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Visual Perception and Cognition by the Means of Interactive Digital Replicas of Museum Artifacts: Leonardo da Vinci's Drawings as if They Were in Visitors' Hands

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Abstract: Technologies and applications developed to assist and promote museum activities and cultural exhibitions have evolved significantly during the last decade, as has been proven by many works published in the scientific literature. This paper addresses a study developed with the specific purpose of understanding the possible knowledge-transfer outcomes of a digitization process meant to replicate original drawings by Leonardo da Vinci in the digital domain, allowing museums' visitors to explore them as if they were manipulating the original artworks through custom interactive artifacts. A report is presented here to evaluate and investigate the didactic effectiveness of the fruition devices set up during a real exhibition, with a focus on the application dedicated to the drawing *Study for the Adoration of the Magi*, part of five artworks by Leonardo selected for exhibition during the reported event. The results encourage the adoption of this kind of technology for disseminating information at different levels, especially when knowledge contents are successfully explicated through proper didactic mediators.

Keywords: real-time rendering; digital replicas; Leonardo's drawings; didactic mediation; effectiveness of educational devices; instructional design/educational technologies; learning and teaching in museums

Citation: Garagnani, S.; D'Ugo, R.; Lupi, A.; Martini, B.; Salvucci, M.; Susta, M.; Tombolato, M.; Barsanti, R. Visual Perception and Cognition by the Means of Interactive Digital Replicas of Museum Artifacts: Leonardo da Vinci's Drawings as if They Were in Visitors' Hands. *Heritage* **2023**, *6*, 1–25. https://doi.org/10.3390/heritage6010001

Academic Editor: Andreas Aristidou

Received: 30 October 2022
Revised: 5 December 2022
Accepted: 15 December 2022
Published: 20 December 2022

1. Introduction

Contemporary technologies for digital documentation play an important role in the safeguarding, management, and enhancement of cultural heritage, as it is nowadays recognized as a human-centered intrinsic value for adaptive reuse [1]. Starting from the early 2000s, there has been a continuous, exponential growth in the technologies adopted to collect and manage data from the digitization of artifacts and sites of interest [2]. However, it is difficult to specify shared standards for digitization, as the indicators that would define them are constantly being redefined due to diverse contexts, regulations, and codes. These often try to isolate and organize parameters and features related especially to digital imaging rather than the replication of the appearance of artifacts, drawings, or paintings.

Since the 1990s, the research has increasingly moved towards a friendly return of information, placing the end user at the center of the experience. Since this shift, visitors to museums, scholars, art historians, curators, and restorers have been relying more and more on digital applications intended for visually exploring and understanding the characteristics of surfaces and materials belonging to many kinds of objects in search of realism, accurate shapes, and responsiveness. Nevertheless, when considering research purposes in scientific fields, the digitization of cultural heritage using advanced approaches is now mainly configured as a domain for experts, while the use of technical knowledge for educational purposes is still a kind of chimera (however, it is recognized as a stimulus for the enjoyment of cultural content by a general audience) [3]. This paper explores the didactic outcomes of the application of a customized strategy based on the acquisition and visualization of ancient fine drawings using digital media to address both the needs of scholars and museum visitors, giving particular care to the educational experience and knowledge transfer fostered by 3D models.

After an introduction to the novel framework developed to narrate cultural details behind the artworks displayed in museums through a custom application called InSight Leonardo (ISLe), a deep analysis of how it was perceived during a real exhibit will be presented. Data and their interpretations are based on *Leonardo, Anatomia dei disegni [Reloaded],* an ongoing exhibition open since 19 April 2022 at the Museo Leonardiano, Castello dei Conti Guidi, in Vinci.

The exhibit, curated by Pietro C. Marani, Roberta Barsanti, Fabrizio I. Apollonio, and Marco Gaiani, aims to make the creative processes in Leonardo's graphic works more understandable through the reproduction and digital presentation of some of his drawings. The event is also targeted at bringing visitors closer to Leonardo's drawing method. His graphic creations were often the result of a deep study process, which led to a sedimentation of ideas on the paper that overlap through repentances, variations, and finishes. The term "Reloaded" in the exhibition title refers to an upgrade of the exhibition, which was formerly organized in Bologna (from 23 November 2019 to 19 January 2020). Five drawings by Leonardo are exhibited in the form of interactive digital replicas on five different 55 inch-wide touch screens, which will later be described.

The interactive drawings, with their respective paper replicas displayed on the side to invite visitors to make comparisons, were chosen as follows:

- *Landscape*, 1473, recto: pen and iron–gall inks, lead point, blind point on paper; verso: pen and iron–gall inks, black and red chalk, lead point, blind point on paper, 194 × 285 mm, preserved at Le Gallerie degli Uffizi, GDSU in Florence, inv. 8P.
- *Study of various buildings in perspective (study for the background of the Adoration of the Magi)*, around 1481, metal point, reworked with pen and iron–gall ink, brush and diluted iron–gall ink, partially oxidized white-gouache highlights (basic lead carbonate), stylus, and compass on light-brown prepared paper, 164 × 290 mm, preserved at Le Gallerie degli Uffizi, GDSU in Florence, inv. 436 E.
- *Two mortars launching explosives*, around 1485 (or shortly after), traces of black pencil (?), stylus tip, pen and iron–gall ink, diluted ink, and watercolor with reworking on the right side, 219 × 410 mm, preserved at the Veneranda Biblioteca Ambrosiana in Milan, Codex Atlanticus, f. 33.
- *Study of proportions of the human body* (known as *The Vitruvian Man)*, around 1490, metal point, pen and iron–gall ink, watercolor–ink touches, stylus on white paper, 345 × 246 mm, preserved at the Gallerie dell'Accademia, Gabinetto dei Disegni e delle Stampe in Venice, inv. 228.
- *Fortress with a square plan, with very high scarp wall and concentric layout, with corner towers and grandiose ravelin in front*, 1507 or later, pen and iron–gall ink on black pencil, 131-207 × 436 mm, preserved at the Veneranda Biblioteca Ambrosiana in Milan, Codex Atlanticus, f. 117.

The five digital replicas were positioned following a precise visitors' path, beginning on the ground floor of the Museo Leonardiano with *Two mortars launching explosives* placed in the room dedicated to Leonardo's war machines. Upstairs, the digital *Landscape* received visitors in a room prior to the main venue. In the main room, a controlled environment located in the tower of the Castello, the last three drawings were presented in the form of kiosks, in which free-to-use desktop computers running the ISLe application were wired to touch screens.

In the same room, *Leonardo, Anatomia dei disegni [Reloaded]* also offered other experiences to involve visitors (Figure 1), such as a physical drawing table on which, following predetermined graphics rules, it was possible to sketch a basic perspective just like in 436 E using tools very similar to Leonardo's; and a "perspective box," in which three-dimensional printed models could reveal, by looking through holes placed in specific positions, the actual shapes and proportions of what is pictured in the background of the *Study of various buildings in perspective (study for the background of the Adoration of the Magi)*, detailed in [4].

Figure 1. The main venue and the setup for the exhibition *Leonardo, Anatomia dei disegni [Reloaded]* at the Museo Leonardiano, Castello dei Conti Guidi in Vinci, with the "perspective box" at the center, *Landscape* on the left, and the didactic table "*Drawing like… Leonardo*" on the right.

The guided route continued with the digital rendition of *Fortress with a square plan, with very high scarp wall and concentric layout, with corner towers and grandiose ravelin in front*. Again, a physical paper replica of the sketch was framed in close proximity to the touch screen to allow for comparisons between proportions, colors, and traits.

Before the final kiosk that hosted *The Vitruvian Man*, an educational table allowed visitors to play with a metallic lead-point pen to replicate the steps that Leonardo took to set up the perspective grid in the original drawing. Users took a square paper sheet from a pile and placed it in positions defined by its shape. In each guided stage, further improvements to the personal perspective were made, starting from reference points on the table that could be connected using the lead point. Eventually, visitors were able to bring their own "*prospettiva*" home with them as a keepsake from the exhibit. This experience was named "Drawing like... Leonardo."

