaScript API that accelerates graphic elements rendering in a web browser by shifting the drawing of the elements to the GPU.

A. Dataset generator

Finding appropriate Big Data datasets for Streaming scenarios is not easy. Since our focus was not yet to test our prototype with actual data, we used our dataset generator to create, send, and manipulate ordinal data using a python server script. For example, it allows the creation of a dataset whose values have a positive trend.

B. Elements

The visual representations of data displayed in the visualization are individual elements created by idioms and transitions that manipulate these representations to convey information as intended. All elements are instances of the three.js library, and the required elements were the following:

- **Dots:** Simple, small rectangular planes that represent individual data points.
- **Lines:** Rectangular plane, where its height and angle of rotation are given by two x and y coordinates. The line thickness can also be changed.
- **Rectangles:** Rectangular plane, with a single position. In this case, the rectangle's size or color can be changed. It is also possible to draw borders surrounding the rectangle, accomplished by creating lines for each border. This approach means the rectangles are comprised of five geometries instead of one.
- **Polygon:** This element is needed to create non-rectangle polygons, and it is possible through a buffer geometry by providing a list of vertices positions. This element allows more flexibility since it does not restrict the shape of the visual representation.

C. Visual Idioms

All idioms that we implemented shared an x-axis that encodes the data's timestamp, constantly updated in real-time (fig. 2). Therefore, the visual elements move towards the end of the visualization from the right (newer data) to the left (older data) of the visualization. The y-axis also encodes the ordinal value for the complete visualization.

1) Ordinal Scatter Plot: Shows every ordinal value received in real-time. The dots are restrained into invisible lines representing each current ordinal value. This idiom is intended to depict the arrival of data points and their distribution over time, as each data point is represented in one dot. However, since it applies no aggregation techniques, it designed only as the starting idiom using Graceful Degradation.

2) Heat Map: The length of each cell encodes a period, and the number of points inside the cell determines its color saturation. This idiom is suitable for various periods, but most suitable as a replacement for the Ordinal Scatter Plot.

3) Line Chart: We present, stacked vertically, one line chart for each possible ordinal value. Each data point in those line charts corresponds to the number of occurrences of that particular value over a certain time interval. This allows us to see the evolution of the distribution of values through time. The vertical scale of the line charts is adapted in real-time so that it can accommodate the values it has to depict at every

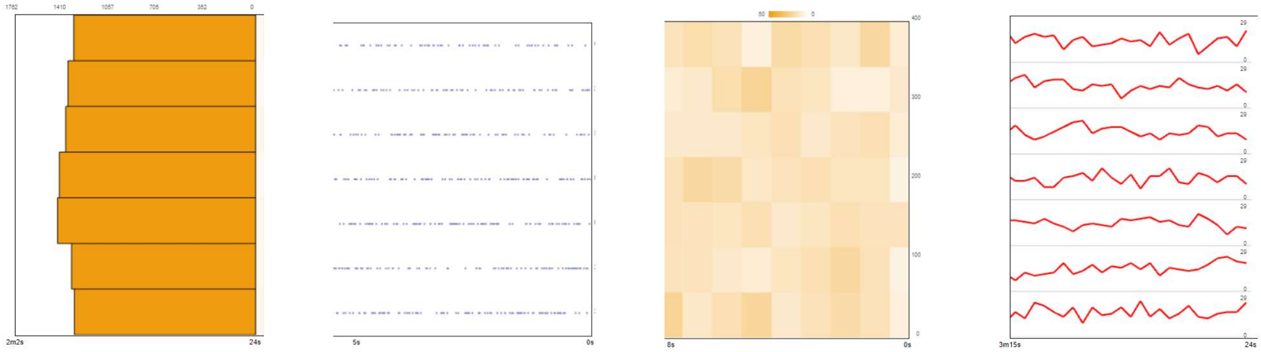

Fig. 2. Visual idioms used in our user study. From left to right, Histogram, Ordinal Scatter Plot, Heat Map, and Line Chart.

moment, taking care to use the same scale for all lines to facilitate comparisons. The idiom was designed to be used as the middle module.

4) Histogram: It worked as the final visual idiom of the data path because it contained information since the visualization initialization. Each bar represented the number of data points for one ordinal value, and the maximum length of the bars was updated to fit the available space in the prototype.

D. Transitions

The transitions referred to in this work are called **horizontal transitions**, which represent the continuity between two idioms, by transforming the elements that represent the data from one idiom to the following idiom's element properties [11], [34]. The goal is to perceptibly show that the information is the same in different aggregation levels. We designed several horizontal transitions, always considering the elements present in the origin and destination visual idioms.

1) Growing Bars: It was applied between the Ordinal Scatter Plot and Ordinal Line Chart (fig. 3). The dots converge on top of a bar in the left boundary of the transition. As a result, the bar will grow to its value in the ordinal line chart. This bar is attached to a line that connects to the following idiom's latest line, creating a seamless connection where there is always a line being produced and growing with each entering dot, giving the idea that they are being grouped by pilling up in a bar whose height is its number of dots.

2) Grouped Dots: It was applied between the Ordinal Scatter Plot and Ordinal Line Chart (fig. 4). The dots converge at the beginning of the respective line segment, giving the idea that the dots group together on the group's future on the ordinal line chart. In addition, the lines' opacity grows the closer they get to the following idiom.

3) Pilot Lines: It is applied between the Ordinal Scatter Plot and Histogram (fig. 5). By scaling the height to zero, the dots convey being merged into a single point. The ordinal values follow a line, and the scaling will almost be unperceivable. After the first third, a single rectangle is created with the dots' size in the following idiom. Once these rectangles hit the idiom boundary, they enlarge to a horizontal bar "pushed" to the following idiom.

4) Morphing: It was applied when the destination visual idiom was either a Heat Map or an Ordinal Line Chart (fig. 6). The elements that leave in the first idiom gradually transform into the elements present in the second. This idea could be done by changing color, opacity, size, and rotation. If more than one element was needed to represent the next element, the first would only morph into a second portion. The element morphing eases the visual transition, and the proportion clarifies how much data is being grouped.

5) Line Squeeze: It was applied between the Ordinal Line Chart and the Heat Map (fig. 7). In this transition, the lines will move towards the boundary while horizontally straightening. Then, after they reach their position in the Heat Map, they increase in height almost as if they were squeezed against the boundary. Multiple lines will likely represent one cell so that each line will depict just a portion.

6) Squares: It was applied when the starting visual idiom was the Heat Map (fig. 8). To understand the number of points inside the expelled element, it divides itself into smaller squares proportional to the total received points in that interval. If the ending idiom is the Ordinal Line Chart, the created squares will transform into small segments by rotating and gradually resizing themselves. If instead, the ending transition is a Histogram, then the squares will enter and increase the size of a bar, like being pushed to the following idiom.

