Visualizing uncertainty in an interactive VR reconstruction of a Cultural Heritage site – with the case study of Pieter De Graeff's "Boekenkamer".

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ABSTRACT

In disciplines dealing with Cultural Heritage (CH), Virtual Reality (VR) technologies have emerged in recent years as useful tools, both for scholarly research as well as for the divulgation of scientific content to a wider public. These applications still face several challenges; most notably, they must meet scientific standards by providing clear information about the level of authenticity of the reconstructed scenario, to allow for external verification. This known problem of historical three-dimensional (3D) reconstructions gets now intertwined with the intrinsic criticalities of VR - a promising, albeit still immature, medium. A solution for effective digital environments, suited for the needs of CH studies, must consider and mediate between all these issues simultaneously.

To address these concerns, we propose here an interactive reconstruction of a domestic library ("de Boekenkamer"), belonging to a Dutch 17th century patrician house. In its final interface, data is integrated with the scenario in different ways, to firstly let the user explore the reconstruction with as much perceptual vicinity to the lost original as possible, and to later let them visualize degrees of uncertainty relative to the scene, whilst providing detailed information about each of its components. A colour-coding system, joined with the display of 'paradata', is exploited to provide a solution, tailored for VR, to resolve uncertainty around the 3D models displayed. The environment can also be navigated by the user, who can personalise the content they intend to see. This paper presents the finished prototype, draws conclusions from the interactive scenario's implementation processes, and reflects upon the results of the tests that have been carried out in with the application – hopefully presenting a structure that can be re-used and adapted by similar future projects.

KEYWORDS

Virtual Reality, Cultural Heritage, Uncertainty, Digital Reconstruction, Interaction, 3D, Library

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1. INTRODUCTION

Visual reconstructions of the past allow us to visualize in a concrete way what would otherwise be relinquished to our imagination; hence they have been a life-long fascination for me, whilst, for disciplines concerned with the study and preservation of Cultural Heritage (CH) they constitute useful tools both for scholarly research as well as means for disseminating research findings and engaging the public (Barker, 2018).

Given the increasing availability of technology, computer-based 3D (three-dimensional) reconstructions have in fact been adopted in most areas of research (Brusaporci, 2017); a rapid digitalisation is naturally affecting humanistic disciplines (Bekele, 2018), whose methods have become subject to the same innovation rhythm that is proper of the technologies they now must rely on. Therefore, if 3D reconstructions were traditionally presented in printed form or as animated picture (Opgenhaffen, 2015), today steps have been made towards immersive virtual environments which can be navigated by the user. Virtual Reality (VR) systems are relatively modern digital media which show promising opportunities of reducing the distance between users and the digital environment (Bekele, 2018); this could favour engagement with the environment itself in novel ways, that could ultimately help us to better understand how someone in the past might have engaged with their real surroundings (Opgenhaffen, 2015). Furthermore, the attention and hype that these technologies have received over the past years (Morgan, 2009) could, for instance, be exploited to attract visitors to a cultural exhibition or a museum. Reconstructions of CH sites (lost and preserved ones) indeed seem like ideal use-cases for the adoption of VR solutions; I believe this to be a fascinating opportunity, coming with a new set of challenges.

1.1. More Than a Pretty Image

There is more to the value of a reconstruction than its existence as a pretty and evocative image in itself. A 3D reconstruction implies a multidisciplinary approach and a broad range of notions, being the result of a laborious process of documentation and data finding; in fact, it may be considered as the *status-quo* of what is currently known about a specific historical subject (Opgenhaffen, 2015). As a consequence, a reconstruction is only as valuable as are the reasons and rationale behind all the decisions that were taken in the (often long) phases of research, gathering of data, testing of hypothesis, and in all the work of understanding and linking notions from different fields into one single coherent scenario. These elements need to be exposed and supplement the 'cold' image with a comprehensive narrative which the user can access and follow, step by step, as would be proper of any other scientific methodology (Benedicho, 2017). Failing in being clear about which kind of data sources were available to the researchers - and on how the rest has been deduced - might ultimately result in misleading

representations with limited scientific value. The representation of the uncertainty in the knowledge behind all the elements of a reconstruction has in fact been described (Benedicho, 2017) as one of the great challenges that one is faced when designing valid visualization systems for CH.

Virtual models have been accepted as a legitimate tool to represent the past, but the journey taken by the researcher has most often been hidden behind the reconstruction (Morgan, 2009). By being able to expose it instead, the resulting visualization system stops being simply a "pretty picture" to become a "digital ecosystem" (Pietroni, 2014). The aim of this ecosystem should be to enhance the communicative potentialities of the reconstruction, "reactivating its relations in space and time and its connections of meanings" (Pietroni, 2014). In practice though, the discipline of making and annotating 'scientifically valid' 3D models for CH is still loosely regulated in general, meaning that guidelines have been developed, but they still leave all implementation details for actual projects to each individual effort (Benedicho, 2017); as a consequence, this becomes even more evident when it comes to the adoption of new media, such as Virtual Reality, where strategies to elevate the "pretty picture" to a "digital ecosystem" are at a very embryonal level.

1.2. The Aim of This Research

Through the implementation of a working prototype, this work aims to contribute towards the design of an effective interface for scientifically valid interactive VR reconstructions of Cultural Heritage. This is could be considered as a solid starting point for future developments, and it is a more elaborate task than it meets the eye, as the specifications for a successful application are numerous and diverse in nature.

For starters, an effective information visualization system needs to be devised to display the reconstruction's background data in VR, to clearly communicate the degree of certainty of the elements of the reconstruction. This system ought to be interactive, to promote a personalised approach to content fruition; this should also make it easier for a single application to be suitable to a wider audience, ranging from the specialist to the mundane user. Requirements of this type are practically dictated by the conditions in which CH applications are often developed, where limited resources of time and money make economy of development a critical factor to keep into account. Systems of this type should then be cheap to make and maintain, flexible to accommodate different adaptations with limited conversions costs, and as future-proof as possible.

A number of VR applications for CH have been proposed in the past, but possibilities for contribution still seem vast, especially in consideration of the quick advancements in the hardware and software options available to developers. Furthermore, this process seems justified as it has been noted that "the presentation of the 3D model in an interactive and freely navigable environment, with connections to

instantly retrievable underlying information, is already technically possible, but generally not within reach of the scholar" (Noordegraaf, 2016).

1.3. De Boekenkamer VR

A virtual reconstruction of a 17th century domestic interior, the personal library (or, in Dutch, "de boekenkamer") of Amsterdam's regent Pieter de Graeff, has been chosen here as a study-case to structure an innovative interface. The choice of this subject was made possible thanks to the collaboration with dr. Chiara Piccoli, a postdoctoral researcher at the University of Amsterdam: by developing selected virtual reconstructions, her research[1] investigates how individuals created and interacted with cultural goods in their homes during the Dutch Golden Age. She conducted all the historical research on 'de Boekenkamer' and provided precious support with 3D modelling; she valued VR as a promising declination of her research aim of having 3D models to act as data integration and hypothesis visualizing platforms, "aiding the development of a methodology to handle uncertainty and annotations in 3D visualizations" (Piccoli, 2019).

The final application design, structured into three 'levels of interest' - three different stages in which content is organised - is the result of the research that was undertaken; the proposed structure is well-suited to both the requirements of CH as well to those of VR technology, and it can be replicated or adapted by similar projects. In the first stage, the user can experience a virtual reconstruction as closely as possible to the original, from a perceptual standpoint; in the second, the user can visualize the uncertainty degrees of the objects composing the reconstruction; in the third, each individual object composing the reconstruction can be at the centre of attention, with its background information exposed. The design started from a blank page, selecting each component of the workflow in order to obtain as outcome an application meeting all the above-mentioned requirements; by doing that, I hoped to provide the community with an up-to-date working example to guide future developments.

The following sections of this paper will firstly discuss the context and background in which this projects is placed, before moving on to describing the design and implementation of the scenario itself – process which started from the realisation of the 3D models and culminated in the realisation of a user interface inside of a game engine. After those sections, the reader will find the results of tests that have been carried with the final application; this is followed by final general reflections on the results and around the process as a whole, outlining the main points of success of the application as well as the main issues that have emerged with it.

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[1] Visualizing domestic interiors in 17th century Amsterdam: 3D/4D data integration and hypothesis testing platforms, https://virtualinteriorsproject.nl/2019/07/12/visualizing-domestic-interiors-in-17th-century-amsterdam-3d-4d-data-integration-and-hypothesis-testing-platforms/

2. RELATED WORK

This section is meant to provide an overview of the methods and the regulations that scholars have already applied to tackle issues related to those that I expected to encounter in the realisation of the prototype. The literature described here provided an operative guide to set the direction and draw the boundaries of the work. Much research had already been conducted on the requirements of CH virtual reconstructions; this made it important for me to aim at synthesizing the knowledge already out there into a functional VR product, rather than 're-inventing the wheel' in terms of the method available.

2.1. Digital Reconstructions for Cultural Heritage

In general, a 3D model can be defined as "a mathematical representation of a concrete entity, in which its features are displayed according to the geometry of their real volume" (Piccoli, 2018); the modelled entity is fully described from any point of view and can be seen from different perspectives with the same level of detail. When these models are embedded with CH, and represented through digital media, they enter the realm of what has been defined as 'Virtual Heritage' (Tan, 2009). These computer-based visualization methods have been adopted in a wide range of contexts to assist the research, communication and preservation of CH (Bentkowska-Kafel, 2016).

An ideal virtual 3D reconstruction of a cultural context was described by Pietroni (2014) as "a digital ecosystem well organized but also communicated in the simplest way for the public". Its main peculiarities ought to be "inclusivity" and "interactivity": the first concept implies that all the data should be integrated in the scenario, and presented in 3D; the second specifies that the user must be part of this context: surrounded by the information, they must be able to act in the digital world and perform decisions on the content they are interested in, benefitting from a personalised approach to knowledge. Besides these operational principles, in general Pietroni (2014) also notes that "the state of the art of storytelling in this field is still very primitive" and further research is needed.