2. Materials and Methods: The ISLe Digital Framework

2.1. The Purpose

Issues in the application of digital frameworks hosting data pertaining to cultural heritage are mostly based on difficult feasibility, overly specialistic training in the acquisition of information, the cost of devices used to perform digitization, and the use of visualization applications that are often too expensive. To overcome these challenges and to offer a possible answer to the need for archival and narrative systems dedicated to artifacts of cultural heritage, a dedicated pipeline was developed to improve the fruition of digital replicas that originate from many input sources and act as surrogates for real objects for the user experience.

This framework, which resulted in a graphical front-end named InSight Leonardo (ISLe) [5] that is the end step of a more complex acquisition process (Figure 2), was originally focused on drawings by Leonardo da Vinci, probably the first artist and scientist who replaced oral descriptions of phenomena with more sophisticated and iconic representations made of texts and graphics. These sketches and texts are extremely rich in content and are often difficult for scholars to investigate through traditional facsimiles or photographic replicas whose features prevent them from having a complete feeling for graphic traits or paper materials, even if the reproductions seem to be accurate. As Adolfo Venturi wrote, Leonardo's drawings are his own "words," as well as his "language," to also quote Carlo Pedretti [6]; they represent the tool used by Leonardo to investigate and explore artificial and natural phenomena, expressed through graphic mastery. His drawings are almost always the result of an elaboration that lasted over time, leading to sketches in which initial traces settle and often overlap inextricably, documenting subsequent variations and re-elaborations.

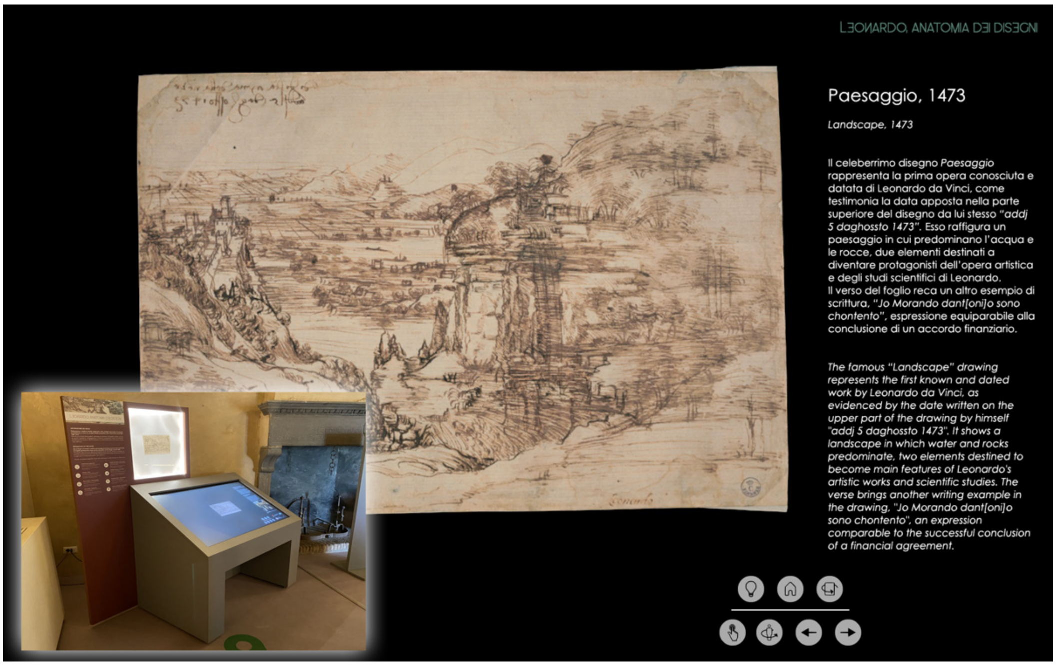

Figure 2. The ISLe application with the touch user interface (bottom right) interactively visualizing Leonardo's *Landscape*, 1473. The application was customized in five different versions (one for each drawing) and then installed on five different kiosks at the museum (bottom left).

Leonardo's drawings have thickness, a three-dimensional quality, and a diversity of visual planes that are revealed by the pressure of the pen or by the density of the material used. These can only be perceived by carefully observing the originals and trying to reconstruct a sequence that can reveal the motion of Leonardo's mind, thus illuminating the creative process that led him to the final proposal. The photographic reproductions and sometimes even the facsimiles unfortunately do not communicate the entire part of this executive work. The flattened replica that is produced using the photographic medium is certainly an obstacle to understanding the genesis of a work of graphic art or of a technical or scientific drawing. Precisely for this reason, ISLe was developed as a digital communicative artifact designed to subrogate, investigate, describe, and communicate drawings, their methods of representation, and their contents, while also accurately reproducing their shape, character, and appearance.

The assumption behind ISLe was mentioned by Leonardo himself, reported in a note on sheet K/P 144 v (held today at the Windsor Castle in London), "*Adunque [per conoscere] è necessario figurare e descrivere* (Therefore [to know] it is necessary to figure and to describe) [7]."

This expresses the perspective that the art historian, the restorer, the person in charge of the collection, and, finally, the simple user can adopt to better understand the message behind the drawings. If traditional photography outputs static representations of a still-life context, drawings can take on a very different appearance by changing the direction of light. For example, glossy areas usually become visible using directional lighting and are not so evident in the presence of diffused lighting. In addition, surface textures are much more pronounced when exposed to directional light sources. To proficiently consider these phenomena, the research gradually began to focus on two generalizations related to the perception of the brightness and color of the artwork in contexts that simulate the three-dimensional environment in which they are placed, together with the definitions of surface properties such as the gloss or roughness of the materials (paper, parchment, canvas, and oil paint). When properly considered in the digital domain, both generalizations aim to digitally show the surface of the reproduced object behaving as it would in real life.

2.2. Background and State of the Art

Since 2010, the research team based at the Alma Mater Studiorum–University of Bologna has developed ISLe with the aim of penetrating and communicating Leonardo's working methods. In fact, to better understand the possible meaning of ISLe application in a museum—which is the best use of it in terms of cultural dissemination—it is appropriate to refer to Werner Schweibenz's words. Schweibenz introduced two central themes, which certainly represent the theoretical foundation of ISLe as an exhibition tool: the shift of emphasis from the centrality of objects to the importance of the knowledge they represent, and the contextualization of a work of art in the knowledge system that is pertinent to it. He writes, "museums were no longer thought of as being repositories of objects only but as storehouses of knowledge as well as storehouses of objects" and also about "the myth that" objects speak for themselves; "forgets that the meaning of an object is learned and established by the context.… Instead of only presenting objects, museums have to create meaning and establish context." [8]

Therefore, ISLe introduces the transposition of drawings into digital forms as interactive, three-dimensional, photorealistic replicas with the aim of recreating two special conditions of use: Leonardo's drawings as if they were in the users' hands and the ability to see what cannot be seen with the naked eye.

Museum visitors can easily zoom in on high-resolution images, change the visible dynamic range, and compare and overlap the front and back of drawings with different shaders or lighting techniques to emphasize the details, colors, materials, and techniques.

Finally, the system integrates semantic and historical–critical annotation to the three-dimensional model through the multimedia environment so that the simple visitor or experienced scholar may explore many extraordinary details with a connection to the studies already made on them or the discovery of hitherto unobserved features (Figure 3).

Figure 3. Recto and verso of a digitized drawing in ISLe: the application fosters an interactive exploration for both sides of the paper, which can be virtually turned using common smartphone gestures. Presented here is the ISLe customization for the drawing *Two mortars launching explosives* (detail).

According to UNESCO [9], the number of museums around the world (104,000 variously distributed) underscores the importance of the cultural legacy they preserve. In the scientific literature, many papers have been written about the digital methods applied to the preservation, documentation, and understanding of humanity's shared CH in these institutions. This is particularly true in the architectural and archaeological fields, which historically count the highest number of case studies related to digital documentation [10].