7) Dissolving Lines: It begins in an ordinal line chart and ends in a Histogram, which has the same logic as the Squares transition for the same ending idiom (fig. 9). The only difference is that instead of splitting the element into squares, it "dissolves" the lines into segments during the transition.

8) Stacking Bars: If the ending idiom represents data through rectangles, then this transition is applied (fig. 10). Here, the starting elements transform into rectangles. After transforming, the resulting rectangles make their way to the end of the transition, where they stack on top of other rectangles, giving the idea that they are being aggregated into a single bar.

IV. User Study

To evaluate the effectiveness of the proposed visual idioms and transitions, we conducted a user study with 24 participants via questionnaires created with Google Forms. There were in total six combinations of visual idioms that we could test. Between the Ordinal Scatter Plot and the Histogram, or Ordinal Line Chart. Between the Heat Map and the Histogram, and Ordinal Line Chart. Finally, between the Ordinal Line Chart and the Histogram, and Heat Map. For each combination, we created a questionnaire, and each participant filled a questionnaire in an order generated using the Latin Square distribution.

Each questionnaire started by explaining both visual idioms used in the corresponding combination. After participants learned how each idiom worked, they had to answer several questions regarding the data presented in each one. Since each idiom is used for different tasks, the corresponding questions will be presented in the following sections.

Then, the transitions created for that combination were presented, and, again, participants had to answer several questions. All idioms and transitions were presented via recorded videos, thus ensuring that the data presented was always the same between different participants (please see this link [1] to watch the videos used, plus a demonstration of how VisMillion worked). Furthermore, it allowed them to rewatch the videos if they needed. Since it was not our goal to compare combinations between themselves, each questionnaire had its set of questions created according to the corresponding idioms and transitions presented. Finally, the data presented in the videos were randomly generated to fit the needs of the study, at 100 points per second. Again, since each transition conveys different information, the corresponding questions will also be presented in the following sections.

[1] https://bit.ly/3PtVsiR

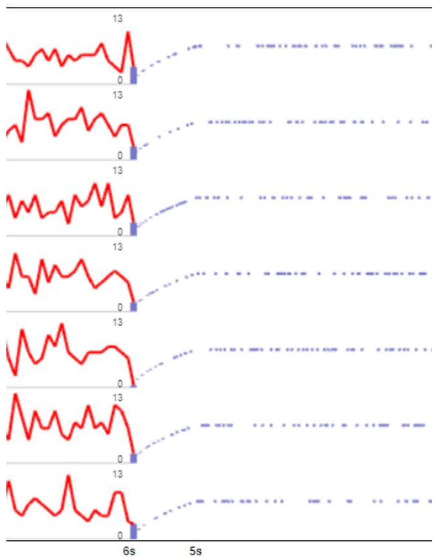

Fig. 3. Growing Bars transition applied between the ordinal scatter plot and the line chart.

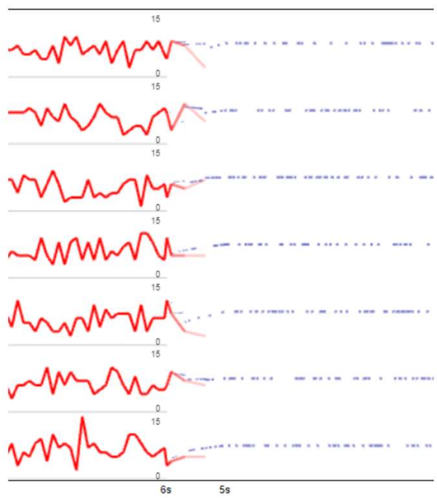

Fig. 4. Grouped Dots transition applied between the ordinal scatter plot and the line chart.

A. Results – Visual Idioms

For the Ordinal Scatter Plot, the video showed an almost binomial distribution on one of the ordinal values, and then suddenly, an agglomeration of points emerged on a distinct ordinal value. The first question tested if participants were able to identify which ordinal value had more data points. The second question tested if they could identify any ordinal value where the number of data points changed significantly. If they did, they indicated which ordinal value via a third question. Participants answered with 100% accuracy the first and second questions, and the third with 83% accuracy. Therefore, **the Ordinal Scatter Plot was an effective visual idiom**.

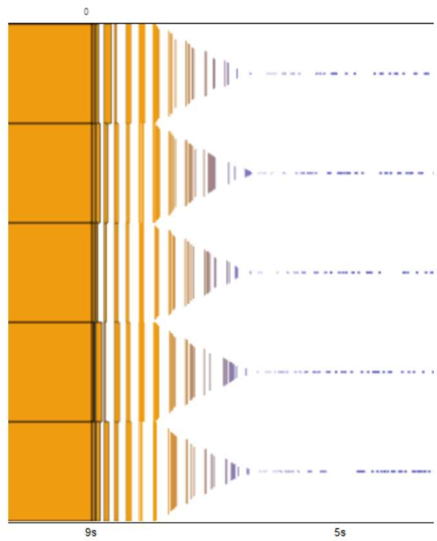

Fig. 5. Pilot Lines transition applied between the ordinal scatter plot and the histogram.

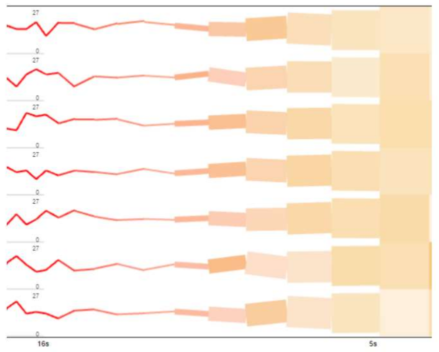

Fig. 6. Morphing transition applied between the heat map and the line chart.

The Heat Map's video followed the same logic as the Ordinal Scatter Plot, and the results were similar. 100% for the first question, 95.7% for the second, and 87.0% for the third. Therefore, **the Heat Map was an effective visual idiom**.

For the Ordinal Line Chart, only the first question was equal to the Ordinal Scatter Plot and Heat Map. The second question asked if they could detect if there were any ordinal values with a positive or negative trend. Then, the third question asked if participants could read the value encoded with the line. The first two questions had high accuracy values, 95.7%, and 78.3%. However, the third only had 56.5%. Therefore, **the Ordinal Line Chart was effective to convey information, except to decode the exact average presented**.

Finally, the Histogram's video demonstrated a simple binomial distribution of points around one ordinal value. The idiom was then tested with just two questions. In the first question, we asked participants which ordinal value had more data points, and in the second we asked the exact number encoded in one particular ordinal value. Accuracy was high for both questions, 100%, and 88.9% respectively. Therefore, **the Histogram was an effective idiom to convey information**.