2.1.1. The advent of Virtual Reality

Monetary costs of producing 3D models only started to drop in the mid-90s, thanks to tremendous technical advancements which, coupled with a parallel growth of the 'heritage industry' (musea and heritage centres), favoured a proliferation of these tools (Miller, 1995). In parallel, a field where much progress has been made is the one of so-called 'serious games', which are digital gaming platforms designed for learning and education rather than centred on mere entertainment (Susi, 2007). Certain

techniques of game-play and game design (such as the use of 'points-of-interest' to guide the attention of the user) can be adopted in the implementation of virtual environments for CH (Tan, 2009).

Today, the increasing development of VR technologies, interfaces, interaction techniques and devices has finally strengthened their efficacy and usability, by offering more natural modes of interaction and motivational elements. "Despite its promise of a photo-realistic, full sensory immersion has not been immediately forthcoming" (Morgan, 2009), VR has been described as a valid tool to interact with digital models, and a precious help in the documentation, recording and conservation of Cultural Heritage, as well as in making culture more accessible to the wide public (Gonizzi Barsanti, 2015); it has also been reported as being a flexible medium, helping a curator in tailoring the cultural proposal to the different kinds of user categories (Gonizzi Bersanti, 2015). Of the eight discriminants that Pescarin's (2014) identified as characterising virtual exhibitions[2], 'interaction' and 'level of immersion' are surely the ones that benefit the most from VR technology – which appears in line with Pietroni's requirements for inclusive and interactive digital ecosystems.

Virtual Reality technologies have also been noted in the past for a variety of practical limitations concerning high costs, development complexity (often involving high maintenance), intricacies in usability and general inaccessibility of the technology - issues which might undermine the needs of a commercially produced mass entertainment industry (Tan, 2009). Further critiques to the use of virtual heritage environments centred on the fact that they are often designed with a minimum opportunity of active participation from users. On an opposite stance, VR environments have otherwise been blamed for a lack of 'thematic interactivity'; this means that users had freedom to move in the environment but, being without any certain goal or objective, they would occasionally end up feeling lost and bored. It emerges how important finding the right balance might be.

2.1.2. VR in practice

Numerous VR interaction techniques and configurations have been implemented to allow the user to control and navigate the virtual content. Ranging from typical mice, joysticks and keyboards to more modern gesture-based control systems, the available offer is a broad one already: generally, the trade-off is between level of immersion and implementation complicacies, and the choice mostly depends on the project's resources. More defined is the choice instead when it comes to the visualization device as, today, an approach based on Head-Mounted Displays (HMDs) is the most sought-after (Gonizzi Barsanti, 2015). This kind of headsets, based on the principles of stereoscopic images, have become more widely available in recent years, some also being available on the market at affordable prices.

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[2] These are: content, scope, duration, level of immersion, interaction, communication, distribution and sustainability.

Often though, due to a combination of low resolution and slow refresh-rate of the display, HMDs have been reported to cause disorientation, nausea and motion sickness; furthermore, it was pointed out that similar headsets isolate the user from the external world and do not encourage interaction between users (Tan, 2009). Still, user's feeling of immersion and interaction is clearly enhanced and widened, whilst setups are considerably more manageable than previously proposed alternatives such as the CAVE[3] system (Dell'Unto, 2013).

Ultimately, to our knowledge, today there are still no systems designed to combine transportability and the highest imaging quality in VR; it is always a matter of trading one for the other in some way. For most use cases in the field of CH, transportability, and general ease of deployment (including costs), appear as more immediately useful than imaging quality per se. Most work on augmented and virtual applications for Cultural Heritage has indeed shifted to mobile devices (Madsen, 2015), demonstrating this need.

2.2. The Issue of Authenticity

Discussions around the methodology of digitally reconstructing historical scenarios started shortly after the introduction of computer-based 3D modelling in the late 1980s. Since then, a main issue of concern for the community has been the lack of transparency, often afflicting these representations, due to the difficulties in visualizing uncertainties in the model (Hermon, 2006).

Much research has been conducted on these topics ever since, and major international guidelines such as the "London Charter for the Computer-based Visualization of Cultural Heritage"[4] (Beacham, 2006) and the "International Principles of Virtual Archaeology", also known as "the Seville Principles"[5] (Benedicho, 2013), have been put forward. These aim to establish the requirements to verify the transparency of a 3D visualization of CH in relation to intellectual integrity, reliability, documentation, sustainability and access (Bentkowska-Kafel, 2016), as would be incumbent upon any other research method (Denard, 2013). These conventions seek to establish solid foundations for the discipline, facilitating the phases of development and implementation of a project; still, they acknowledge that the "range of available computer-based visualization methods is constantly increasing", and that "these methods can be applied to address an equally expanding range of research aims" (Bentkowska-Kafel, 2016). Therefore, they specifically do not provide precise standards or begin-to-end workflows, but

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[3] Large scale projection systems that surround the user and provide a reasonable level of immersion, but also require high development and installation costs, a large physical space and almost no movability.

[4] Full text retrievable at http://www.londoncharter.org/fileadmin/templates/main/docs/london_charter_2_1_en.pdf, last accessed 22 October 2019.

[5] Full text retrievable at http://smartheritage.com/seville-principles/seville-principles, last accessed 22 October 2019.

rather establish broad principles (which have been of guidance for this project as well); if a virtual model can be de-constructed, and its data are transparently presented for critical evaluation, then it can be seen as scientifically reliable (Denard, 2013).

Cultural Heritage is not self-explanatory and a purely aesthetic experience is not sufficient, but, in fact, it requires good storytelling to be able to convey (Pietroni, 2014). In the following sections, an overview introduces the most effective strategies that have been deployed so far to address this concern.

2.2.1. Paradata

One kind of data is worthy of special attention in CH, *paradata*, which essentially describe "the dynamic nature of the process involved in interpreting and creating visual representations" (Baker, 2007) from the researcher's point of view: paradata can include, for instance, an account of the decisions that the researchers had to make and of the paths they have discarded. Paradata do not describe the object itself, but rather the process alongside it. Mostly descriptive, this information has potential to be a vital resource for verification, understanding and learning, if exploited: the relevance of a reconstruction also lies in the skill of the researcher in communicating the multi-disciplinary journey they took, and narrating the thinking process which lead to the conclusions that were taken. According to Baker (2007), there are four fundamental points to consider in order to take the best out of this potential "treasure house". The first two points suggest that paradata documentation should (1) identify the decision-making processes that occur during research, and (2) capture the intellectual capital invested in it. Furthermore, (3) paradata should be recorded with the minimum overhead within a project; finally, (4) they should be disseminated in an easily accessible form together with the virtual object they refer to.

Paradata offer great potentialities for the introduction of narrative elements, but no standards have been defined by the community for their exact scope (Noordegraaf, 2016). The display of this miscellaneous data should be tailored to the medium of the project, as well as require appropriate information visualization techniques to avoid information cluttering and overload for the user.

2.2.2. Classifying the Uncertainty of a Reconstruction

Three-dimensional reconstructions can have a persuasive function on the viewer and may end up representing more than what is actually known, resulting as misleading, at best, or even as 'propaganda' (De Vos, 2019; Piccoli, 2018). For these reasons, what is real or authentic in a digital model should always be distinguishable from what is not; authenticity must be a permanent operational concept in any project in this field (Benedicho, 2017).

There are no standards on how to display transparency which may serve as a reference to us (Noordergraaf, 2016). Of the several methods that have been proposed, two main strategies would be applicable to our case scenario: one based on the principles of *'fuzzy logic'* (Hermon, 2006) and the other based on '*class-based evidence*' (Resco, 2014).

With the 'fuzzy-based' approach, derived from the mathematical principles of "fuzzy logic" and membership functions, uncertainty for the individual elements of the reconstruction is described as an absolute value. This value is attributed by the researcher in the interval [0, 1], quantifying their opinion about the reliability of the reconstructed object's features. Further attributes, such as 'importance' of the element in the reconstruction, can be valued in the same way and added in a mathematical function to calculate the mean uncertainty of the whole visualization. Critiques point out that this method should be used with caution, as they are only an expression of a subjective evaluation done by the researcher (Brunke, 2017). Nevertheless, fuzzy sets also offer some strengths: they offer a strategy to record part of the decision-making process of the author, which is subjective in nature. All the values obtained are absolute and each part of the reconstruction gets one of its own; the results can be used for analyses on the overall reliability of the model, or for visualizations (as the obtained values can be mapped to visual properties, such as colour or transparency).

A 'class-based uncertainty' approach represents a contrasting attempt, which is defined as the "classification of sources" (Brunke, 2017). This classification works by creating 'classes' based on the type of sources that were available for each object. For instance, an object can be derived "from material remains", or "from period images" – each constituting a class. Each object would be classified this way, according to the type of data available to the researcher, which is an indication of the degree of certainty. With this method, it is problematic to have neat distinctions between classes, as the line is often blurred; furthermore, this will probably end up with differing uncertainty values within one class. Still, a 'class-based' approach produces a strong link between the end result and the background sources, whilst at the same time ensuring some kind of objectivity (Brunke, 2017). Typically, classes can be mapped to colours in the resulting visualizations: each object would be rendered in the corresponding distinctive colour. Like this, no extra tables or lists are needed, and quick evaluation can be performed with the right balance of details and subjectivity.

The choice to adopt any of these methods depends largely on the available data and the aim of the researcher, but both offer an acceptable scale of values to distinguish elements in a visual way in the digital reconstruction.