Additionally, the COVID-19 pandemic also impacted on the perception of museums, during which lockdowns did not prevent the cultural domain from finding alternative solutions to guarantee the fruition of their assets, exploiting the possibilities offered by digital tools [11]. Unfortunately, the digitization of cultural assets is still a marginal practice. In fact, in more than 40 years, only 35% of European CH has been digitized, while 27% of it is barely archived in Europeana, the web portal that provides cultural heritage enthusiasts, professionals, teachers, and researchers with digital materials in the form of artworks, books, music, and videos on art, archaeology, fashion, science, sport, and much more [12]. However, during the last decade, a wide number of studies have been published on virtual exhibitions [13], the availability of three-dimensional interactive reconstructions [14,15], the introduction of low-cost solutions for digital museum events [16], and the analysis of their outcomes [17]. Several of these studies cover specific features when it comes to analyzing drawings and manuscripts. For paintings, colors and artists' techniques are usually captured using multispectral bidimensional images such as X-rays, UV fluorescence, and IR reflectography [18], which can be harmful for inks, papers, and parchments. If paintings reveal useful data with these approaches, the same cannot be said for drawings or manuscripts, whose colorimetric features are limited when compared to the color range of paintings. Hybrid processes were therefore introduced in literature to accurately reproduce three-dimensional artefacts, such as the Fraunhofer Cultlab3D [19] or Witikon [20]. However, these methods are expensive, and they often need well-trained operators, requirements that seem both to be impractical for small- to medium-sized museums, which often cannot rely on adequate funding sources.

2.3. Research Questions

Due to the reasons expressed in the previous sections, an integrated approach to prepare non-experts working in museum areas with robust, easy-to-use workflows based on low-cost widespread devices for the study, preservation, dissemination, and restoration of cultural heritage artifacts seems more than necessary [21].

Usually, these possible users need a global perception for the objects to be manipulated, following a common generalization related to the perception of lightness and color while also approximating material–surface properties including glossiness or roughness. Some efficient answers to the lightness and color digitization problem come from single-camera, multi-light techniques. Among these, the Reflectance Transformation Imaging (RTI) technique, a per-pixel function-fitting technique that interactively displays objects under variable light conditions, originally introduced by Thomas Malzbender, is the most known [22]. Using photo-realistic object relighting, RTI also mimics surface characteristics, considering orthographic cameras and light sources at an infinite distance. The original RTI solution, developed by Cultural Heritage Imaging [23] and later improved by ISTI CNR [24], consists of a point light source, a camera, and a reflective sphere to define light orientation from the reflections on it. There are downsides to this method, including that it is often generated by a slow process which needs complex devices to output accurate results, such as light domes, etc. It should be noted that RTI does not follow physical rules to replicate surface–material characteristics, overlooking effects such as self-shadowing, inter-reflections, and complex light–matter interactions. However, the lack of three-dimensional geometry limits the visualization of all those elements still visible to the naked eye but not responsible for the global shape definition of the model, often stored in large files that are hard to manage by unskilled operators on consumer devices. On the other hand, some common mathematical approaches are used to properly visualize the optical properties of materials (color, surface texture, translucency, and gloss), such as the Bidirectional Reflectance Distribution Function (BRDF) [25], which describes the real light reflection by introducing a highly accurate radiometric reproduction. Its measurements usually require tools that are sometimes impractical to use where the objects that are to be digitized are preserved. For example, the Portable Light Dome system (PLD), developed at KU Leuven [26], is a possible solution that was successfully experimented with for archival documents [27]. The system captures and models the BRDF of non-Lambertian surfaces, using reflectance maps as input to model lower-dimensional analytic or tabular BRDFs. It aims to show virtual relighting and other enhancements in Real-Time Rendering (RTR). The Four Light Total Appearance Imaging of Paintings [28] is another interesting application that uses photometric stereo and CG techniques to virtually reproduce the shape, color, macrostructure, and microstructure of the artwork or drawing. This solution requires typical digital camera equipment and some strobes to capture the diffuse color and macrostructure of paintings and drawings.

2.4. Methods Applied in ISLe

Taking five photographs of an original drawing, ISLe was developed to digitally reproduce the three-dimensionality of the paper by restoring the entire quality and surface reflectance, rendering colors with an imperceptible difference to the sight of an expert observer, and replicating the texture with a 50 μm resolution. The aim was to appreciate not only the elaborate graphics in the drawing but also the preservation problems due to corrosion generated over centuries by the acidity of the inks. In detail, the workflow behind ISLe can be summarized in three stages: acquisition, reconstruction and rendering, and interaction.

The acquisition stage aims to investigate the surface properties of the drawings: their shape, their reflections, and the light parameters from a photographic acquisition. The reconstruction and rendering stage rebuilds them mathematically, using a solution developed to display the surface with micro- and macroscopic fidelity. Finally, the interaction stage is meant to allow user-friendly exploration based on the common gestures implemented on multiple devices (projection walls, PC monitors, touch tables, tablets, and smartphones).

The acquisition stage is also the beginning of a procedure especially developed to be as least harmful as possible to CH objects. In fact, the photometric acquisition relies on:

1. An LED-based lighting system that avoids the typical problems with fluorescent illuminators that prevent the acquisition of reflected information at certain light wavelengths [29]. More details on the light-system development are described in [30];
2. An accurate and safe on-site, 48-bit color IMAGES capture, supported by a precise, fully automated Color Correction (CC) from raw images based on SHAFT (SAT & HUE Adaptive Fine Tuning) software [31];
3. A custom solution developed to replicate the original surface with micro- and macroscopic fidelity (Figure 4);

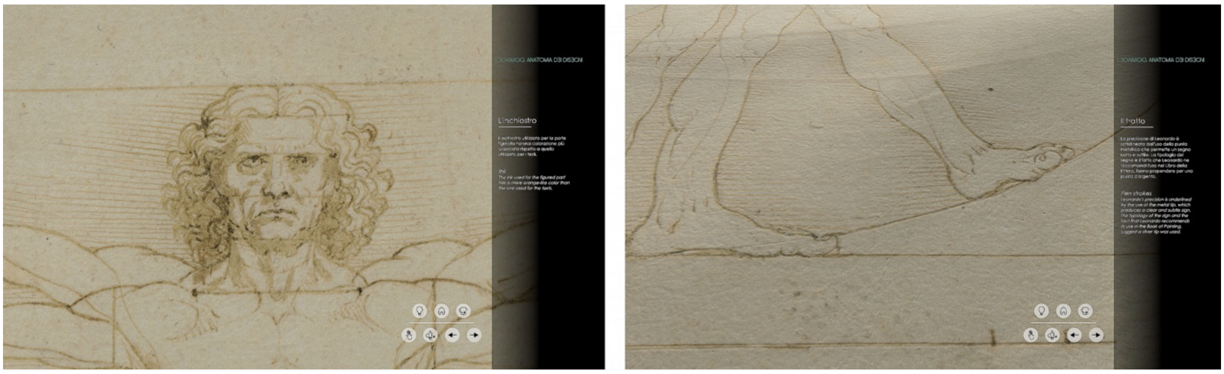

Figure 4. The accurate replication of surfaces in ISLe: in this figure, macroscopic and microscopic features for the replicated drawing *Study of proportions of the human body* known as *The Vitruvian Man*, by Leonardo can be seen.

4. A custom software environment meant to accurately visualize the communication artifact using a low-cost, real-time rendering engine;
5. A kiosk visualization device for museum visitors equipped with custom interfaces based on common touch gestures.

This workflow requires five pictures to be taken with a Color Checker with pre-measured spectral color targets [32] to translate the camera's sensor responses into a device-independent colorimetric representation. The reference target usually consists of the X-Rite ColorChecker Classic as detailed in [33], which shows 24 standardized patches with known reflectance. The three-dimensional models generated following the pipeline include a macrostructure, which describes the shape and the geometry of the object, a mesostructure, in which all elements still visible to the naked eye are represented but are not responsible for the global shape of the model (for example, small bumps), and a microstructure, which replicates the not-visible microscopical structure.

The final visualization is based on the faithful representation of the generated three-dimensional model in a dedicated virtual scene in which materials and lights are replicated in the digital domain, taking advantage of a Real-Time Rendering (RTR) software usually adopted in video game design. The graphic player also relies on an adaptation of the traditional, multitouch interaction paradigm to fit the exploration of two-dimensional–three-dimensional contents in order to minimize uncommon gestures and allow users to explore the virtual drawings from different points of view and under different light conditions (Figure 5).