B. Results - Transitions

The questions regarding the transitions always targeted each transition's aggregation, fluidity, and logic. Aggregation represented how well participants understood how the data shifted from one idiom to another. Fluidity represented how smooth participants thought the transition was. Finally, the logic represented what exactly was happening to the data between visual idioms. In the first question, participants had to answer with a Likert scale from 1 (Totally Disagree) to 5 (Completely Agree) to "The data points are being aggregated." In the second question, again with a Likert scale from 1 (Little Smooth) to 5 (Very Smooth), to "How smooth is the transition?". Finally, participants had to select one true sentence from a set of three. Each one explained how the transition worked, but only one was correct.

In some combinations, we proposed more than one transition (for example, between the Ordinal Scatter Plot and the Ordinal Line Chart). To understand if there were statistically significant differences (when two transitions were proposed) for aggregation and fluidity, each combination of transitions underwent a *Wilcoxon Signed-Rank Test* except for one transition that found a non-normal difference median distribution, in which we tested with the *Sign Test*. Then, for the logic, the question's result had to be tested with the *McNemar's Test*. However, no significant differences were found in any combination for the logic test.

1) From the Ordinal Scatter Plot: To the Ordinal Line Chart, we proposed two transitions. The Growing Bars had statistically significantly better results with $p < 0.0005$ in aggregation and fluidity. Growing Bars had 5 (1) on aggregation and fluidity. Grouped Dots had 4 (1) on aggregation and 3 (2) on fluidity. Therefore, **the Growing Bars transition was better than the Grouping Dots between the Ordinal Scatter Plot and the Ordinal Line Chart**.

2) From the Heat Map: To the Ordinal Line Chart, we proposed two transitions. Morphing had statistically significant better results with $p < 0.008$ in fluidity, but not on aggregation. Morphing had 4 (2) on fluidity, and Squares had 3 (1) on

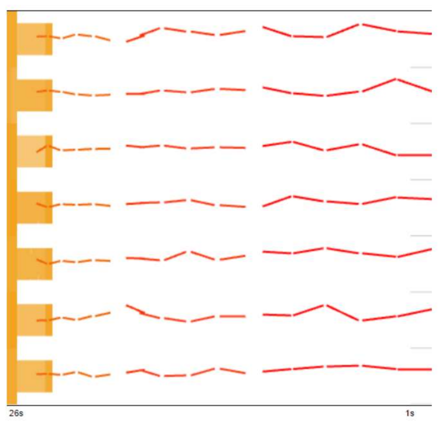

Fig. 7. Line Squeeze transition applied between the line chart and the heat map.

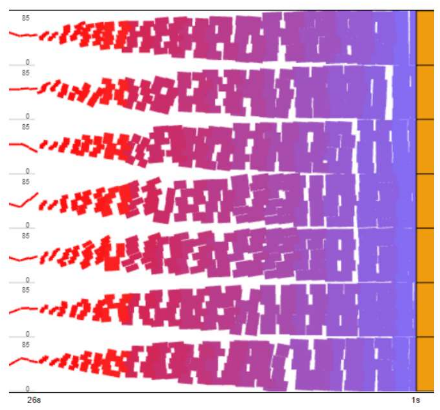

Fig. 8. Squares transition applied between the heat map and the line chart.

TABLE I
THE MOST SUITABLE TRANSITIONS. HEAT MAP (HM), LINE CHART (LC), HISTOGRAM (H), AND SCATTER PLOT (SP) COMBINATIONS.

	HM	**LC**	**H**
SP	-	Growing Bars	Pilot Lines
HM	-	Morphing	Stacking Bars
LC	Morphing	-	Stacking Bars

fluidity. Therefore, **Morphing was a more suitable transition between the Heat Map and the Ordinal Line Chart**. To the Histogram, The Stacking Bars had statistically significant better results with $p < 0.038$ in aggregation and $p < 0.005$ in fluidity. Stacking Bars had 5 (1) on aggregation and 4 (1) on fluidity. Squares had 4 (2) on aggregation and 4 (1) on fluidity. Therefore, **the Stacking Bars transition is a more suitable transition between the Heat Map and Histogram**.

3) From the Ordinal Line Chart: To the Heat Map, we proposed two transitions. The Morphing had statistically significant better results with $p < 0.002$ in aggregation and $p < 0.001$ in fluidity. Morphing had 4 (2) in aggregation and fluidity. Line Squeeze had 3 (2) in aggregation and 3 (1) in fluidity. Therefore, **the Morphing is a more suitable transition between the Ordinal Line Chart and Heat Map**. In the Histogram, we proposed two transitions, and there were no significant differences in aggregation and fluidity. The preference values decided that **the Stacking Bars is a more suitable transition between the Ordinal Line Chart and Histogram**.

C. Summary

The Ordinal Scatter Plot, Heat Map, Line Chart, and Histogram all showed positive results in the questionnaires, with most questions answered correctly by most of the users, proving to be good representations for ordinal data presented in VisMillion. The Line Chart had good results in understanding trends and for value comparison, yet the identification of the exact values returned poor results. The most suitable transitions of the suggested idiom combinations can be found in table I. From our work, we were able to define several design guidelines for Ordinal Big Data Streaming:

- The Ordinal Scatter Plot, Heat Map, Line Chart, and Histogram are effective idioms.
- Line Chart is not good to identify specific means;
- The Growing Bars transition should be used between the Ordinal Scatter Plot and the Line Chart;
- The Pilot Lines transition should be used between the Ordinal Scatter Plot and the Histogram;
- The Morphing transition should be used between the Heat Map and Line Chart and between the Line Chart and the Heat Map.
- The Stacking Bars transition should be used between the Heat Map and Histogram and between the Line Chart and the Histogram;

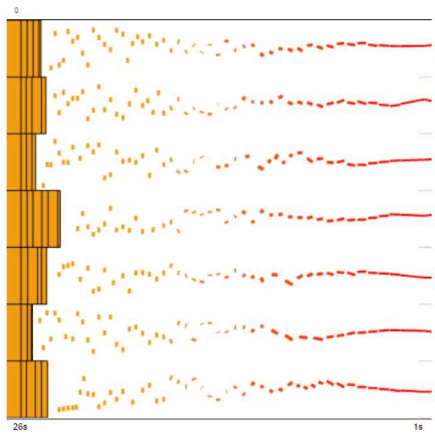

Fig. 9. Dissolving Lines transition applied between the line chart and the histogram.