2.2.3. Visualizing Uncertainty

Values obtained through uncertainty classification are then usually mapped to the visual rendering style of the object itself; individual colours work as a transmitter of information, representing a degree of uncertainty (Dell'Unto, 2013), as illustrated in Figure 1.
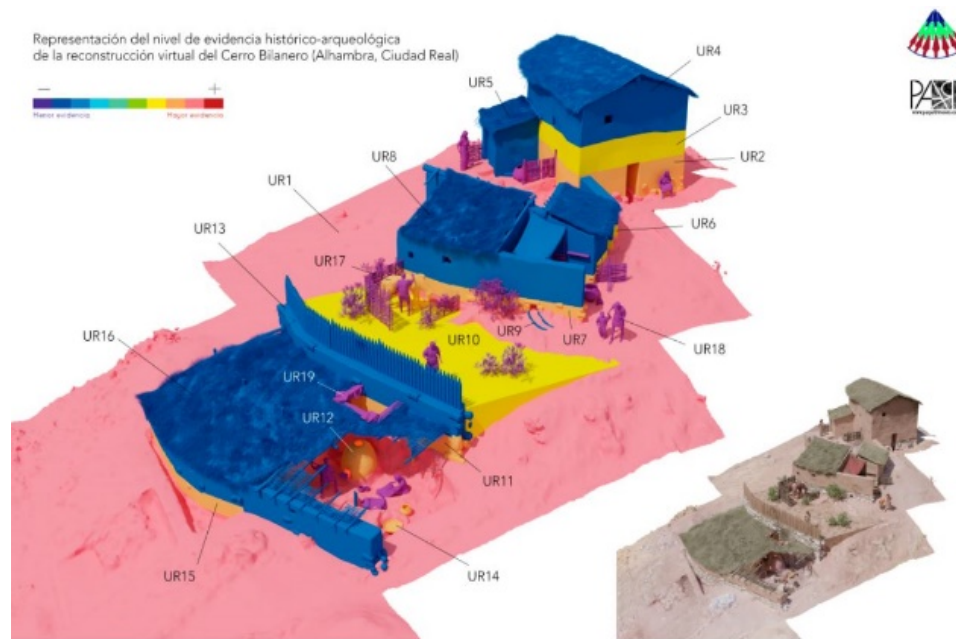

Fig.1. Possible uncertainty visualization system, as proposed by Resco (2014). The reconstruction is divided into RUs (Reconstruction Units) and applies an uncertainty level to each with a "class-based" method, with a scale of 10 colours.

As reviewed by Brunke (2017), many colour-mapping techniques have been proposed to date. These solutions include a gradient between two colours, as well as the use of complementary colours instead; some used a high contrast, while others used similar tones to the original colours (such as using a "ghost-colour", a subtler form of the original colour). Desaturation has also been used to indicate areas of the model with lesser degrees of certainty, as well as mappings using a monochromatic colour scheme or with only grey tones. Simple wireframe solutions have also been noted as effective to show uncertain elements, as the blank spaces cannot be misinterpreted; combined approaches have also been proposed.

The choices of colours or harmonies have been dependant on the researchers' interpretations and scopes, but they all seem to agree that relation (between colour and uncertainty value) and description (with detailed data documentation) are essential to the outcome (Frischer, 2007).

2.2.4. Photorealism

The use of photorealistic techniques is made tempting today by their ease of deployment with modern digital tools or, alternatively, by a pressure coming from the "increased expectations of a public used to a diet of high-quality multimedia-media presentations, from school learning software upwards" (Miller, 1995). With relatively little effort, it is possible to achieve a very detailed reconstruction which might be stunning to the eye but, if carefully looked at, might reveal to be a 'double-edged sword', as Eiteljorg (2000) describes it.

In fact, a better drawing doesn't correspond to a better underlying hypothesis: a high level of detail in the reconstruction may be persuasive because of the level of realism, and provide a superb sense of a particular situation but, at the same time, it may convey to the viewer far more then what is really known about the subject, therefore covering the uncertainty of the scene (Frischer, 2007). Nevertheless, photorealistic renderings should always be the goal, as long as they are based upon solid evidence (Reimersdahl, 2008). Despite not distinguishing between real and interpreted structures (and therefore not being suitable to display uncertainty), a photorealistic approach can be adopted if mixed with other style directions (Brunke, 2017) and, as stated in the second of the Seville Principles, different levels of detail, resolution and accuracy might be required by an effective visualization. Depending on the purpose of the visualization, a photorealistic rendering might be unnecessary, or even misleading. It is fundamental to always keep in mind the function of the visualization itself, and tailor the level of detail to the project's requirements.

The VR experience could take advantage from a photorealistic rendering of the image, to create an immersive digital experience that better approximates a real one; as long as the final product is based on genuine data, Physically Based Rendering (PBR) materials can be used to improve the aesthetic qualities of the visualization. In modern computer graphics software, image files that hold photos of real objects can be easily imported as textures for the models. For each surface, PBR combines to the colour texture a set of 'maps' (such as 'ambient occlusion', 'normal', 'displacement', 'reflection' and 'gloss' texture maps – as in Figure 2) of the same texture, each describing a different attribute of the same object (Manferdini, 2008). This allows to encode more accurate lighting behaviour and material imperfections, without having to further modify the geometry of the object. These methods are very powerful but should be used carefully, as the result is necessarily information-dense and might imply undocumented notions, such as spatial information or about material and construction techniques.

Fig. 2. Some 'maps' used in Physically Based Rendering materials – in this case representing wooden planks. From left, diffuse map, reflection map, normal map and gloss map. Each encodes different information about the behaviour of the final PBR material.

Lighting conditions should also be held into account, as they contribute towards a reconstructed image that is 'perceptually and physically valid" (Devlin, 2001). Devlin et al, chose the Roman frescoes of the 'House of the Vettii' in Pompei to show how diverse accurate lighting simulations can affect user's perception of a scene (Figure 3).
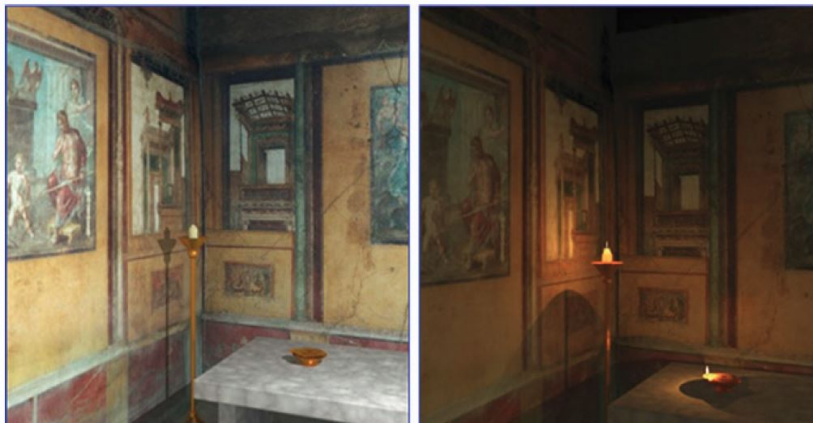

Fig.3.   A digital 3D visualization in different simulated lighting conditions, (from left) modern lighting and olive oil lamp. (Devlin, 2001)

A scene, in order to approximate 'perceptual equivalence' to the original, needs to account for a large number of factors – including the materials and physics of the light source, which might require advanced calculations and simulations. Furthermore, traditional imaging technology is only able to capture a fraction of the 'dynamic range' - the ration between the maximum and minimum light intensity that can be perceived in a scene – that the human sight can, necessarily affecting the perception of the scene (Chalmers, 2017).

3. IMPLEMENTATION

The final result is previewed online at: http://boekenkamervr.pronxi.com/

"De Boekenkamer VR" is an immersive Virtual Reality experience, which lets the user navigate a 3D reconstruction of an historical scene and obtain information about its background. In this immersive diorama, the user is firstly guided into the reconstruction, and is then given instructions on how to follow the path they are most interested in.

The following section will describe the whole production process, from the creation of appropriate 3D models to the implementation of an application logic with a game engine software. This doesn't mean to be a detailed technical guide nor a precise account on the historical evidence (the latter one especially has been over-simplified in consideration of the scope of this paper), but rather an overview of the start-to-finish multi-disciplinary process involved, in order to reflect on the several type of considerations that a researcher-developer has to keep in mind when designing for VR in this field.

3.1. Software Choices

I started my research from a blank slate, setting out to choose the software and platforms that might better suit the project's needs between the options available on the market; in fact, these choices affect factors such as economy, accessibility or scalability of the product. In general, I tried to use tools that would communicate and work well together – possibly being free to use.

3.1.1. 3D Modelling Software

Blender (version 2.80) was chosen as the 3D modelling software. Blender is a free and open source platform which covers the entire 3D creation pipeline, developed by the Blender Foundation[6]. The software offers high-end production standards and is publicly available as open software, which is the biggest selling point for the economy of a CH research project[7]. The features provided by Blender are well-suited to this project also because they are tailored to creative 3D creation, for artists and small teams; the software is relatively easy to learn, and well documented. Nevertheless, projects involving

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[6] https://www.blender.org/foundation/

[7] Dr. Piccoli, who contributed to the modelling effort, had indeed been previously using Blender for the modelling of other 3D reconstructions in her "Virtual Interiors" project.

something like complex large-scale mechanical or architectural designs, might benefit from functions and features of licenced CAD programs which are lacking in the free-to-use Blender.