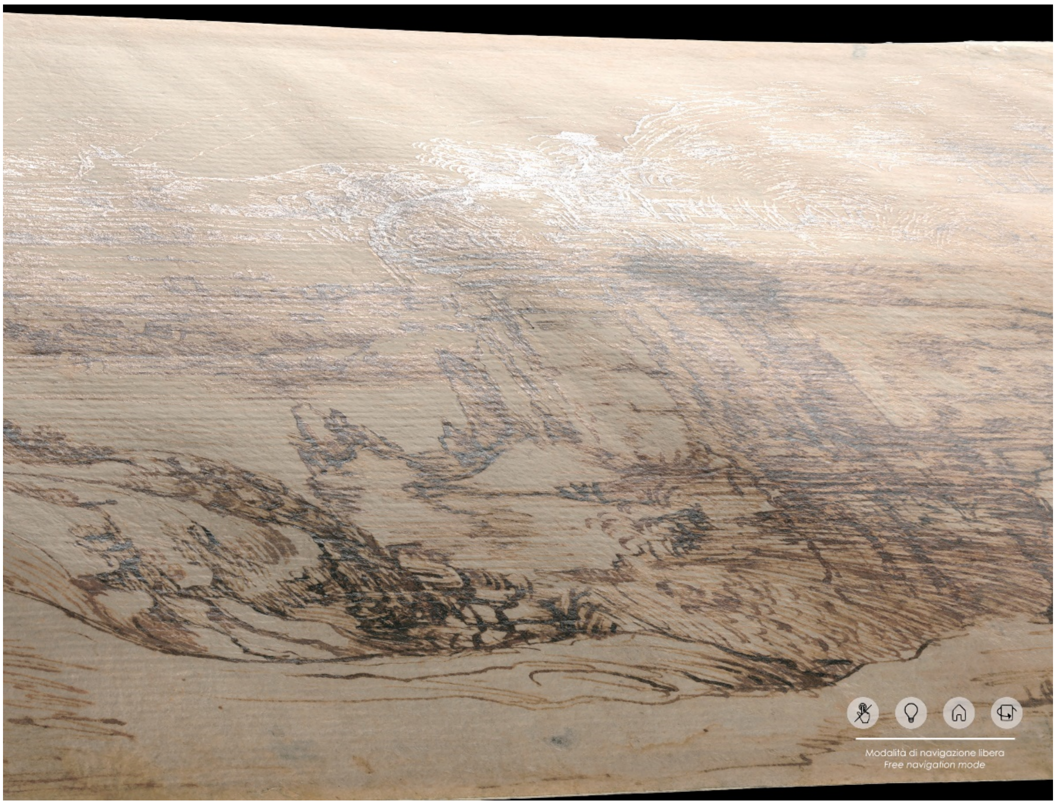

Figure 5. The light behavior in ISLe. Under different light sources, the replicated drawing, with its inks and materials, offers an accurate visualization of shades and reflections. This picture shows a detail of the drawing *Landscape* by Leonardo in ISLe.

3. Investigations on Didactics

3.1. The Purpose of the Research

Cultural artifacts, including those referred to as cultural assets (texts, paintings, drawings, sculptures, scientific inventions, etc.), mediate our relationship with the world, leading us to experience them through the construction of associated meanings, contributing to the development of skills and training.

This type of mediation takes place intentionally in museums. Therefore, museums can be understood as institutions which, through the cultural objects hosted in them, produce (or should produce) formative effects. However, the possibility of producing lasting training effects in a plurality of different subjects depends on the effectiveness of the didactic mediation of the fruition environments.

In a large number of museums, what was once called the "education department" has been transformed into the "cultural action department" due to a long reflection on the communicational function of such an institution in a process of reprioritization of the purpose of museums as they abandoned the nineteenth- and twentieth-century paradigms in favor of a more evident cultural role [34]. In recent decades, most museums have shown changes in the acquisition of their exhibitions, in their display, and in engaging in spreading the values embedded in their exhibitions. Nonetheless, the debate on the diffusion of values continues to focus on the term and function of educating the public, even if attentions are shifted away from old media and messages to new forms of learning identities [35]. Whether in handbooks [36] or in the international committee for the development of professional standards of ICOM [37], the educational function still remains one of the principal purposes of any kind of museum. For this reason, the focus of our investigation is on the instructional and didactic purpose that each museal institution—even the culturally-centered one—should foster in its broad educational design. This line of inquiry is pursued with the awareness that educational strategies at the museum are no longer a subsidiary support to formal schooling, but that they need to continue reflecting on their instructional efficacy regardless.

Following the technical section in which ISLe was detailed, this contribution also presents a study on the didactic effectiveness of the devices adopted as part of the exhibition *Leonardo, Anatomy of drawings [Reloaded]*, with a particular focus on the drawing *Study for the background of the Adoration of the Magi* (around 1481). In particular, the effectiveness of ISLe with respect to the understanding of the knowledge content integrated in the device is investigated.

The strength of the ISLe system, as well as that of the other devices exhibited to observe Leonardo's drawings, concerns the quality of the didactic mediation operated in relation to the work and to potential users. This means that the device is to be considered more effective when the training outcomes it produces are evident and relevant in those who experience it. To completely fulfill this task, it is therefore necessary to set up fruition contexts that let the users explore complete and meaningful experiences in both a cognitive and an emotional sense, particularly experiences that arouse interest and allow for the acquisition of knowledge and deeper understanding.

On the sidelines, it can be observed that all these effects are implicit in the conception of the museum as a public institution which is aimed at education as well as at conservation and knowledge. The museum is what it is because, there is first a visitor who visits it, who implicitly asks it for questions, and to whom the museum itself defines exhibition criteria.

3.2. Theoretical Background

In addition to being one of the crucial objectives of education for active citizenship, the so-called heritage education (the field of studies and educational activities, born in the 2000s, that is dedicated to the enhancement, protection, and knowledge of cultural heritage) [38] is a priority task for any country, especially those with a high density of cultural heritage. In this direction, museums play a crucial role in responding to the social demand for education by making the works and knowledge associated with them available to a wider audience.

Currently, museums—at least those that consciously accept the challenge to offer devices for the fruition of works capable of facilitating their understanding—tend to respond through highly interactive and technological display solutions. This trend can be translated into forms of mere entertainment or knowledge-oriented forms of education.

The use of technology today seems to dramatically expand its potential for participatory and effective use. In some ways, this is true. In any case, this is a revolution that is not achieved simply by putting technological tools in the hands of users, and it should be considered that the first technology used by museum visitors was handheld in 1952 at Stedelijk Museum [39]. At the same time, it is necessary to make adequate, educational mediation choices and to be aware of their effects on cognition and visitors' motivation to learn. Therefore, the introduction of technological devices must ensure that the implicit knowledge in cultural objects is associated with the perceived reality of the used devices, with knowledge that emanates in a direct and dynamic way, progressively becoming more accessible and explicit. From a didactic point of view, cultural objects can be conceived as knowledge that is crystallized in certain forms. They are therefore objects to be known and objects through which we acquire knowledge. At the same time, they are the task and the medium of the user experience (the learning process can be aimed at the knowledge of the object itself, but it can also "cross" the object to gain knowledge of something else). When visitors in a museum linger in front of an unknown cultural object, they assume more or less consciously a questioning attitude, searching for its content of knowledge (for example, consider a painting or a sculpture), its instrumental meaning (consider the reconstruction of a Leonardo machine), or its anthropological and cultural meaning (such as historical and archaeological finds). These contents and meanings constitute the implicit message in cultural objects (even when it is not uniquely defined, as in most works of art) and are what the experience of use should reveal. In regard to the complex nature of this experience, Wertsch [40] suggested that an authoritative shift from an object-based epistemology to an object-based dialogue has occurred during the last decades in museums, moving away from the idea of an object speaking for itself and going towards a new dimension in which there is a dialogue between objects and visitors. In order to maintain an object-centered learning experience framework, museums should put more emphasis on the strong transaction between objects and visitors. In this sense, from an educational perspective, the work is fully realized only when it successfully reaches its recipients; that is, when the communicative act implicit in it is completed [41]. Among the factors to be considered in offering the visitor the possibility of a more conscious use, there are exhibition choices that are adopted and, in particular, the didactic mediation choices of the fruition devices. The artwork always has something to communicate to those who look at it. The communication process takes place when the work "reaches" the recipient in a cognitive and emotional sense. In other words, if the artist communicates with us through their artwork, then the use of it implies that its content must be understood. For the museum, this raises the problem of understanding the artworks. From the point of view of learning, this implies two factors: the mastery of knowledge associated with cultural objects and the mastery of the symbolic codes with which cultural objects are represented [41]. In order to perform its communicative function, a sign object—that is, an artwork—must let the recipient access the knowledge associated with it and express the code upon which the understanding and interpretation of those signs depends. Additionally, since knowledge is implicit and there are no "natural" and "self-evident" iconic codes, a museum must offer explicit and more or less mediated forms as devices to support learning.