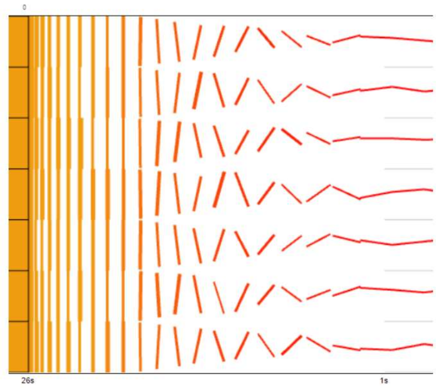

Fig. 10. Stacking Bars transition applied between the line chart and the histogram.

V. DISCUSSION AND FUTURE WORK

Our prototype was able to fulfill some major goals of Big Data Stream: real-time interaction, visual scalability, and personalization [5], [13], [17], [29]. It now supports horizontal transitions for ordinal and quantitative data, and vertical transitions for quantitative data, and allows customizing modules with different visual idioms. However, VisMillion does not yet support data processing and user assistance. Our data was generated by use to test certain scenarios in our user study.

Furthermore, participants were able to see effectively see data via the proposed visualizations, both in individual idioms and corresponding transitions, which is also important in the big data stream pipeline [13], [21], [29], [31]. Finally, VisMillion effectively conveyed information, giving the wanted overview these systems need to have [13], [29]. We believe the future for VisMillion is to integrate the missing components needed for Big Data Stream. First, real streamed datasets are usually dynamic [5], and their size leads to unprepared systems overflowing [5], [13], [15], [29]. Then, due to this dynamic restriction, VisMillion must be able to adapt according to the data it received to help users detect anomalies [10], [30].

VI. Conclusion

Big Data Streaming visualizations are currently a challenge in research. There is the need to develop systems that handle vast datasets in real-time, represent them without producing visual clutter, and allow people to overview data across time. VisMillion works as a solution by presenting information in different periods, each with a specific visual idiom, via Graceful Degradation, resulting in different levels of aggregation between them. We proposed visual idioms and transitions for the streaming of ordinal big data. We explored via a user study which visual idioms and transitions were the most effective, and defined guidelines for choosing combinations.

Acknowledgements

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Session 2: Virtual and Augmented reality I

chair: Nuno Rodrigues

Tangible Objects in Virtual Reality for Visuo-Haptic Feedback

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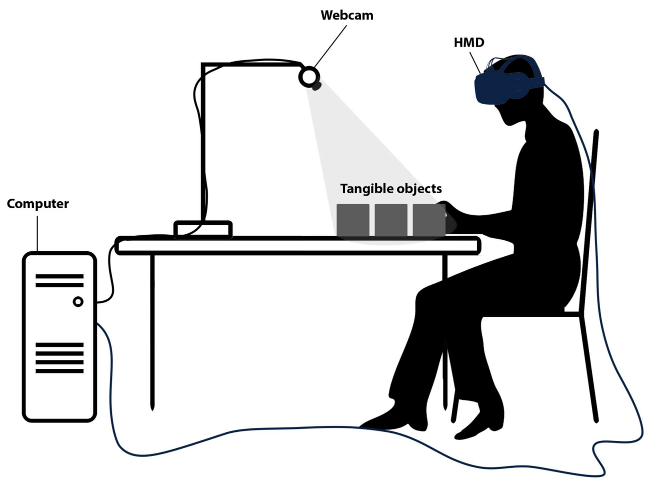


Fig. 1: In the proposed approach, tangible objects are tracked using a marker-based method for passive haptic feedback. Each object is tagged with a static image captured by cameras to determine the object's position and orientation in the virtual world.

***Abstract*—Including tangible objects in Virtual Reality (VR) can improve the interaction and immersion in virtual experiences. Users' hands are freed to interact directly with physical objects and thus receive realistic haptic feedback that complements the primarily visual information offered by the Head-Mounted Display (HMD). The challenge in this area relies on tracking and mapping physical objects into the Virtual Environment (VE). Most methods require attaching sensors to the objects being tracked, usually resulting in object-oriented solutions, making the system inflexible to track different props. In this paper, we propose a marker-based approach that uses computer vision to make the system flexible to different objects, requiring few additional hardware resources. Using the developed prototype, we conducted a user study to analyse hand representation's impact on the performance of tangible object manipulation tasks. We studied three conditions for hand representation: no hands, a realistic model of the human hands, and an abstract model (two spheres). Our results showed that users were able to interact with the proposed tangible system easily. Of the three hand conditions, participants performed better without any hand representation and took longer to complete the task under the abstract model. These results suggest that passive haptic feedback may be sufficient to give users a good spatial perception of the tangibles, discarding the need for a visual representation of the hands in this context.**

***Index Terms*—virtual reality, haptics, physical props**

I. INTRODUCTION

Virtual Reality (VR) mainly relies on visual and audio feedback generated by the Head-Mounted Display (HMD). Although the handheld controllers commonly used in VR produce vibrating patterns, they offer poor haptic feedback and imply a learning curve to introduce working with them.

Haptics becomes essential to improve immersion, interaction, and imagination by transmitting information that is hard to interpret only through vision and audio. One open challenge relies on more abundant haptic feedback patterns, such as texture, thermal feedback and skin stretch. The standard handheld controllers poorly offer these sensations. Although more complex devices (e.g., Phantom Desktop, wearable devices) could reproduce more tactile stimuli, they are expensive solutions not always comfortable and suitable for all scenarios. True haptic interfaces should allow users to interact with the system with their bare hands for highly realistic stimuli. Approaches have been proposed to integrate tangible objects into the virtual world. Most methods require attaching sensors to the physical objects, usually resulting in object-oriented solutions, making the system inflexible to track different objects.

We propose a marker-based solution to create tangible VR experiences with high-quality haptic feedback and low hardware costs. Marker-based approaches are commonly used in Augmented Reality (AR) applications for tracking static images (markers) through computer vision technology. We suggest applying these methods in VR applications.

Although tangible interfaces allow users to manipulate physical objects with their bare hands, haptic cues may not dispense with the representation of hands or at least some indication of their location in the virtual space for a better spatial perception. However, although realistic virtual human hands can increase embodiment – i.e., the user has the perception of owning the avatar's body – it may not be the best approach as they may obscure user visibility in certain tasks. To better investigate this topic, we conducted a user study to analyse the performance impact hand representation can have on manipulating tangible objects in VR. We are interested in analysing whether the hand representation offers a better spatial perception of the arrangement of physical objects or, on the other hand, if passive haptic feedback is sufficient for intuitive manipulation. To this end, we set the following research question:

Research Question: *Does the hand representation help the user perform the proposed tasks in a tangible VR context?*

II. Related Work

The core concept of VR is the multisensory stimulation of the user, which makes it possible to feel present in a virtual world. HMDs produce visual stimuli, and headphones provide audio information. The handheld controllers produce vibrations that stimulate the touch; however, haptic feedback goes far beyond vibration patterns. In the real world, textures, shapes, materials and temperatures are sensations that influence human perception and emotions within a VR experience. To enhance the realism of virtual experiences, it is essential to transport these haptic sensations to VEs.