3.1.2. Game Engine

The game engine is the place where the 3D scenario gets enhanced to a digital environment, and where the interaction features are implemented. There are a number of options available, such as Unreal Engine 4 (UE4), the Cry Engine or the Unity Engine; each has strengths and weaknesses and, while the first two present a better workflow for 3D and desktop applications, Unity does so for 2D and mobile use-cases. I chose to work with Unreal Engine 4, mainly because, other than it being entirely licensed as free-to-use (even for commercial purposes[8]), I appreciated its '*blueprint*' scripting language (which allows to quickly code relatively advanced scripts in a visual form) and the fact that "it is probably the best tool for achieving realistic results" (Bekele, 2018). As previously said, better looking graphics should not be the main goal, but realism isn't necessarily about that; realism is affected by factors such as how, for instance, light is rendered by the game engine and how that affects perception.
On the down-side, Unreal Engine is often said to be less immediately accessible for a beginner when compared to alternatives like Unity, which could constitute an argument against it for a field where a large portion of scholars comes from a background in humanities. In any case, performance between engines is comparable and, due to the lack of agreed conventions, the choice ultimately comes down to the implementer's taste or practicality (Bekele, 2018).

3.1.3. VR Platform

The first version of "de Boekenkamer VR" has been implemented for the HTC VIVE[9] platform; its functionalities are well supported by Unreal Engine 4, which facilitates development with premade '*blueprint*' scrips to easily integrate with VIVE's functionalities (and avoid having to hard-code basic components for functionality, like player's movements). The system consists of one headset, two hand controllers, two infrared sensors and wiring. The user's position is tracked by the wall-mounted infrared sensors (Figure 4); the head-set incorporates an accelerometer, a gyroscope and a proximity sensor. The headset uses a Dual-AMOLED 3.6'' screen with resolution of 1080 x 1200 pixels per eye (2160 x 1200 pixels combined) and a refresh rate of 90 Hz, providing a 110° field of view; it is powered by a computer

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[8] Or at least until the application hits $1.000.000 of lifetime revenue.

[9] https://www.vive.com/us/product/vive-virtual-reality-system/

running Windows 10, with 16GB of RAM and Nvidia GTX 1060 set as the entry level graphic-card required.

This first set-up was chosen mostly for reasons of immediate availability. This is a relatively expensive VR setup, on the high-end of the market; retailing at around 650 €, plus the cost of the computer necessary to power it, it is probably too expensive for most users but not for cultural institution interested in the technology. Given a powerful enough computer, the resulting experience one of the best available today, with decent resolution and refresh-rate to limit unwanted motion-sickness consequences.
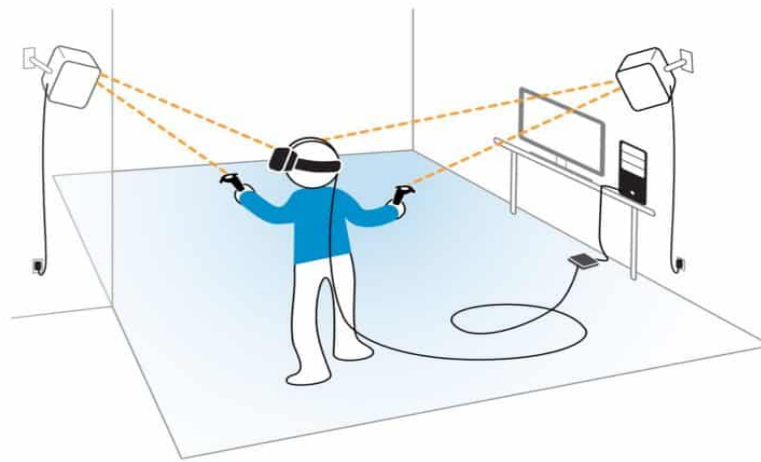
Fig. 4. Schematic drawing of a VIVE-like set-up[10]. The headset's and controllers' positions are tracked by the wall-mounted sensors.

I do not believe it to be the most suitable option for this project, and future versions of the application for cheaper and lower-end devices (such as Oculus Go, or Quest) are planned; these cheaper set-ups definitely are a more immediate solution to issues related to economy and scalability, albeit sacrificing the quality of the experience. Thankfully, Unreal Engine makes it possible to adapt a project to suit different target platforms (with relatively small effort), if the application is carefully designed.

Not only the issues related to paying for the equipment have to be kept in mind, but also those related to its maintenance (Tan, 2009): the simpler the setup, the easier it will be for non-specialist staff to operate it (in the context of a museum, for instance). In that case, affordable costs, overall user-friendliness and lack of external wires and sensors come at the price of, obviously, much poorer quality of the image and of the overall experience.

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[10] retrieved at https://www.realite-virtuelle.com/oculus-rift-vs-htc-roomscale/

3.2. The 3D Reconstruction

After setting the workflow between software components, the following step involved building the digital space that would serve as a study-case for the implementation of an effective interactive visualization system. The focus of this work is not on the reconstruction per se, but rather on the design of an application to contextualise and enhance the 3D models. Still, an account of the modelling phase is included here because, firstly, the features of the 3D objects have to be designed for their largest context, and, secondly, because behind the modelling phase lie most of the very information that need to be exposed, for whom a brief account should suffice to give an impression to the reader. Ultimately, the choice of subject was ideal for this work, being backed-up by rich sources of miscellaneous nature, bringing many of the issues commonly encountered in this discipline together in a tiny physical space.

3.2.1. Herengracht 573, Amsterdam

The subject of the reconstruction, '*de Boekenkamer*', was a small room inside of a patrician house overlooking the Herengracht canal in Amsterdam (Figure 5). The land-lot at number 573 of the Herengracht was bought by Pieter de Graeff (1638-1707), regent of the city and member of one of the most important local families; he laid the first stone of his new house on the 17th April of 1665, in the apex of the period known as "the Dutch Golden Age". He moved in around one year later with his wife Jacoba Biker, in late April 1666, whilst work on the house continued for several years; in a room at the second floor, just above the entrance hall, the owner set his private library, 'de Boekenkamer'.

These events, as well as many more, are known to us through de Graeff's diary which survived to this day. This personal diary is a precious document indeed, spanning for about four decades and offering us "a wealth of details about the construction phases of the house, the agreements he made with his neighbours and with the craftsmen and painters whom he commissioned works to, and the types of materials he used" (Piccoli, 2019). Furthermore, in the Amsterdam City Archive survives a detailed inventory of the household properties, in which items were recorded room by room in preparation of the auction that shortly followed de Graeff's death. These are exemptional first-hand documents that served as primary sources for the 3D reconstruction.

This case study offers a rich dataset to work on, whilst still not being devoid of complexities and uncertainty. With time, the large house has in fact undergone several modifications and interventions to accommodate the different needs and tastes of the succeeding owners; the building still exists today, and was lastly occupied by the Museum of Bags and Purses[11], which opened in 2007. The room

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[11] https://tassenmuseum.nl/

occupied by the library was one of the smallest in the building (about 280 x 630 cm) and went through heavy modifications over the centuries, being today completely unrecognizable[12] to its original function (Figure 6). The fact, that a modern-day visitor would not be able to relate the space to its original state, makes the reconstruction particularly interesting.

Fig.5 (left). Front views of the building as it appears today and as represented in *Caspar Philips'* drawing (1768-1771), already showing the modifications made in the first half of the 18th century.
Fig.6 (right). Interior of the building today hosting the Museum of Bag and Purses. The picture has been taken from inside of where "de Boekenkamer" would have been.

3.2.2. The 3D modelling workflow

The 3D modelling work itself was a collaborative effort between Piccoli[13] and myself[14]. The objects for this scene were created for this project using Blender (Figure 7), and most of them were generated with 'box modelling' techniques[15]; this is a style where a primitive shape is used to constitute the basis for the final model; this basic shape is then used to sculpt out the final model, by 'subdividing' its surfaces progressively to add detail. This is a fast way of reconstructing objects in the scene, without needing any procedural 3D geometry creation technique.

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[12] The walls of the room have been partially demolished to open space for a larger exhibition hall, and the window overlooking the canal has been covered entirely.

[13] She set up the Blender scene with the planimetry of the real building; she then modelled the ceiling with beams, the doors, all the books, the print-boards and the folded papers.

[14] I re-modelled the walls and made the window, the shelves, the cabinet and the floor.

[15] A few others – some books, from surviving examples of volumes present in de Graeff's library, that were physically available - were based on 3D photogrammetric models, generated with free-to-use Meshroom.

Fig.7. A rendered view of "de Boekenkamer" in Blender: this software was only used to produce the 3D models to be imported into the game engine.

The workflow generally proceeded by creating the geometry of the models first; then, we would move on to the 'UV mapping' phase in Blender. This essentially is the process of 'flattening' the 3D model mesh to a 2D surface, in order to be able to use a flat image to apply a texture to the whole object; texture and mesh now share a spatial 'u-v' coordinate that is applied back into the 3D space for a correct 'texture mapping' of the object (Figure 8). All textures[16] where chosen from free online libraries[17], which provide high quality imagery that could be adapted for the purpose.
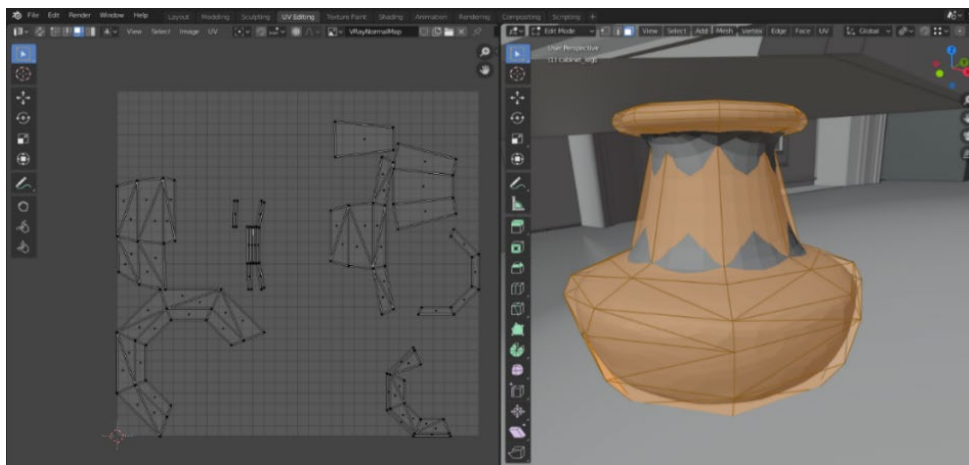
Fig.8. Blender (2.80) interface showing the "UV unwrapping" of the cabinet's leg. To the left, the surface of the curved object gets flattened for a 2D texture to be mapped to it; to the right, the geometry of the 3D object.