Regarding the mastery of knowledge; cultural objects and digital devices give shape to a particular "text of knowledge" which corresponds, in general, to the work of adaptation—called the institutional didactic transposition—which makes the cultural object accessible and suitable to be enjoyed in a conscious way. The concept of didactic transposition [42] was born in the context of school teaching but can also be used effectively in extracurricular fields and with museums in particular [43]. The adaptation work of knowledge that occurs during the processes of didactic transposition concerns, more specifically, the relationship between scientific knowledge, knowledge that must be learned, and knowledge that is actually learned. This relationship must be adequately calibrated from a didactic perspective. In fact, if the fruition device offered scientific knowledge directly it would be rather inaccessible to most visitors. If, on the other hand, the fruition devices were limited to offering a common-sense knowledge, they would be useless to a visitor who wanted to increase their knowledge or satisfy their own interest and curiosity.

In the case of Leonardo's drawings, this problem is strongly relevant as they are works that retain different types of knowledge that risk remaining implicit and, therefore, inaccessible. These types of knowledge include historical–artistic knowledge, linked to Leonardo and to the artistic production of his time; and scientific knowledge, related to architectural design, the methods of perspective construction, and the techniques of material execution. This knowledge requires a didactic adaptation to make it suitable for transmission and learning. This implies building a certain narrative that is offered to the visitor to contextualize the knowledge provided by the work's exhibition. In the case of the *Study for the background of the adoration of the Magi*, the main subject of this didactic investigation—the narration—is focused on Leonardo's drawing method and on the tools and techniques of material execution. In this sense, the narration offered is the result of the transposition of the contents of scientific knowledge into knowledge suitable for learning.

Regarding the mastery of symbolic codes; transpositional choices concern their organization in the presentation of different types of didactic mediators used and the selection of knowledge contents. Didactic mediators are the different forms/codes adopted to represent knowledge in reality. They support the typically human ability to "translate" the reference reality into mental representations or to transfer the data coming from the experience into other formats/codes. As for the specific transposition operated on the drawing object of this investigation, there are two codes mainly adopted: the word, used in the elaboration of descriptive and explanatory texts, and the image, used in different formats from the high-definition digital picture to the augmented image enriched with graphic signs for descriptive and explanatory purposes. The use of images to enhance the understanding of teaching content is an important area in the field of didactic research. In Peirce's triadic conception [44], the image is a "sign" conceived as a relationship between three entities: the represented object, the representative sign (the actual image), and the interpretant. In this respect, the didactic choice of images must take into consideration that their effectiveness is not absolute, but instead depends on variables related to the interpreting subject (i.e., the visitor) and therefore also on the visitor's prior knowledge. For this reason, as was argued by Damiano [45], iconic mediators cannot be considered self-sufficient, but must be integrated with other mediators. On the other hand, the contextual use of multiple mediators requires controlling their effects on cognitive load [46,47] as well as consistency with respect to instructional purposes [48]. In this work, it was interesting to focus attention on the images that are useful for promoting the understanding of how to integrate different didactic mediators (e.g., the written and iconic mediators). The use of images as instructional tools involves several issues: the different types of images in relation to their communicative function (images to describe, to explain, etc.); the degree of schematization and formalization of images in relation to the progressive process of abstraction and conceptualization of the selected content; and the principles of multimedia learning [48–50].

Multimedia learning is a theory developed by Mayer [49; 50], a psychologist at the University of Santa Barbara, California. It is a multimedia learning model. Mayer starts with the distinction of two psychological perspectives [51] from which it is possible to look at multimedia. The first perspective focuses on attention and perception aspects linked to the format that conveys information, and the second is interested in the processes of assembling information of different types in a coherent representation. Mayer's model is an integrated model that considers both Paivio's [52] concept of double coding, an approach according to which different visual and verbal processes coexist, and the concept of cognitive load [46], which establishes a limited possibility of information processing for each channel and therefore a processing damage caused by an excessive load. Based on an extensive research program aimed at experimentally determining which teaching methods are effective for learning, Mayer provides empirical evidence of ten fundamental principles.

In relation to the ISLe application framework, which contains text and static images in its visualization stage, some of these principles are relevant:

- The multimedia principle: people learn better from a presentation that combines text and figures than from a presentation that uses text or figures only.
- The spatial contiguity principle: people learn best when corresponding text and figures are presented close together on the page or screen.
- The temporal contiguity principle: people learn best when corresponding text and figures are presented simultaneously rather than sequentially.
- The coherence principle: people learn best when no extraneous words, images, or sounds are included in the presentation.
- The signaling principle: people learn more deeply when cues are added to the presentation that emphasize the main ideas and the organization of words.

3.3. Research Questions

As has been previously mentioned, one of the purposes of this contribution is to investigate the didactic effectiveness of the fruition devices set up in the exhibition, with a focus on the ISLe device dedicated to the drawing *Study for the Adoration of the Magi*.

In particular, the effectiveness of ISLe in promoting the understanding of the knowledge content through the visualization device itself is investigated.

To consider these objectives, the following research questions were investigated:

- Q1. What is the usability level of the devices in the exhibition (e.g., the perspective machine, touch tables and path “Drawing like... Leonardo”)?
- Q2. Are the devices capable of eliciting the visitor’s interest and curiosity?
- Q3. What is the visitor’s perception on their understanding of the knowledge content?
- Q4. Does the combined use of didactic mediators support the visitor’s understanding?
- Q5. Which individual learning variables affect the methods of use?

3.4. Methods Applied in Surveys

The didactic survey was an empirical investigation that was divided into two directions: a quantitative survey aimed at a random sample of visitors of different age groups and carried out through the administration of a multiple-choice questionnaire; and a qualitative survey aimed at a small group of visitors and carried out through video footage of the visitor’s interactions with the touch table. Again, presented here are the outcomes of these studies for the drawing *Study of various buildings in perspective (study for the background of the Adoration of the Magi)* only.

3.4.1. Quantitative Survey (Questionnaire)

The survey was proposed to a total of 112 users, and it aimed to assess the effectiveness of its use context based on two variables: the subjects (origin, gender, age, and educational qualification) and the objects (the usability of the devices, understanding of Leonardo’s way of drawing, and the materials and tools for material execution). A quantitative survey through the administration of a multiple-choice questionnaire was carried out to detect some information on the users’ profiles and the perceived quality of effectiveness of the devices set up during the exhibition. The questionnaire was divided into two parts. The first part was aimed at detecting personal information on the users of the exhibition (origin, gender, age, and educational qualification). The second part, consisting of 11 multiple choice items, comprehensive of multiple-answer options for most of the questions, was aimed at detecting the usability of the devices considered from time to time, the quality of the user experience for each device, and the degree of understanding of the knowledge embedded in them. The structure of the questionnaire is described below.

Questions 1–3 investigated the perspective machine:

1. The use of the perspective machine was easy:

-Yes

-No

2. The comparison with the work through the perspective machine was (more options):

-Active

-Original

-Arduous

-Interesting

-Not really inspiring

3. Thanks to this installation (more options):

-I learned something new about Leonardo’s painting.

-I understood how Leonardo designed the painting.

-I discovered looking through the two *opercoli* which real forms correspond to Leonardo’s architectural drawings.

-I better understood how Leonardo sketched.

Questions 4–7 examined the touch screen device—ISLe:

4. The touch screen device was (more options):

-Easy to use

-Intuitive in navigation

-Difficult to use

5. The comparison with the drawing through the touch table was (more options):

-Active

-Original

-Arduous

-Interesting

-Instructive

-Not really inspiring

-Dispersive

6. Thanks to the touch screen tables (more options):

-I have seen things that I could not have seen in the original drawings.

-I learned something new about Leonardo's drawings.

-I appreciated the details of the works better.

-I was able to grasp the structure of the drawings.

-I better understood the aspects related to geometric construction.

-I understood that the realization of a painting implies having many kinds of knowledge.

-I found the text support in the navigation menu useful for better understanding the drawings.

7. While exploring the designs on the touch tables (more options):

-I kept focused on the digital reproduction of the drawing without considering the physical reproduction.