A. Haptic Interaction in Virtual Reality

Enabling haptic feedback in VR has contributed to more realistic virtual experiences such as surgical training [1], rehabilitation [2], or storytelling [3] scenarios. Haptics means both force feedback – simulating object hardness, weight, and inertia – and tactile feedback – simulating surface contact geometry, smoothness, slippage, and temperature. Haptic feedback can be classified into three categories [4]: active, passive and a combination of active and passive.

Active haptic feedback consists of computer-controlled actuators that exert forces on the user during operation. Lightweight vibrotactile actuators, skin stretch mechanisms, Phantom haptic interface, and wearable devices (e.g., gloves) are examples of active haptic devices.

Passive haptic feedback does not require actuators since the physical props in the real environment provide tangibility to virtual objects. It is a low-complexity approach that provides highly realistic haptic feedback by letting users interact with real objects, called proxies or props.

Mixed haptic feedback combines the strengths of active and passive haptics. The actuators are not used to actively render forces on the user but to transform the prop itself to change how it feels. This enables a single prop to provide different passive haptic impressions. A prominent example is the concept of encounter-type haptics or Robotic Graphics [5].

Besides these approaches, other techniques rely heavily on pseudo-haptics [6] that use visual feedback to trigger haptic perception. Other concepts like redirected touching [7] and haptic retargeting [8] use the visual dominance effect by warping the virtual space or the user's hand to modify how users touch tangible objects.

Active haptic feedback provides flexible feedback; however, the complexity, limited mobility, or limited workspace are significant limitations. Passive haptics offers much more realistic feedback by enabling touching real surfaces and materials. The challenge relies on mapping everyday props onto VEs; they need to be appropriately tracked to determine their position and orientation in the virtual world.

B. Sensor-Based Approaches to Tracking Physical Objects

Developing tangible interfaces in VR usually requires additional hardware to track physical objects' position and pose. Diverse systems have been proposed, from active to passive haptics. Most methods involve attaching sensors or devices to the objects intended to be tracked. In recent years, the Vive Tracker has been frequently used for this purpose as it allows accurate gathering of position and pose information [9, 10]. The Bonita Vicon system has also been used, attaching its markers directly to objects and/or the user's body [11–13]; one or more optical cameras then track the markers. Other works propose the creation of their own devices or systems to be subsequently incorporated into tangible objects [3, 14, 15]. Below we will present research works that exemplify the different methodologies listed.

Cheng et al. [9] created a game with props to make the experience more engaging. One of the objects used was a ball on a pendulum representing objects that move and demonstrate proactive behaviour, such as a group of flying droids that physically attack the user. The tracking was ensured by attaching Vive Trackers to the physical objects used. Another method was presented by Tingyu et al. [12], using the Bonita Vicon optical tracking system. Whenever users grasp the physical object, they also hold its virtual representation since the system tracked subjects' thumb and index fingertips using markers placed on the dorsal side of their fingers. A 3D-printed support was used to ensure a good matching between the positions of the tangible object and the virtual object.

Harley et al. [3] developed a system for diegetic tangible objects in VR narratives. A device-agnostic sensor unit was attached to the physical object, featuring active and passive haptics. In this work, the tactile sense's inclusion helped immerse the user in the narratives being told. Also presenting a new toolkit, Arora et al. [15] proposed VirtualBricks as an alternative to conventional VR controllers; it is a LEGO-based toolkit to create custom controllers, enabling actions such as shooting targets using a gun or catching a fish by rotating the fishing reel.

The examples covered comprised a variety of methods used to integrate tangible objects into the virtual world. All methods involve adding devices to the system beyond the standard VR setup, and solutions like Tingyu et al. [12] require prior knowledge of the props so that the system can be custom designed. Such approaches are adequate to ensure that the desired objects are accurately tracked and mapped into the virtual world; however, adding hardware to the system every time a new prop is introduced shows to be expensive and challenging to scale solution.

C. Marker-Based Approaches to Track Physical Objects

A typical marker-based AR system consists of a camera, a processing unit, a display and markers [16]. The camera captures the real-world scene containing the markers while the processing unit generates and renders the virtual contents over the captured scene. The display unit - usually a smartphone display - shows the seamless integration of the virtual object with the real world. For marker detection, a global thresholding method has been used that is prone to illumination changes and blurring. The marker's inner boundary includes an image fed to the system a priori, and the identification is achieved through template matching.

Vuforia Engine[1] is a SDK widely used for AR development that employs computer vision technology to recognise and track planar images and 3D objects in real-time. Briefly, the Vuforia library uses Natural Feature Tracking (NFT) algorithms with an approach similar to Scale Invariant Feature Transform (SIFT) to detect feature key points and determine the scale of the marker. Thus, the target images should be markers rich in feature key points, i.e., images with sharp, spiked, chiselled details and contrasts, with bright and dark regions and well-lit areas. Knowing the image and its key points beforehand, Vuforia will track them to calculate the object's position and orientation. The more key points, the less likely tracking failures will occur. This computer vision technology allows multiple markers to be tracked simultaneously, requiring only one camera and static images previously fed to the system.

Mobile VR comprises virtual experiences in which a smartphone is used as HMD. This VR category allows using AR methods since smartphone cameras are compatible with this technology. Cardoso and Ribeiro [17] proposed a tracking solution for smartphone-based VR. The system does not require additional hardware instrumentation since the smartphone used to display the VE also detects a physical book's pages through marker-based computer vision. The book pages have been marked with target images that will be crawled and rendered in the virtual world with the desired content.

Applying marker-based approaches to standalone and stationary HMDs will pave the way to create tangible experiences that are cheaper and more flexible to diverse objects; adding a new prop would only require presenting the system with the new target image to be tracked.

[1]Vuforia Engine: https://developer.vuforia.com/ - Last accessed 15/07/2022

D. Virtual Hands

Some tasks in VR demand hand representation, or at least some reference about their position in the virtual space. In particular, controller-free tasks usually require a more realistic model of the hands to enhance body ownership, i.e., the feeling that the artificial body is one's own body and the source of sensations.