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[16] Other than books' ones.

[17] poliigon.com, cc0textures.com, texturehaven.com

The models would then be exported in the *.fbx* file format, to be then imported into Unreal Engine 4; this is a proprietary file format, owned by Autodesk, which is often used to provide interoperability between digital content creation applications. This is a robust and versatile format, but it is proprietary software. Support for a relatively new file format (glTF 2.0), open-source and non-proprietary, is currently in beta-testing on UE4 and will be considered for future expansions.

The *.fbx* file contains the geometry of the object and the UV mapping of the texture onto it; the textures themselves were imported in UE4 independently as high resolution (3k, or 4k) *.jpg* images. Their behaviour with the Unreal Engine's shader system was scripted with the *blueprint* scripting method; the ensemble of these relations can be saved into a re-usable PBR *material* component[18]. Together with a *diffuse map* (defining the colour patterns), I often used a *normal map* (to simulate the relief patterns) and a *reflection* and *gloss map*s (to obtain more accurate light-reflection behaviours.

Levels of Detail (LODs) were also generated inside of UE4: this allows for the geometry of the object to be reduced progressively as the user moves further away from it. For instance, a model of the window counts around 20.000 polygons, but they are only rendered together when the user is close to the window in the reconstruction; through 3 steps, they scale down to 1.400 polygons; LODs are important in improving software performance (in large compositions especially).

3.2.3. Reconstructing the room

The process of modelling progressed in parallel with the gathering of information, moving from detail to detail in the scenario. Besides the previously mentioned sources, other references for us have been surviving material culture, structural information from the house's building history, comparisons with period images and comparable real interiors of the period which have survived to this day. Without a detailed visual or written account, the reconstruction of an object, which requires research and links between notions from different disciplines, is always the best possible approximation. Rather than rendering the unknown with primitive shapes or solid renderings, I preferred an approach where a photo-realistic view of the most likely informed hypothesis is made available with the information the user needs to understand it, validate it or confute it[19]. Not only a photo-realistic rendering is more engaging, but, as long as it is based on informed assumptions, it might favour a discussion around the object that an overly simplified reproduction would not be able to trigger in the same way.

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[18] Materials cannot be passed directly from Blender to Unreal Engine; the two software use different render engines and visual scripting methods. Even if materials were made in Blender, they had to be separately done in UE4 as well – after importing the same PBR textures. Most of the materials used here had simple behaviours, which made it easy to double the effort.

[19] How this data, coming alongside the object, is structured and visualized will be discussed in later parts of this text.

Reported below are some of the decisions taken in the realisation process, to give the reader an impression of what kind of information goes to constitute the *paradata* that needs to be made available to the user, alongside what kind of elements the uncertainty classification was based upon. Following the approach proposed by Resco (2014), we divided the scenario into different Reconstruction Units (RUs); each of these is a coherent object within global scene. Based on the sources, we identified eight reconstruction units for "de Boekenkamer": Walls, Ceiling, Roof, Doors, Window, Shelves, Cabinet and Books.

The original room volume of the 'Boekenkamer' could be inferred from the existing and surviving portions of walls, and from cadastal documents of the City of Amsterdam illustrating the floorplan; these drawings were also useful in determining that this room had previously a ceiling with wooden beams, which are now lost or hidden beneath the current ceiling. As for the flooring of the room (Figure 9), we know from the owner's diary that he bought a number of medium-sized oak ('eikenhout') axes[20], although it is not clear whether they were meant for this room in particular; without a direct reference, the way these were mounted, or coated has to be inferred from parallelisms with contemporary surviving examples and known building techniques.

Fig. 9. A rendered view of de flooring of the room, in Unreal Engine 4.

Highly detailed images might imply details that do not seem relevant to the general user, but might be relevant to the specialist; we generally modelled the simplest plausible version of the object, leaving aside non-documented embellishments and flamboyancies. With this approach, I modelled for instance the cabinet ("kast"), whose presence in the room we inferred from the probate inventory that was made after De Graeff's death, listing all his properties room by room[21]; the inventory provides the item's economic value and tells us it was made of oak, but nothing else about this cabinet's appearance is

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[20] C. Piccoli, pers. comm. Leiden, June 2019

[21] C. Piccoli, pers. comm. Leiden, July 2019

known. It has been modelled based on the simplest contemporary example that could have been suitable to the context (Figure 10).

Fig. 10. Picture of a real 17th century Dutch cabinet ("Kast") next to a digital counterpart in UE4.

The 'cabinet' Reconstruction Unit actually groups several objects, with the cabinet itself but also the printing boards. This is because the inference of their existence is derived from the same source, but also because the aspect of the first directly affects that of the second: if the cabinet was taller, which might as well have been, the boards might become hidden behind it, suggesting a possible re-positioning elsewhere (above the doors, for instance). This is clearer in the VR experience than in other representations of the room, demonstrating how the technology can indeed stimulate discussion around different possibilities[22] in the reconstruction. The prints' textures were blurred in UE4 by reducing their pixel density, in order to give an impression of their look, but hiding undocumented details which could not be without meaning to a specialist eye[23].

As for the cabinet, we proceeded for the shelves in the room, whose design was based on contemporary examples adapted to fit the physical constrains of the room. The main inspiration for the shelves of the 'Boekenkamer' was the Bibliotheca Thysiana in Leiden, a well-preserved example of 17th century library[24], which hosts a collection in many ways comparable to the lost de Graeff's; in fact, the sizing and spacing of the shelves were used as exact reference, whilst decorations were simplified. The exact number of books present in the real de Graeff's shelves is impossible to know, although an esteem can be obtained by seeing how many would fit in the dimension of the shelves, when modelled according to the size of

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[22] Ideally, the final user would be able to dynamically visualize both possible versions of the reconstruction. This feature is not included in this state of the prototype, but is planned for future developments.

[23] A print on a wall could, for instance, imply notions about the owner's political or religious opinions.

[24] Many thanks go to Prof. Dr. Paul Hoftijzer, curator of the library, who kindly arranged two private visits for us, and generously answered many questions and allowed us to photograph the spaces and the collection.

the room[25]. Modelling each book correctly would have simply been too time consuming, so we referred again to the content of Bibliotheca Thysiana, where I had taken many large resolution pictures of the books lining on the shelves. In Blender, these pictures were mapped onto solid blocks that were then roughly shaped accordingly[26]; a few of these 'blocks' were created and then placed repetitively to fill the shelves (Figure 11); materials were created in UE4 with normal maps to give a slight effect of dept. This is the most accurate solution we could implement in the time available. Some elements, like jambs and doors have been based on evidence from other contemporary houses[27].

Fig. 11. A rear view of the room in Blender, showing the geometries of several objects.

A final mention goes to the style of the ("kruiskozijn") window (Figure 12), which was obtained by comparison with the aspect of the house next to de Graeff's, as it appeared in an early drawing; this made sense since we know[28] that an agreement existed with the owners of the neighbouring houses about the facades' appearance.

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[25] A surviving auction catalogue, drafted two years following de Graeff's death, lists more than two-thousand volumes in the owner's collection; however, this doesn't necessarily correspond with the actual number of books that he had owned - in fact, evidence has recently been found suggesting that there were more (C. Piccoli, pers. comm. 2020).

[26] Piccoli curated the models of these general 'blocks' of books.

[27] Piccoli realised the models of the doors.
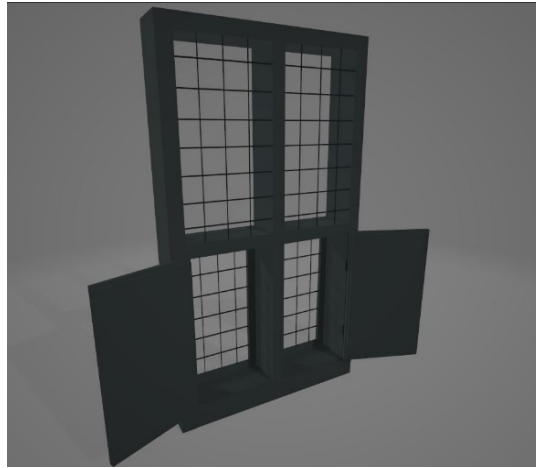
[28] C. Piccoli, pers. comm. Leiden, July 2019

Fig. 12. The room window, rendered in Blender in 'solid mode', with no texture and material information applied.

3.2.4. Lighting

As previously stated, correct lighting simulation can greatly affect perception, but might require calculations which go beyond the scope of this project at this point. In UE4, I designed a single, controlled lighting condition - with natural lighting from the outside, on a summer morning with clear sky. Using *static* lighting, where light is pre-computed and saved rather than calculated for each frame (as would happen for dynamic lights which can be affected by the course of gameplay), guarantees a neat performance advantage, which is useful when trying to meet a decent frame-rate on low-end devices.