-I happened to turn my gaze to the physical reproduction of the drawing.

-I needed the comparison with the physical reproduction of the drawing to better orient the vision of the digital reproduction.

Questions 8–10 focused on the installation "Drawing like... Leonardo":

8. When I tried to draw like Leonardo (more options):

-It was easy.

-I had a hard time drawing the lines.

-I had a hard time following the written instructions to do the drawing.

9. Trying to draw as Leonardo was (more options):

-Arduous

-Interesting

-Instructive

-Not really inspiring

10. Thanks to this experience I understood (more options):

-That the architectural part of the drawing is drawn in a "calculated" way.

-How Leonardo represented depth in the drawing.

-How Leonardo constructed the perspective of the drawing.

-How Leonardo drew the staircase.

Finally, Question 11 investigated the perceived quality of the user experience.

11. This visit (more options):

-Gave me a positive and enriching experience.

-Allowed me to look at Leonardo's works in an unprecedented way.

-Allowed me to achieve a different conception of painting.

The questionnaire was handed out to visitors at the end of the visit. The compilation was individual.

3.4.2. Qualitative Survey (Video Interviews)

The qualitative survey involved a small group of visitors of different ages (between 15 and 60 years old) who agreed to be filmed during the interaction with the touch table representing the drawing 436 E (*Study of various buildings in perspective (study for the background of the Adoration of the Magi)* and who expressed their thoughts aloud according to the Thinking modality. This methodology made it possible to collect useful qualitative data together with quantitative data to answer the research questions. The applied methodological research was set on the Think-Aloud Protocol (TAP). The seminal work on TAPs was issued by Ericsson and Simon [53], who tried to understand how verbal reports could be manipulated as data in order to collect and use them. This documentation technique becomes a valid way to investigate cognitive processes because it contributes to recording what people store in short-term memory as they respond to an instruction to think aloud and verbalize information about their cognitive activity. After an extended review and great enrichment of their first work, Ericsson and Simon [53] stated that, even if verbalizing during the thinking process can be problematic or rambling, it is the only way to gather information before it is stored in the long-term memory, considering that—from that moment on—the subject could not remember the process by which cognition was achieved. The TAP technique can go from one extreme, in which a user is asked to perform a task while verbalizing what they think; to another extreme, in which a user is involved in a formal research protocol with defined rules. The TAP technique applies to a wide range of situations from qualitative to quantitative, requiring low experimenter training in the qualitative mode. In this case, TAP was used in the less-structured form. This choice was based on the context in which the data was collected (occasional visitors to the exhibition) and the type of qualitative analysis we intended to carry out. We were interested in detecting clues on the level of understanding of the users from which to infer the degree of didactic effectiveness of the user device.

The survey conducted therefore aimed to detect:

- The levels of understanding of the users regarding the different contents;
- The methods of use of the various mediators offered by the ISLe user device/system.

In particular, the contents and mediators that made up the bound path of the ISLe "guided exhibition" mode of use were considered.

The contents integrated into the different guided frames (the positions in the drawing with explanatory written captions) were the following:

- The materials, tools, and techniques for the execution of the lines of the drawing;
- The method used by Leonardo to create the perspective construction starting from the perspective grid;
- The way in which geometric objects and figured objects are created within the design.

The didactic mediators used (Figure 6) are the following:

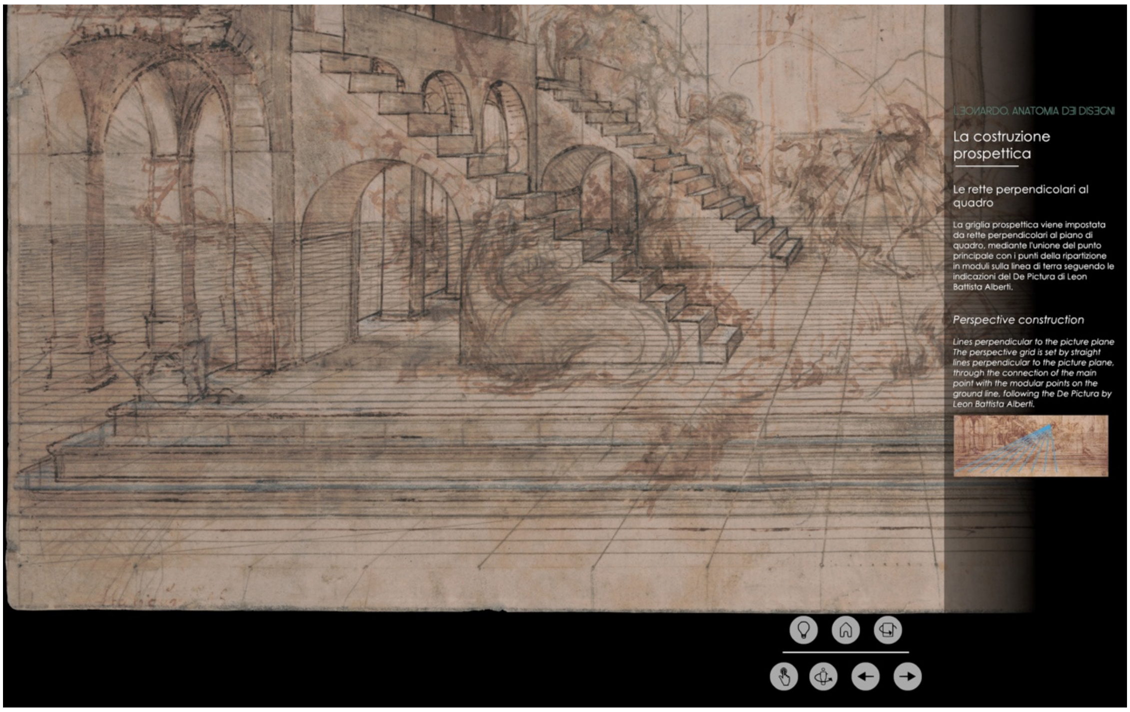

Figure 6. The "guided exhibition" mode in ISLe: visitors could browse different frames of the three-dimensional models, exploring details almost invisible to the naked eye by simply touching navigation arrows on the screen. Three types of didactic mediators are in each guided frame: the model, written texts, and augmented or supplementary images in captions. This figure represents ISLe's interface for a frame belonging to the drawing 436 E, *Study of various buildings in perspective (study for the background of the Adoration of the Magi).*

- Painting images, i.e., high-definition images selected to highlight the details of the drawing, the three-dimensionality of the stroke, and other elements otherwise difficult to perceive in the original;
- Written text which was present in the window on the right of the display, functional in providing information and describing construction procedures (the perspective grid, geometric objects and figured objects);
- Augmented images, i.e., pictures of paintings/drawings enriched with index signs that helped to relate the information provided in the text to the painting/drawing;
- Supplementary images, i.e., additional images that referred to information or elements cited in the text.

The verbal audio–video recorded reports were transcribed and categorized focusing on the relevant cognitive process highlighted by evident signals (both verbal and behavioral). An equilibrated protocol with few interactions with the respondent was applied, and in some circumstances only (e.g., in the case of errors, long silences, uncertainty, and unsureness).

In response to the specificity of the investigation's goals, the mass of recorded data was neither reduced nor segmented. An analysis template was developed in form of analytical grid where data were collected and organized. (Table 1).

Table 1. Interview template as developed for the survey: frames represent each preconfigured view in ISLe, in which visitors could see the drawing and read some captions in two languages.