The Rubber Hand Illusion, initially presented by Botvinick and Cohen [18], was a pioneering study on the virtual body and how the human brain resolves visual and perceptual stimuli, leading to a rubber limb's appropriation. Further studies have shown that the virtual hand's structural and appearance differences might affect the sense of ownership, presence and performance. Lin et al. [19] compared six geometric models with distinct appearances to investigate the effects of different realism levels, render styles, and sensitivities to pain on the virtual hand illusion. Experiment results indicate that the illusion can be created for any model, even for an abstract model such as a wooden block — nevertheless, the more realistic the model of the human hands, the stronger the effect. In another similar experiment, the results were the opposite. Grubert et al. [20] studied the impact of different hand models on typing performance. The results revealed a high input rate, low error rate and user preference for a minimalistic fingertips model. In contrast, a more realistic hand representation had a higher error rate. It suggests that minimalistic representation may enhance keyboard visibility while realistic hands do not allow as much visibility. There are several other studies on the impact of different hand models on presence, embodiment and perception in VR experiences [21–24]. A realistic human hand model can increase body ownership and presence; however, it can impair performance if the chosen hand model is not suitable for the task at hand.

Some HMDs (e.g., Oculus Quest 2, HTC Vive Cosmos) have built-in cameras capable to track users' hands. As an alternative to embedded sensors, hands can be captured by two main approaches: optical trackers or inertial trackers [25]. Optical trackers include vision-based systems such as the Microsoft Kinect or the LeapMotion. These systems' advantages are that they are cheap and easy to use (plug and play). On the other hand, they may not be suitable for applications where the hands are not always clearly visible. Inertial trackers or data gloves offer a more accurate representation; as a drawback, they are more expensive, requiring proper calibration and data filtering to obtain acceptable tracking performance. Other more invasive approaches rely on devices that are attached to the user's hand (e.g., Vive trackers, gloves, Vicon Bonita system) or camera-based solutions that use computer vision to detect markers previously placed on the user's hands [17, 26, 27].

III. Tangible Objects in VR for Visuo-Haptic Feedback

Our vision is to create a scalable and flexible tracking system suitable for objects with different morphologies. To this end, we propose a marker-based approach for VR applications, in which physical objects are pre-tagged with target images known in advance by the system. These markers are tracked in real-time by cameras that can be positioned in the play area (e.g., standard webcam) or installed on the HMD (e.g., ZED Mini), as shown in Fig. 1.

Fig. 2 presents a high-level architecture that shows the connection of the main components of the proposed framework. The user receives visual and audio feedback through the HMD and passive haptic feedback by interacting directly with tangible objects. The objects are tracked by an application that uses a camera and computer vision technology to recognise and track the planar images stuck to the objects. The position and orientation gathered are then used in the VR application responsible for rendering the virtual world, including the virtual representation of the props.

As a proof of concept, we applied this approach to track three tangible objects – one cube and two triangular prisms (right triangle) – whose top face was previously marked with a static image, as shown in Fig. 3. We used a webcam placed above the table and the Vuforia SDK to determine in real-time the position and orientation of each object. According to these coordinates, real objects were mapped into the virtual world, as illustrated in Fig. 4.

In this example, we can evidence the capabilities of the proposed haptic system. The user had to arrange the objects to match the puzzle displayed at the head of the table. This task would become more time-consuming if the user had to rearrange the pieces using the handheld controllers. Allowing the user to assemble the objects with their bare hands offers greater precision, especially in the more detailed rotations; the interaction becomes more natural and effective.

Starting from this system, we built a VE to study different interaction scenarios. Namely, we explored the effect of latency during the tangibles' manipulation and a novel haptic redirection technique using non-Euclidean geometry [28]. However, in this paper, we will only present the scenario where we study the impact on the performance of the hand representation in the manipulation of tangible objects in VR.

IV. Virtual Hand Models

To study the impact of representing virtual hands in a passive haptic feedback scenario, we defined three conditions: no hands (H0), human hand model (H1) and abstract hand model (H2). We were primarily interested in investigating whether the virtual hands – whether more realistic or minimalist – help users perform the tasks by complementing the haptic

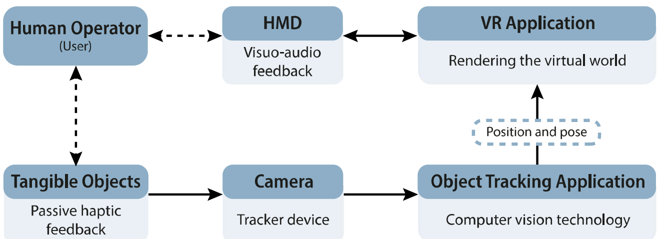


Fig. 2: High-level architecture of the marker-based system.

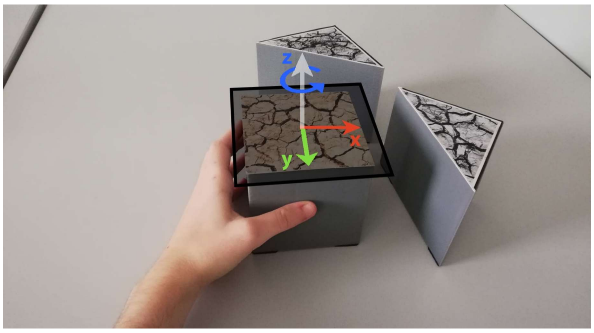


Fig. 3: The tasks used as a case study required the user to rearrange the tangible objects by translations along the x-axis and z-axis and rotate them about the y-axis (vertical).

Fig. 4: Proof of concept of the marker-based approach using a webcam and three objects tagged with static images.

feedback with visual cues about hand position in the virtual space. Subsequently, we intend to investigate whether there is a significant performance difference between a more realistic or minimalist hand model. That is, we wanted to analyse whether there is a benefit between using a more realistic model similar to human hands or whether it is sufficient to use a simpler model that only works as an indicator of the hands' position in the virtual world.

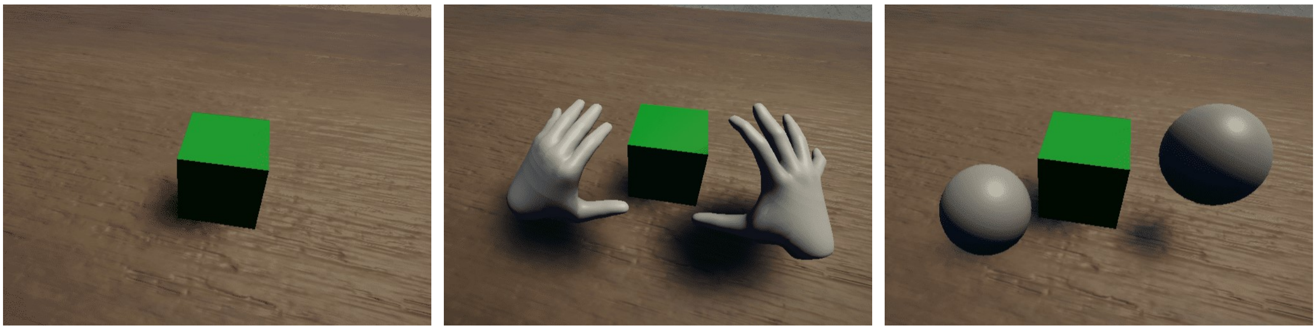
Fig. 5 shows the three conditions studied. The human hand model was implemented using the Vive Hand Tracking SDK. This tool uses the built-in cameras of the HTC Vive Cosmos headset to track the hands. The engine supports left- and right-hand tracking with inner-level positional tracking, consisting of 21 points: four points per finger and one point at the wrist. The hand model is dynamically rendered through the position of the 21 points. The abstract model reuses the exact mechanism for tracking hands, but a sphere model is used instead of hands; the sphere model provides a simple way of presenting the hand position without any indication of orientation.