I positioned the sun in the scene with the *Sun Position Calculator* plugin, which allows to precisely control the sun light object in UE4. We used the geographic coordinates of the building, on a plausible year for the reconstruction (1694) and the date (9am, 27th July) to obtain the correct sun location, and oriented the room accordingly. The natural light (a *directional light* object in UE4) comes through the window and illuminates the room by bouncing on the objects' surfaces simulating real light behaviour[29]. Inside of the room, I added a *Sphere Reflection Capture* and a *Lightmass Importance Volume,* necessary for correct render of the lighting behaviour. I also added an *exponential height fog* actor which, if used

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[29] I raised the light bounces on surfaces in UE4 as much as possible: in reality, light waves bounce back and forth multiple times, while in computer software the number of bounces tends to be limited because its simulation is computationally expensive. One advantage of using a static lighting condition is that it allows for more a complex lighting simulation, which might in turn impact on realism of the scene: if the light bounces more times the resulting space is naturally brighter, which avoids the introductions of extra lights to compensate. Very recently, Ray Tracing technology has been introduced in 3D graphics; this technique traces the path of light and simulates the effects of its encounters with virtual objects. The technique can produce a high degree of visual realism and it is already supported by UE4 (since v.4.22); unfortunately, no system with a graphics card powerful enough to run it in VR was available to us.

delicately, can simulate the density of air and desaturate the scene slightly, making it look more uniform and natural to the eye in VR.

The exterior of the house, which can be seen from the window, was added as well with a panoramic HDRI (*High Dynamic Range Image*). They are made by combining several pictures of the landscape, with different exposures, into a 360° panorama image; this image is mapped onto a three-dimensional dome surrounding the scene. The HDRI that was used depicts a canal view in modern day Amsterdam[30], in a location not-too-far from Herengracht 573; the street layout is roughly the same but, not to fall in obvious anachronisms, the image was blurred to the point where it creates an approximation of volumes whilst partially hiding the most modern features. I implemented it in UE through a *backdrop actor*, which also allows to regulate its interaction with illumination and reflections[31].

3.3. Uncertainty Coded

While the room environment in Unreal Engine was being assembled, I set out to establish which data to visualize with the model, and ad to find an effective structure to do so. The uncertainty level was finally evaluated for each of the Reconstruction Units; each class was mapped to a colour, with a *class-based* classification method as a general framework – with the goal of being able to render the object in the application in *solid-mode[32]* with the corresponding colour upon user's request. This is only meant to serve as first orientation and source of comparison, since colours are easily readable transmitters of information. Contrarily to other related works - which used scales of up to ten - we relied on an uncertainty scale of four colours only. Even if might not be sufficient to cover the whole range of nuances and uncertainty-class possibilities, we reckoned that having a very schematic system would reduce confusion for the user which, in the final VR application, might be easily overwhelmed with content; these colour-charts also ought to be supported by explanatory text, and we preferred to limit it at this stage to avoid disorientation for the user. A more detailed insight on each object's background data will be obtainable from the user through other features of the application, hopefully compensating for a possible lack of clarity of the minimalistic colour-scale.

The logic structure of the colour-coding chosen palette was inspired by design choices by Strothotte (1999) - although reworked and adapted to the specificities of this new scenario - and goes as showed below in Figure 13.

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[30] This HDRI image was made publicly available, by CG artist and open source advocate Greg Zaal, at hdrihaven.com/hdri/?h=tears_of_steel_bridge.

[31] Piccoli curated the HDRI set-up in Blender.

[32] An object is rendered in *solid-mode* when its surfaces are of a single uniform colour, without any material property.
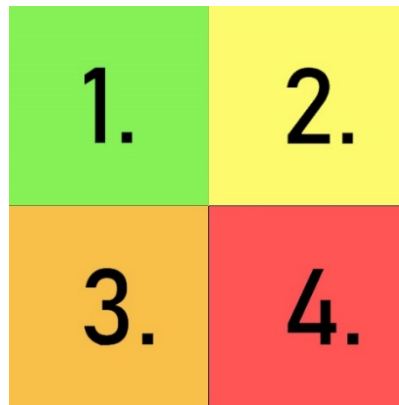
Fig.13. Palette of 4 colours chosen to represent classes.

1. (Light Green, #87f257) - We know the object's position, and we know its geometric properties. This applies to surviving materiality, things that have been found on site or detailed accounts. [Walls]

2. (Yellow, #fdfa6d) - We know the object's position, and we have elements to speculate about its geometric properties. Conclusions on structural properties of the object can be drawn by the physical remains (physical constraints, for instance), or by other strong type of evidence (e.g. from a drawing or written account). [Ceiling, Floor, Window, Books]

3. (Orange, #f8c049) - We can assume the object's position, and we have elements to speculate about its geometric properties: certain elements may be obtained by knowing how objects were constructed in a certain period of history (period features), or can be concluded logically from other buildings/objects of the same period (analogies). [Doors, Shelves]

4. (Red, #ff5555) - We can assume the object was there, but we have no element to speculate about about its look; this is information derived from other data within the model (deductions), or coming from very 'noisy' sources. [Cabinet]

Another possible point of weakness could lie in the fact that each RU is made by sub-components which could themselves be individually considered. For instance, a 17th century 'kruiskozijn' window is typically made by several parts, such as a frame, window shutters, hinges, an inner metallic frame that holds the glass in place and the glass panels themselves; all these parts together constitute the Window RU but, if taken individually, might differ in terms of what is actually known about them.

I have also tried to augment this class-based classification with a method based on *fuzzy-logic*, as prescribed in prior literature. As it puts a value on the subjective judgements of the research about the reliability of his sources – conclusions which the user can independently reach by examining paradata – and significantly adds to the amount of data that needs to be displayed, I deemed it redundant and, again, opted for an option that would reduce cognitive load for the user.

3.4. Paradata Documentation

Paradata (examples with actual content can be found in the *Appendix* of this paper) were organised in the Microsoft Excel comma-separated spreadsheet format (.xls). They can be parsed inside of Unreal Engine, to be then printed onto the intended surface or object in the reconstruction; externally stored data allows for much easier data manipulation and is a useful tool for a co-ordinated effort between historian and developer which, in practice, rarely are the same figure.

Paradata documentation for each object contains five broad categories:

1. Provenance
2. Decisions
3. Evidence. Five types of evidence are provided for:
4.   1. Architectural Evidence
          2. Archaeological Evidence
          3. Documentary Evidence
          4. Precedent Evidence
          5. Analogy Evidence
4. Dependence
5. Alternatives
(6). References
(7). Images

This structure has been proposed by McCurdy (2010) for VR applications for archaeology, and it aims at simplifying and standardising the process of collecting all the important bits of precious data about the objects; not all points are always applicable to every asset, and in such cases the fields are left blank. The fifth component, 'alternatives', is included as a discouragement of the 'single reconstruction', where viewers buy into the one option presented without pausing to consider alternatives. 'References' is a list of resources which doesn't get printed with the other information in the final application, but is accessible in the project folder inside of the *.xls* file; 'images' are string names for the image files to be used, which Unreal Engine can automatically reference.

3.5. Application Design

As a consequence of the research goals, I wanted the application to serve a set of purposes: firstly, I wanted to let the user explore the reconstruction as perceptually closely to the real past as possible, through an immersive experience; then, I wanted to show levels of uncertainty relative to the objects in an effective way. Furthermore, I desired to display paradata about the elements present in the visualization.

Finally, I wanted the user to be able to take decisions on the content they intend to see. This potential user might come from a variety of backgrounds: thus, this virtual environment needs to become a 'context' where multiple and diverse cultural experiences may occur at different levels for different users (from layman to expert) according to their level of interpretation (Tan, 2009). I wanted to do so by allowing them to explore in a non-linear, open-ended interpretative way for a better participative and learning experience: for the non-specialist, a VR experience might be engaging in itself, while for an expert it only represents a starting point for further enquiry.

All the elements were set at this point to design a practical interface for a VR application that could fit all of the specifications.

3.5.1. Application Structure

The narrative pattern underlying our hierarchical structure of choice is best characterised as a 'Martini Glass' model (Segel, 2010). This visualization structure begins with an author-driven approach; the visualization relies then on interesting default views or annotations. When the narrative set up by the author is complete, the visualization opens up to a next stage where the user can freely explore the possibilities offered to them by the interactive experience. The structure recalls in fact the shape of a Martini glass (Fig. 14), where the stem stands for the single-path author-driven narrative, and the widening mouth of the glass for the paths made available through user-driven interactivity.
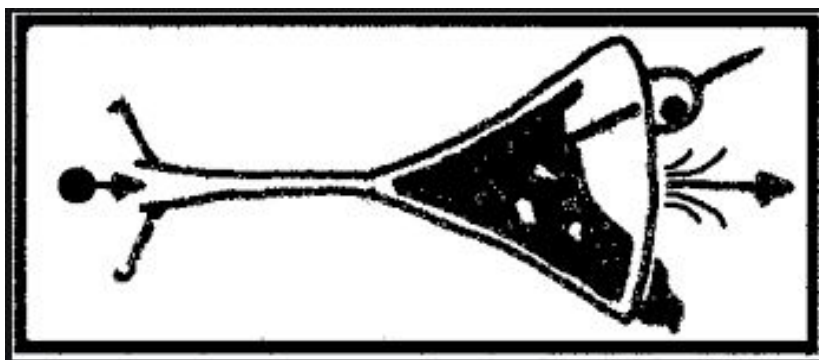
Fig.14. Martini Glass model (Segel, 2010)