ID Number for the Interviewed User …						
Frame	**Knowledge Contents Implicit in the Drawing**	**Reference to the Written Text**	**Reference to the High-Definition Image**	**Reference to the Lateral Images (Augmented or Integrative)**	**Understanding of the Knowledge Contents**	**Level of Understanding of the Drawing**

0	Starting view (Exhibit mode)	Drawing presentation	
1	Paper (recto)	Materials and tools used in the drawing	
2	Ink (recto)	Paper type	n/a
3	Pen strokes	Materials and tools used in the drawing	n/a
4		Ink types	n/a
5	Perspective grid	Trait execution	
6		Incisions, lead point, iron–gall ink	
7		"Calculated" perspective construction (following Leon Battista Alberti's indications)	
8	Perspective construction	Ground line	
9		Ground line's modules	
10		Horizon line	
11		Main point and golden section	
12		Perpendicular lines from the central point	
13	Geometric objects construction	Parallel lines to the ground line	
14	Free-form objects construction	Approximation beyond the 12th parallel line	
15	Paper (verso)	Approximation of the first two stairs	n/a
16	Ink (verso)	Stairway proportions	n/a
17	Holes and furrows (verso)	Stairway slope	n/a
18	Preliminary lines (verso)	Some traces of the grid construction and geometric elements	

The template grid is made up of a double-entry table in which the frames are shown in rows (a home frame plus 18 other frames) and the video analysis categories are shown in columns. These categories concern:

- The cognitive content of the drawing-rendered image;
- The references that the user makes to the written text. This allows for the recording of the interactions with the textual part;

- The references that the user makes to the high-resolution image. This allows for the detection of the user's assumptions and interpretations about the meaning of the text;
- The references that the user makes to the augmented or supplementary images placed in the right part of the picture. This allows for the detection of the use that the user makes of additional contents to support their understanding;
- The understanding of knowledge contents. This allows for the determination of whether the knowledge implicit in the drawing was accessible to the final user;
- The level of understanding of the design. This allows for the evaluation of the overall outcome of the interaction with the mediators and the degree of interest and motivation of the user.

Starting from this structure, by reading the interactions relating to each framework, it was also possible to detect whether the user could coordinate the information offered by the various mediators and therefore relate this coordination with the level of understanding assessed.

The research hypothesis, in fact, is that a more extensive and recursive use of text and images corresponds to a more advanced level of understanding.

4. Results

4.1. The ISLe Worflow and Its Technical Results

To date, ISLe has been used during five different exhibitions in which it has presented many different functions and customizations. Its reproduction of visually realistic three-dimensional models proved to credibly replicate interactions between surfaces and the whole light spectrum.

ISLe communicated knowledge and culture by reproducing and analytically showing the three-dimensionality and features of Leonardo's graphic signs. The whole system proved to be efficient following two paradigms: "drawings explored as if they were in your hands," and "3D models showing what you cannot see with naked eyes." The visualization platform customized to reach these goals was also tested during the first exhibition of *Leonardo in Vinci, at the origin of the genius,* which was opened at Museo Leonardiano in Vinci in April 2019 and was visited by more than 140,000 people.

Subsequently, the first *Leonardo, drawing anatomy*—initially hosted at the Museum of Palazzo Poggi in Bologna (Italy) with more than 12,000 people attending—was recently moved back to Vinci, where another 100,000 visitors attended the same event. This remarkable amount of museum visitors and their collected feedback on the application interface proved that the platform was successful in narrating, at different levels, which details are behind these noticeable and famous artworks.

While scientific results in the technical development of the workflow, the framework, and the different pieces of software have been explored and already published, a novel perspective on the didactic value of the process' outcomes will be detailed in the following paragraphs.

4.2. Analysis of Results from the Didactic Pespective

4.2.1. Questionnaire Results

Registry—Only 17% of people who took part in the survey lived in the same province where the Museum was based, while 76% came from Italy and 5% were foreigners. The age was decidedly heterogeneous: 22% were between 18 and 30 years old, 26% were between 31 and 45 years old, and 27% were between 46 and 65 years old. Regarding qualification degree, 40% declared that they obtained a high school diploma, while 35% obtained a university degree.

The perspective machine—The survey on the perspective machine found that 78% of interviewed people (88) declared that the use was easy (D1). The actual comparison with the artwork through the perspective machine (D2) revealed instead that the interviewed visitors attributed the following percentages to the various answer options provided by the specific questions: in their opinion, it was active in 21% of cases, original for 56%, tiring in 13% of the answers, interesting for 50%, and highly stimulating (in fact, only 2% of people interviewed, indicated the opposite).

The users who answered the questionnaire, due to this installation (D3), thought it was also possible to learn "something new about Leonardo's painting" (40%), 35% declared "to have understood the way in which Leonardo worked," and for 40% of users it was possible "to discover through the two small holes the real shapes corresponding to the drawings of Leonardo's architecture." Finally, a further 18% also believed they better understood "how Leonardo drew."

The ISLe Touch System—Regarding the analysis on the touch screen devices, 46% of surveyed users declared that "it is agile in use" and reported that it was "intuitive in navigation." Only 10% of the interviewed visitors expressed a possible "difficulty in use," consequently making our group assume its simplicity (D4).

The comparison with the artwork through touch (D5) was thus considered active (22%), original (50%), not at all arduous (92%), interesting (43%), instructive (41%), very stimulating (98%), and not at all dispersive (93%).

The users who answered the questionnaire regarding the use of the touch tables (D6) indicated that they "saw things that they would not otherwise have noticed in the original works," (45%), that they have learned "something new about Leonardo's drawings" (30%) and, optioned by almost 40% of the respondents, were able to "better appreciate some details of the works ," grasped the structure of the drawings (27%), and understood, in some cases, aspects related to geometric construction (18%).

It is worth concern that very few people (11%) said that they "understood that creating a painting involves the need to possess many kinds of knowledge," and that only 20% of visitors found the supporting captions in the navigation menu useful for better understanding the drawings.

By asking the users what happened to them during the exploration of the tables (D7), the respondents attributed the following percentages to the different answer options provided by the question: about 30% admitted "to have been focused on the digital reproduction of the drawing without considering the physical reproduction." However, another 30% declared "to have looked to the physical reproduction of the drawing" from time to time.

The comparison with the physical reproduction of the drawing, intended to better orient the vision of the digital reproduction, was considered an important aspect for understanding and was reported for 28% of the answer options.

"Drawing like… Leonardo"—"Drawing like… Leonardo" (D8) was considered easy (30%). While 37% said they "had some difficulty in drawing the lines," only 22% found it difficult to follow the written instructions to draw properly.

For almost 28%, trying to sketch like Leonardo (D9) was a bit tiring, but 60% reported that it was also interesting and, for 25%, instructive. Certainly, however, it was a new and particular situation that only 2% of the respondents considered "not very stimulating."

Thanks to this experience (D10), 33% of users declared that they have understood that the architectural part of the design is traced in a "calculated" way; 30% declared that they have understood how Leonardo built the depth; and 44% declared that they understood how Leonardo built the perspective of the drawing. Of the visitors, 28% also declared that they achieved an understanding of how Leonardo designed the staircase.

Preparation of the exhibition—Overall, users reported a visit that turned out to be a positive and enriching experience (60%), which allowed them to look at Leonardo's works in a new way (52%). Finally, a few (10%) indicated the learning of a different conception of painting as given.

The outcomes and results presented in this section are summarized in Figure 7.

Figure 7. A graphical summary of the results from the didactic perspective, with the percentage reports for the questions in the questionnaire proposed to 88 visitors of the exhibition.

4.2.2. Video Research Results

The results related to the categories that made up the analytical grid and the different frames are presented, grouped by type of content:

(a) Materials, tools, and techniques used by Leonardo for the execution of the lines of the drawing (frames 1–3, 15–18);

(b) The method used by Leonardo to create the perspective grid (frames 4–6);

(c) The method used by Leonardo to create the perspective construction (frames 7–12);

(d) The methods of realization, within the drawing, of the geometric objects (frame 13);

(e) The method of implementation, within the design, of the figured objects (frame 14).

Regarding point (a), a full reading of the proposed text, made by most of the users, favors the understanding of the methods of use of the tools and of the methods of material realization of the strokes on the paper. Those who searched for the elements suggested by the text in the high-resolution image gained, with some surprise, deeper knowledge. Reading the text was sometimes hindered by the lack of understanding of the meaning of some specific terms (e.g., wire rod, iron–gall ink, white lead, recto, verso). In the case of laid wires, referred to in the frames dedicated to the front and back of the paper, some users compensated for the linguistic obstacle by using the supplementary image on the right of the frame (frame 1) or the high-definition image (frame 15).

Regarding point (b), the combined use of the different mediators was overall effective in identifying the ground line in the original drawing, the 12 modules into which it was divided, and the 9 submodules. For all users, it was difficult to understand the procedure "from large to small" used to trace the submodules. This was highlighted by the error of the measurement length of the last submodule, which measures 5 mm instead of 3 mm.