V. User Study

To evaluate the developed system and answer the research question, we conducted a user study. This section presents the adopted case study, user study design and protocol.

A. Case Study

The chosen task was purposely designed to avoid introducing bias from complexity. The objects have simple geo-



(a) No hands (H0). (b) Human model (H1). (c) Abstract model (H2).

Fig. 5: The three hand models studied.

metric shapes, and the game has basic object manipulation (translation and rotation). As a case study, we designed the Puzzle Game (Fig. 4), in which the users interact with the tangible objects to assemble the figures displayed in front of them. In this context, a puzzle is a construction composed of a square and two triangles, with different arrangements and orientations. The user must use the tangibles to recreate the displayed figure. The game ends after the user successfully completes four puzzles, displayed one after the other.

B. Experimental Design

The user study assessed the user's performance and preference under the different hand model conditions. More than evaluating performance, we were interested in knowing their opinion about the different hand conditions. A hand model may be suitable for performance improvements; however, it may not suit user preference or vice versa. For this reason, after the participants performed the task under the three different conditions, they were asked to rank the three models in order of preference (from most to least preferable). To minimize breaks in presence, the preference question appeared embedded in the VE, as shown in Fig. 6. Participants answered the question aloud to feel free to substantiate their choices.

All the participants performed the three hand conditions (H0, H1 and H2). The order in which the conditions and the puzzles were presented to the participants was counterbalanced using the Latin-square assignment by systematically varying the order in a full permutation. Therefore, we did not choose a fixed order that could bias the results by learning or fatigue factors. In each condition, the system recorded the time it took participants to complete the task, i.e., the completion time of four puzzles; the researcher recorded the participant's answer to the preference question, as well as their justifications, comments and behaviours demonstrated throughout the experiment.

C. Procedure

All participants performed the experiment in the same room, under the same external conditions. The researcher started by briefing the participant on how to move the tangible objects to avoid covering the target images. Then the participant was equipped with the HMD, and the researcher presented the Puzzle Game. The research questions were not revealed so that the participant's behaviour would not be biased. The researcher only warned the participant that there might be some differences during the game, and a question would appear at the end of the experiment. After completing all the conditions, the participant was asked to fill post-experiment questionnaires regarding cybersickness (Simulator Sickness Questionnaire (SSQ) [29]), presence (Igroup Presence Questionnaire (IPQ)[2]) and a demographic questionnaire to gather data about age, gender, sight problems, and VR and video game experience.

VI. Results

This section will start by presenting the raw results, which are detailed in the tables and graphs. An in-depth discussion will follow in the next section. The data were analysed using the Friedman test for repeated measures and the Wilcoxon signed-rank tests with Bonferonni correction for post hoc pairwise comparisons. It was measured at a 0.05 confidence level.

[2]Igroup Presence Questionnaire: http://www.igroup.org/pq/ipq/ - Last accessed 15/07/2022

Fig. 6: Preference question displayed after the user performs the three hand conditions under study.

A. Demographics

A total of 28 participants (20 male and 8 female) aged between 18-35 (M = 23.00, SD = 3.66) took part in the experiment. Participants were university students of science and engineering courses from the authors' affiliation; all participants took part in the study on a voluntary basis. In the characterisation questionnaire, 16 participants indicated they had never used VR before, and 15 reported playing video games frequently (every day or every week).

B. Performance

After running the Shapiro-Wilk normality test, we verified that data reject the assumption of following a normal distribution. Therefore, the Friedman test was the statistic used to compare the completion times of the three conditions.

There was a statistically significant difference in completion time depending on which hand model was displayed, $\chi^2(2) = 6.000$, $p = 0.050$. Post hoc analysis with Wilcoxon signed-rank tests was conducted with a Bonferroni correction applied, resulting in a significance level set at $p < 0.017$. As highlighted in Table I, the significant difference lies between H0 and H2 ($Z = -2.550$, $p = 0.011$), where condition H2 showed a longer completion time, suggesting that the abstract model led the user to take longer to complete the task.

We can thus verify that participants showed better performance when they executed the task without any spatial indication about the virtual hands (H0). Complementarily, the results suggest that the abstract hand model (H2) led the users to take longer to complete the task. Relatively to the more realistic hand model (H1), the results showed that it did not cause a significant impact on performance.

C. Preference

After playing the Puzzle Game under the three conditions, each participant was asked to rank the three conditions in order of preference, from most to least preferable. The collected answers are presented from the stacked bar chart in Fig. 7. Analysing the results, it is clear which hand model is most and least preferred by the participants. The majority of the population (71.43%) reported preferring to perform the task without any representation of the hands (H0). As a less preferable option, most participants (64.29%) chose the abstract model (H2). In turn, the human model was more often (53.57%) chosen as the second option (H1).

D. Qualitative Feedback

The participants who preferred performing the task without any hand representation gave identical justifications. As they could perceive the objects by touch, they did not feel the need to see the hands. In some cases, the hands even got in the way because they partially covered the (virtual) objects.

The Vive Hand Tracking SDK used to track the users' hands presented occasional errors. Although sporadic, these tracking breaks showed to be distracting and annoying for some participants. However, some of the participants who chose the hand model as a second option complemented their choice by saying that if the tracking worked perfectly, they were likely to prefer this model in the first place.

When the abstract model appeared, some participants did not immediately realise that the spheres represented hands. In particular, nine participants thought that the spheres were obstacles to making the task more difficult since, in their opinion, the spheres covered their field of vision. Even so, three participants reported preferring the abstract model because it offered a visual reference about the position of the hands without being so distracting compared to the human model.