With this structure, the author-driven narrative functions first and, like the stem of the glass, it can be of different length (corresponding to a different degree of authoring). User-driven interaction follows separately, and metaphorically results in different mouth shapes for the glass as different are the paths the user can take. "De Boekenkamer VR" has consequently been organised into subsequent stages, or levels, each of them corresponding to a function intended for it (as in Figure 15). User's decisions guide the experience through the stages' hierarchy.
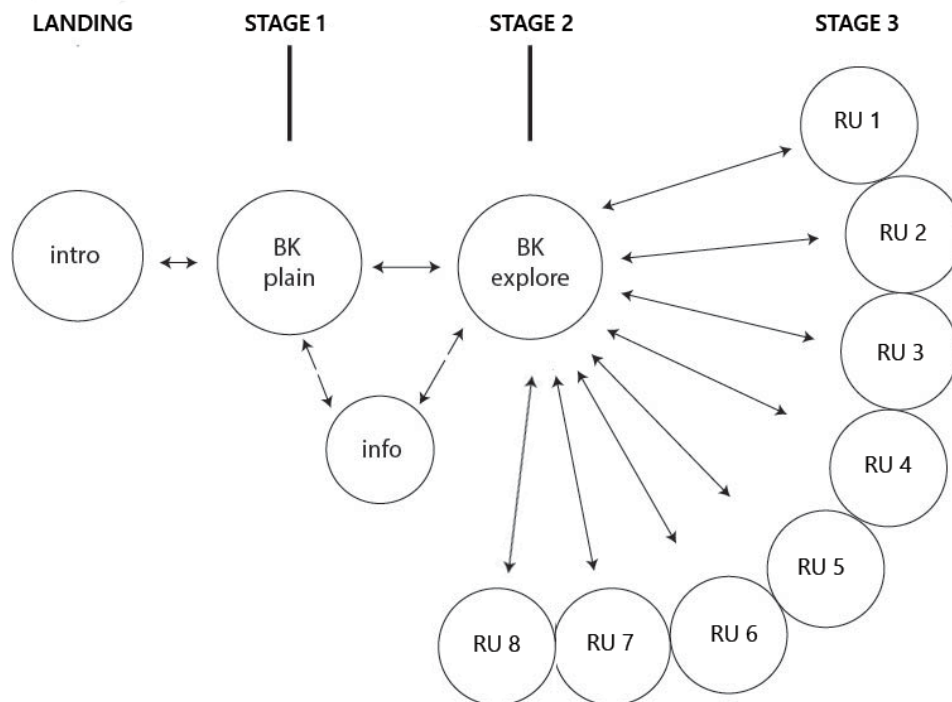
Fig.15. Flow diagram of "De Boekenkamer VR'', reflecting the Martini Glass structure.

3.5.1.1. Overview

With the structure proposed here (Table 1), I offer a solution for CH reconstructions that respects Pietroni's (2014) requirements for 'inclusivity' (the user is immersed in a scenario where all the data are integrated and are in 3D) and 'interactivity' (the user acts in the digital world, making choices on contents and paths, which favours a personalized approach to knowledge). This is a template structure that can be easily adopted, adapted and improved by similar projects.

	Goal	Features	Thumbnail
1st Stage	Explore the space	- Reconstruction only	
2nd Stage	Visualize uncertainty (single and multiple RU)	-Colour mappings -Uncertainty indicator -Red pointer	
3rd Stage	Know more about each RU	-Object reconstruction placed in a different context -Tables with sources and data -Alternative reconstruction hypothesis	

Table 1. Overview of the main components (the three stages) of the application structure.

3.5.1.2. Landing

When the user wears the VR headset, he is firstly presented with a 'landing' title page. He can proceed through three introductory slides with a brief background to set the scene - similarly to what an 'establishing shot' does in filmography (Thomson, 2009); this provides the user with titles and historical information. The opening slides serve to give a context, but also to let the user familiarise with the most basic action of clicking to proceed. This set-up is not often familiar to the general user, meaning that precautions need to be taken each time to guarantee that they can get acquainted with it. After making sense of orientation in the headset and having familiarised with the controller, by skipping through the introductory slides, the user receives instructions about the reconstruction space they will find at Stage 1 of the application (Fig. 16).
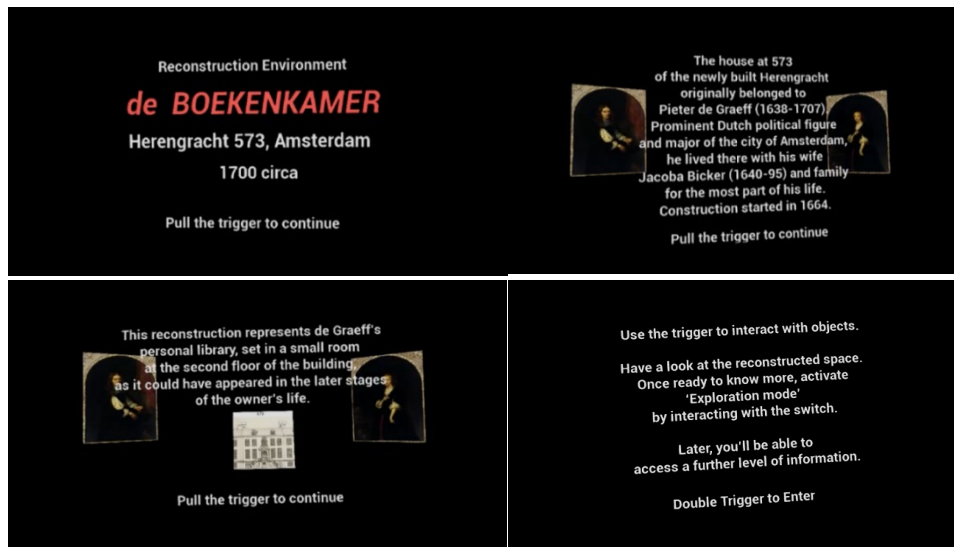
Fig. 16. Screenshots of the four introductory slides.

3.5.1.3. First Stage

In the first stage, the user can experience the digital reconstruction of the room, being able to move around freely in the virtual reality environment. The objective of this stage is to make the user experience the environment as closely as possible to the real scene; hence the reconstruction appears 'clean' of widgets, graphics or non-diegetic elements, with two exceptions. Over the door in the back of the room there are two buttons. Pressing the '*exploration mode* switch' button allows the user to enter Stage 2. This is the only widget text that the user can find at Stage 1 of the application (Fig. 17), with large font and high colour contrast (white over dark brown), therefore we hoped that it would be difficult to miss, at the same being not obtrusive in the overall experience. By interacting with a sphere-shaped button placed just underneath, the user can enter an 'info' section (functioning similarly to an '*about us'* web page, providing a brief on the project itself and its developers).

I had originally tried other solutions for the placement of these buttons, involving fixed text on several parts of the field of view - as a sort of Head-Up Display - but I found HUD solutions not to be well suited for VR, as they can be quite unnatural to the human sight; we found that embedding text over diegetic elements was a preferable solution to guide user navigation, when possible.
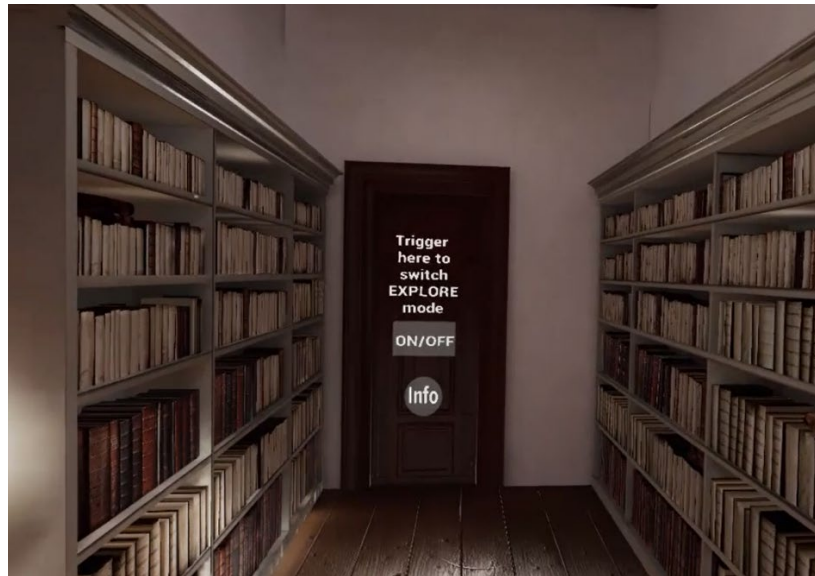
Fig. 17. Screenshot from the first stage of "de Boekenkamer VR". Over the door in the back of the room, the clickable switch transports the user to the second stage.

3.5.1.4. Second Stage

In the second stage, uncertainty coding is visualized: the colour of each reconstruction unit is rendered according to it. We then have that, for instance, the model of the cabinet, with a value of '4' in the uncertainty scale, is rendered in red. Each object is superimposed with some text with quick facts describing identity and salient features (Fig. 18). In this case, the use of non-diegetic elements was justified by 'reduced search' for the user (meaning he has little effort to do in order to find the information he needs) as that can have a positive impact on the clarity of the visualization. In general, with every component, it was considered how the design choices relate to visual thinking criteria (Ware, 2005) and how they aim to enhance cognition whilst limiting sensory overload and visual clutter.

Fig. 18. Screenshot from the second stage of "de Boekenkamer VR".

Two widget panels also appear in the centre of the reconstruction (Fig. 19); they contain useful information needed by the user to put the colour coding in context and make sense of it.
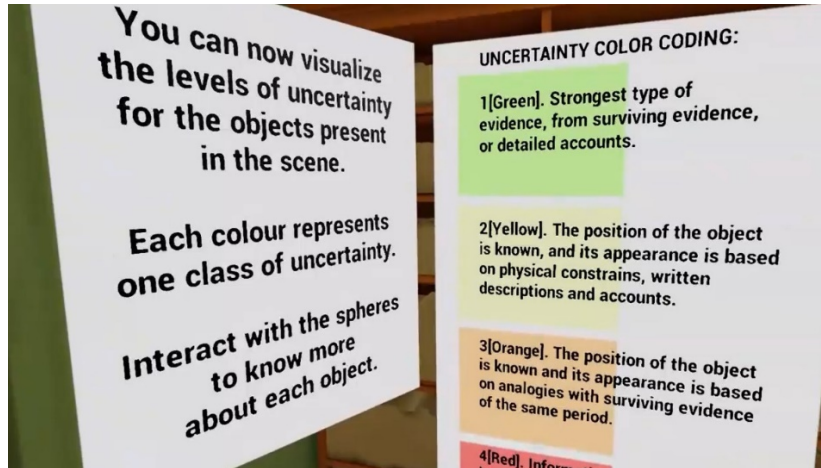
Fig.19. Widget information panels appearing at Stage 2.