The users' understanding was made evident by the gesture of pointing with the finger modules and submodules. In many cases, users made use of the augmented image, placed on the right of the picture, which highlighted the division with colored index signs. The image was so effective that it was sometimes observed immediately after reading the text and before observing the high-definition image. In particular, a young user first interpreted the modules on the basis of the text reading as the "portions of the floor delimited by the lines converging at the main point." Subsequently, following the researcher's suggestion to observe the augmented image, he correctly understood the construction of the grid. On the other hand, users who did not refer the subdivision to either the high-definition image or the augmented image did not understand the essential elements of the perspective grid, thus compromising the understanding of the whole drawing.

Referring to point (c), it was easy to identify the horizon line and the main point in all cases in which users looked at the augmented images on ISLe that highlighted the line and the point from which the parallel lines departed from the ground line. Only in some cases did users understand that the horizon line was placed according to the golden section of the view. The reference to this content, considered to be very specific, sometimes hindered the attempts at understanding. Additionally, the use of the augmented image close to the three-dimensional model is decisive because it highlighted the main point as the point of intersection of the horizontal and vertical segments traced according to the golden section. This was similarly true for understanding how Leonardo traced lines perpendicular to the view plane. It is worth noting that only a few users understood the matter in depth, grasping the fact that the perpendiculars to the plane of the switchboard exactly intersect the points of the module distribution on the ground line. It was difficult to understand, however, the procedure for drawing the lines parallel to the ground line and the interpretation of the supplementary image—which showed the famous drawing of Manuscript B kept at the *Institut de France* in Paris—exhibited as a detail on the ISLe interface, close to the three-dimensional model view of the drawing representing something similar to that detail. In this case, the difficulty in interpreting the image compromised the possibility of referring to it the content of the text and therefore the understanding the progressive degradation of the lines parallel to the ground line. The understanding of the fact that the procedure for drawing the first 12 parallel lines is consistent with what is expressed in the drawing of Manuscript B was supported by the text.

That is, the users seemed to remain at the level of declarative knowledge reported in the written text. This fact is variously interpreted by users in relation to their previous knowledge. The higher this knowledge, the more users were willing to believe that Leonardo proceeded with the approximation in an intentional manner. The approximate character of the perspective construction was, however, intuited by most users when they resorted to the augmented image that highlighted the depth of the first steps of the two stairs, which was similar rather than being half of the other.

Regarding point (d), the knowledge contents of the drawing, which find an explicit reference in the text, concerned the way in which the length, height, and depth of the staircase were determined and the fact that, once these quantities were determined, the steps were drawn freehand. Most users looked at the augmented side image that highlighted the triangle identified by the length, height, and segment that connects the highest point and the bottom edge. The use of this image constitutes a valid support for the understanding of the way in which Leonardo inserted geometric objects in the perspective picture. In some cases, users perceptually intercepted the correspondence between the edges of the steps and the lines perpendicular to the view plane.

Considering point (e), it is noted that the augmented image, where the segments that delimit the box-limit within which the figures and horses were traced, was crucial for understanding the meaning of what is reported in the text. Explicit references from users were frequent.

5. Conclusions

In this section, the research results (RR) are discussed, elaborating on presented quantitative and qualitative surveys and considering the answers received to the research questions (Q).

RQ1. What is the usability level of the devices adopted during the exhibition (e.g., the perspective machine, touch tables, and the path "Drawing like... Leonardo")?

RR1. Based on the data collected in the quantitative survey, the usability of the perspective machine and the touch tables is very high. The experience "Drawing like... Leonardo" is more difficult, due to both the harder understanding of the instructions to let visitors perform the drawing autonomously and the unusual tools used. The outcomes from the touch tables show how the data collected in the qualitative survey reveal the users' trend to behave as if they were in front of a smartphone screen even when they are in "guided tour" mode. This trend sometimes prevents the correct use of the device as it discourages the sequential exploration of the drawing's frames.

RQ2. Are the devices capable of eliciting the visitor's interest and curiosity?

RR2. The quantitative survey found that, for most users, the devices are perceived as interesting and very stimulating. The qualitative survey partially confirmed this finding. In fact, the users who participated in the video recording of their interaction with the touch table of the 436 E drawing showed curiosity and interest in the visual details and information they had access to, but this interest was not always sufficient to support the motivation to understand in depth the contents proposed.

RQ3. What is the visitor's perception on their understanding of knowledge contents?

RR3. Based on the data collected in the quantitative survey, the users' perception with respect to the understanding of knowledge contents is high, both in the case of the "perspective machine" and for touch devices. The qualitative investigation allows for the detection of finer information on this point, as it concerns the most complex drawing (how Leonardo created the perspective construction) and with a higher density of knowledge content. In fact, it is necessary to specify that the perceived knowledge is different from the understanding achieved and that it can be used, frame after frame, to gain a deep understanding. In the case of the ISLe touch table of drawing 436 E, an approximate understanding of the contents of the different traces allows us to understand that the drawing was made in a "calculated" way, rather than freehand, but it is not sufficient to understand Leonardo's method of drawing, contrary to what most respondents to the questionnaire seemed to claim. The qualitative investigation on the interaction with drawing 436 E reveals that, for most users, only a partial understanding of Leonardo's method was achieved, mostly limited to the identification of the perspective grid (how it divides the ground line into modules and submodules and how it traces the horizon line and main point).

RQ4. Does the combined use of didactic mediators support the visitor's understanding?

RR4. The qualitative survey on the 436 E drawing states that users who more frequently resort to the different types of mediators involved in the "guided tour" mode and combine the mediators with each other gain a better understanding. This happens to users who read the text in full and try to trace the references of what they read in the images. Even those who compare the images with each other, before or after reading the text, or by searching the high-definition image for the signs indicated in the augmented image, reach a level of understanding that lets them to advance along the path. The reference to the text is, in any case, fundamental for interpreting the images. On the other hand, users who limit themselves to the linguistic understanding of the text without referring to the images lose the motivation to learn and desist from trying to understand. This is confirmed by the fact that these users quickly scroll through the pictures almost without commenting. Some factors consistent with the multimedia learning principles mentioned above contribute to the coordinated use of images during the drawing's navigation.

RQ5. Which individual learning variables affect the methods of use?

RR5. Based on the results of the qualitative survey, it is possible to state that the individual learning variables that affect the quality of the users' experience are the preferential learning method, the level of linguistic comprehension possessed, the level of previous knowledge, and the level of personal motivation.

The preferential learning modality indicates the person's "sensitivity" to visual and linguistic codes. Although everyone can interpret both codes, the subject's cognitive activation may be better in one case than another. In this sense, the offer of different mediators—visual and linguistic— potentially intercepts the widest kind of users.

The level of linguistic understanding greatly influences the ability to construct meanings to refer to the proposed images. The qualitative survey makes it possible to detect that unknown or technical terms as well as characteristic expressions of the geometric or architectural lexicon hinder the understanding of the contents.

The level of previous knowledge constitutes the background to which new knowledge is anchored and therefore affects the interpretation of the meaning for the text and images. Personal motivation usually supports the learning effort and is the result of a good didactic mediation of the knowledge contents. The qualitative survey shows the real motivation of users to be engaged in the learning experience. The complexity of the drawing and its epistemic density can, in fact, imply the ability to persevere in the cognitive effort. However, when the user can support their motivation, the result is an effective experience on both a cognitive and an emotional level.

The whole process, from the original digitization of drawings to the analysis of the efficiency of the framework from a didactic perspective, proves that, when technologies just like ISLe are introduced in a museum exhibit surrounded by other kind of experiences, they substantially foster a deeper attractiveness and understanding in visitors with different levels of curiosity and interests.

Author Contributions: Conceptualization, S.G., B.M., and M.T.; methodology, R.D.; software S.G.; validation, R.D., S.G., B.M., and M.T.; formal analysis, investigation, A.L. and M.S. (Mirko Susta); resources, R.B.; data curation, M.S. (Marta Salvucci), B.M., and M.T.; writing—original draft preparation, R.D., A.L., S.G., B.M., and M.T.; writing—review and editing, S.G., A.L., and M.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank all members of the research team who developed ISLe over the years, coordinated by Marco Gaiani and Fabrizio I. Apollonio, including Andrea Ballabeni, Giovanni Bacci, and Riccardo Foschi. The authors would also like to thank Davide Giaffreda and Davide Prati for the logistics and building support for physical devices.

Conflicts of Interest: The authors declare no conflict of interest.

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