VII. Discussion

The results obtained in our user study made it possible to verify that the representation of hands in the tangible VE does

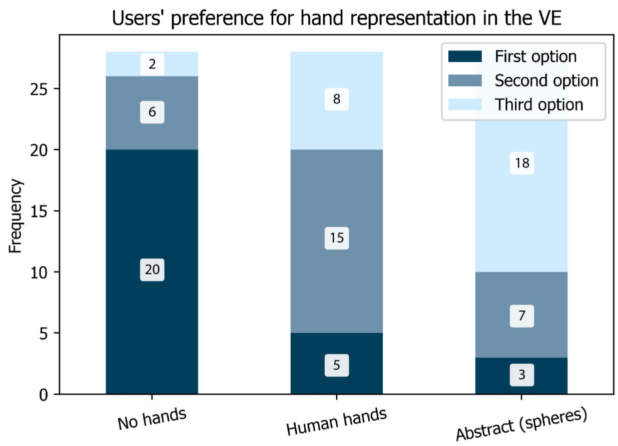


Fig. 7: Stacked bar chart with the participants' answers collected on the preference question.

TABLE I: Statistical results regarding participants' completion time for each hand model condition. The shaded grey cell highlights a statistically significant difference between conditions.

	Completion Time (seconds)		**Friedman Test** α = 0.05		**Pairwise Comparisons**		
Conditions	*Mean*	Std. Dev.	χ^2	*p*	*Pair*	*Z*	*p*
H0 - No Hands	110.27	29.43	6.00	**4.99×10^{-2}**	H0 - H1	-0.96	3.39×10^{-1}
H1 - Human Model	115.45	27.70			H0 - H2	-2.55	**1.08×10^{-2}**
H2 - Abstract Model	122.04	26.50			H1 - H2	-1.43	1.51×10^{-1}

not contribute to improved performance. Although the human hand model (H1) did not significantly affect performance, it did not improve it either. Yet, users took more time to complete the task under the abstract model condition (H2), showing a significant decrease in performance. These results can be justified by our 1-to-1 mapping between the real and virtual spaces offering such precision that participants could easily situate and handle the tangibles in front of them, even with the VR headset on; the visibility of virtual objects was shown to be compromised when adding the virtual hand representation, acting as a distracting factor. Regarding participants' preferences, we could verify that most preferred performing the task without any representation of the hands (H0). Comparing the human model (H1) and the abstract model (H2), the model more similar to the human hand was preferred by most participants.

The statistical results are in line with the reported observations made throughout the session: the hand models studied could have acted as obstacles during the task, or the occasional errors in hand tracking mechanism could have been distracting for users. The population showed a significant preference for performing the game without any hand representation, only using haptic memory, which turned out to be the condition with the best performance results. Similarly, the abstract model was the least comfortable for users, reflected in the weakest performance among the three conditions.

These findings suggest that hand representation may be dispensed in VR experiences with passive haptics since the haptic feedback showed to be sufficient for users to have an excellent ception of the physical objects and then to perform the task without any difficulty.

Additionally, from the cybersickness (SSQ) and presence (IPQ) questionnaires, we validated our implementation. The results of the SSQ suggest that the environment created was pleasant for the users, who did not show symptoms of discomfort beyond the expected mild fatigue at the end of the experience. The IPQ results generally show participants' engagement with the virtual world. However, the questions assessing user involvement with the VE showed that most participants continued to pay attention to the real world. This score can be justified by the participants having answered aloud the preference question. This decision was made to encourage the participants to think aloud during the experience. In fact, it allowed us to gather valuable information about the users' opinions. In return, it could have avoided the total abstraction of the real world. Although this score does not invalidate the implementation of the system, it can be a relevant result to motivate a different design of questionnaires where it is crucial to ensure the total immersion of users.

In brief, users interacted with the tangible objects intuitively, as if they were handling them naturally in the real world. Even without the representation of hands, participants were able to have a good spatial perception to locate objects on the table and manipulate more than one object simultaneously with translation and rotation accuracy. This intuitive interaction would be hardly achieved using standard handheld controllers. Therefore, we consider that the proposed approach offers intuitive interaction complemented by realistic haptic feedback that makes the experience more natural and engaging.

VIII. Conclusions

This paper proposes a marker-based approach to integrate physical objects into VR experiences. We conducted a user study with 28 participants to validate the developed prototype and investigate the impact of hand representation on the manipulation of tangible objects.

We started by presenting different methods to integrate everyday objects into VR experiences to improve the sense of presence and immersion. Most methods require attaching sensors to the objects, using Vive trackers, Bonita Vicon system markers or device-agnostic sensor units. While all of these approaches are valid and serve the purpose of creating more immersive VR experiences rich in haptic feedback, they position themselves as purpose-designed systems for a given object, making it complex and expensive to scale the system for multiple and diverse props. We suggested applying computer vision algorithms commonly used in AR applications to create cheap, scalable, and flexible VR systems for physical objects of different shapes and sizes. These mechanisms allow collecting real-time information about the position and orientation of each object; this information is made available to the VR application to render the VE and the virtual representation of the physical entities. In hardware-based approaches, including a new object requires adding hardware to the system; this does not happen in our marker-based approach. Adding a new prop only requires marking the object with an image and adding that image to the marker database that the system must track.

The hand representation in VEs provides the user with information about the position of their hands in the virtual space. This information is usually indispensable in experiences without haptic feedback; users have to rely on vision to know where they are pointing or what objects they are grasping. Our study suggests that virtual hands may be dispensable in a VE with passive haptic feedback if the tangibles offer enough tactile information for a good spatial perception. Moreover, in the scenario studied, the representation of hands was an obstacle for some participants who reported that the hand model blocked their view. These results join other related work presented in section II-D, highlighting the importance of adopting appropriate hand models for each context. Depending on the task, minimalist models may be preferable to more realistic models, or vice versa. In the case explored, haptic information showed to be sufficient for users to handle tangible objects. Thus, answering our research question, our study does not support the hypothesis that hand representation can significantly help users perform haptic tasks. The tangibles had shapes and sizes that showed appropriate for intuitive interaction, ruling out the need for virtual hand mapping. Participants not only performed better in the no-hands condition (H0), but it was also their preferred condition. The hand models H1 and H2 behaved as obstacles for some users by partially hiding the virtual objects. In particular, the abstract model (H2) caused a significant increase in task completion time.

In a nutshell, as contributions, we highlight our marker-based approach as a scalable solution to integrate different physical objects into VR experiences, offering the user realistic passive haptic feedback that can dispense with virtual hand representation.

IX. Future Work

As ascertained by the related work surveyed (section II-D), the results and subsequent conclusions may be partly task-dependent. The tangibles in our scenario had simple geometric shapes easily perceived through touch, which could have made it possible to dispense with the representation of hand position in the virtual world. In future work, we aim to test objects with more complex properties and mark multiple faces to mitigate the possible occlusion of the markers due to users' hands. We also seek to experiment with more complex tasks and scenarios where the tracking camera is installed on the HMD to enable higher mobility tasks.

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