I also used '*points of interest*' (POIs) to navigate the user at this stage: each RU is marked by its own POI (physically represented by a translucent grey sphere with some text in it: by interacting with a chosen POI sphere, the user can access the next stage, which is indeed RU-specific (Fig. 20).

Fig. 20. Widget text for 'the Books'. Note the small sphere next to the text: clicking on it will bring the user to the third stage.

3.5.1.5. Third Stage

In the final stage, each object receives its own dedicated ideal space - like a room in a real exhibition - where it is presented in the centre of the scene, surrounded by informative widget panels placed in a circular fashion (designed to focalise user attention). Such panels contain text and images (pictures,

drawings, paintings) representing the research and decision-making process, ultimately constituting the essence of paradata. This third stage has the function to dig deeper into the history of the reconstructed object, and has less limitations for the amount and size of content that it should reasonably display. It is visualized as a digital environment separated from the Boekenkamer itself (in practice, this is a new level in UE4). This means moving away from the main visualization, potentially creating confusion for the user, but with two potential benefits as well; for starters, it might be interesting to visualize the object in a different perceptual context. Secondly, I noticed that it was a very hard task to 'physically' fit even half of the information that we wanted to display in the very narrow space of the Boekenkamer (panels and objects would overlap very often, and text and images would often be too small to be comfortably readable in the sub-optimal resolution of the head-mounted displays); I reckoned that creating a new blank space would have been a much better design choice for information clarity and display (Fig. 21). A button to return to Stage 2 is also present in the scene.

Fig. 21. Screenshots from the third stage of 'de Boekenkamer VR'; every object receive its dedicated 'exhibition space'.

All the books together received a single level, for now. In it, the user can currently find the same information display as in the other levels, with panels and central object; the 3D model displayed here[33], is a photogrammetry-based reproduction of one specific volume out of those supposed to have been in de Graeff's library[34]. This was chosen as exemplary for the others, as they share similar sources, and is particularly interesting as it might have a relation with the building style of the house itself[35]. This is the only glimpse the user has on the actual content of the library, and should be expanded in the future, by allowing the user to choose between different books to access their content[36].

3.5.2. User Interaction

One of the global aims was to be able to keep the software as cross-platform compatible as possible. It is indeed possible to partially follow the same workflow for different target platforms in Unreal Engine 4; the scene is prepared in the same way, and then the project would need to be tweaked in some of its graphic parameters to be optimised for the different target hardware; the user input would also have to be adapted to match the features of the new platform, by re-coding the *blueprints* responsible for the user interaction in UE4[37]. I developed the whole interaction for it not to use more than two buttons, which is what is shared by most VR devices' controllers. For instance, both the 'low-end' Oculus Go and the 'high-end' HTC VIVE share a central round clickable trackpad (usually used to control movements in the virtual environment) and a gun-like trigger on the back of the controller (mappable to different interaction needs, but generally functioning as a left-button of a mouse controller). Despite developing the prototype on the HTC VIVE, I aimed at making as little use as possible of VIVE-specific features and controls, limiting ourselves to the two mentioned buttons on one single controller (suitable for left or right-handed equally). Furthermore, the application was set up to use only one out of the pair of controllers commonly used with the HTC VIVE, once again to make it easier for the application to be adapted to different purposes (as most of low-end devices rely on this setup).

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[33] Piccoli selected this book and realised the 3D model.

[34] From a surviving copy of the same edition, currently preserved at the Leiden University Libraries' Special Edition.

[35] C. Piccoli, Home-making in 17th century Amsterdam: Investigating visual cues in domestic interiors by means of a 3D digital environment, submitted for publication.

[36] I had implemented a feature that allowed to upload PDF files (or access them through the web), to display the content of books in a PDF viewer. This feature of UE4 was working on desktop, but it is currently (v.4.24) not supported in VR. Future releases of the game engine might provide better support and make it easy to visualize book content inside of dedicated panels.

[37] The process of deploying the finished application to different devices might differ quite significantly.

In the three 'opening slides' of the application, the user is prompted to advance by pressing the back trigger. This is always used with a click function throughout the application, and it serves as the main interface control.

When the user reaches the first stage, he can now interact with objects; it is at this point that he can use a red pointer straight in front of his controller (about 1 meter long), which is meant to be of help with the interactions and it is always present. The user can hover the pointer on the interactable switches in order to activate them; when this happens, the switch-object renders in a light-blue colour to signal its activation state and give visual feedback to the user (Fig. 22). Now, the user can pull the trigger to 'click' the switch. This works with all buttons, such as each RU's sphere that links to the relative environment at Stage 3, or the '*return to Boekenkamer*' button that will make the user return from there to the main visualization.

Fig. 22. Light blue colour signals a switch activation; the item can now be interacted with by pulling the trigger on the back of the controller.

The round trackpad on the controller is used for navigation: the user can press it to 'tele-transport' to a location he wants to. The new location is marked on the scene by a blue beam appearing straight out of the controller (Fig. 23), which the user can use to help guiding his way; this is commonly used by VR applications and it's designed to help with orientation.
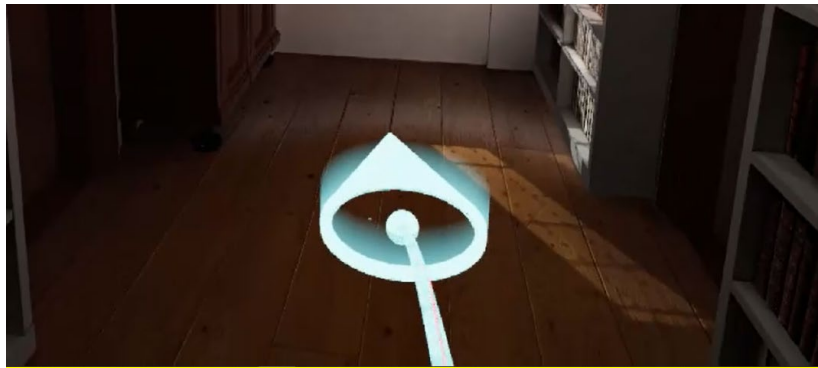
Fig. 23. This blue marker is used to signal the location the user is tele-transporting to.

With the VIVE set-up, thanks to the wall-mounted infrared sensors that can track the headset's position and orientation in space, it is also possible to simply travel the visualization space by physically walking around[38]. This is not possible on lower-end devices such as the Oculus Go, where only tilt, pan and yaw movements are captured by the internal sensors of the headset.

The final result is previewed online at: http://boekenkamervr.pronxi.com/

4. EVALUATION

This section is concerned with the process of evaluation of 'De Boekenkamer VR'; it collects the description and outcomes of the tests that we have run with multiple users, as well as personal reflections that emerged during the entire development process. The general purposes of this section are to inform the reader on the successful, and on the less-so, parts of this project, as well as to outline the most promising aspects, together with those that will still be the most problematic going forward.

4.1. Testing 'De Boekenkamer VR'

An optimal way, to confirm whether the application was meeting the expectations, was to make it meet a public who could provide external feedback. I had two objectives in mind when planning for the tests: firstly, I wanted to see how people would do in this digital environment - if they could get to the stages they wanted to, incurred in any glitch, were able to press all the buttons, read what they were supposed to be reading, or follow the flow of the application - in essence, making sure that the app itself was designed well enough in terms of user experience. Secondly, but most importantly maybe, I wanted to

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[38] Collisions in the application have been set to not let the camera pass through any solid object.

verify that some of the very assumptions the work was based on were in fact correct. For instance, would all users follow the same path, or could they personalise the experience according to their interests? Would they leave the experience having had a clear impression of the uncertainty degrees of the scene? In a similar application, would graphic quality be a concern at all for the actual users? Would they appreciate this content being in VR, or would have they just liked it better to navigate the same reconstruction space and access the information from a more familiar device (like a desktop pc)? Answering questions of this kind was fundamental to validate the purpose of the whole effort.

4.1.1. Method

To verify the general functioning of the application, participants were not given a time limitation and were encouraged to explore the environment to their own liking, following the development of the narrative. At the end of their experience, they were each given a questionnaire to complete. The questionnaire was based the well-known SUS (*System Usability Scale)* by Brooke et al. (1996), with additions inspired by the paper by Ozok (2009), which extends the SUS' functions, and targets the user's satisfaction with three-dimensional digital representations. The resulting questionnaire consisted of twenty statements[39] to be graded by the users on a scale [1, 5], depending on how well they agreed with them. The results would provide us with a solid indication on the user's opinions about their overall satisfaction and enjoyment with the product, on how easy was it for them to use it, on whether they felt that there was enough detail in the image or clarity in the instructions, or whether they would have preferred to have similar information in 2D instead. Furthermore, the participants were also asked four extra questions about demographics (age and sex) and their previous experience with VR devices. At the end of the questionnaire, they were also encouraged to write some feedback down in a few lines, together with what they would have liked to see changed in a future release. For the duration of every test, the developer would follow the user's actions through the display monitor of the laptop powering the VIVE, which has proved to be a very useful feature to immediately determine the troubles that users fell into.

The application was tested with 10 participants (Fig. 24), in two different sessions. Aged between 22 and 46 (4 females and 6 males), half of them were researchers[40], working on the Virtual Interiors project the University of Amsterdam, while the other half was represented by master students of the archaeology faculty of the University of Leiden.

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[39] These can be found in the Appendix section, a.5.2.

[40] Coming from a set of different back-grounds, such as history, cinema studies, human-computer interaction, and archaeology.

Fig. 24. User testing "de Boekenkamer VR" on HTC VIVE. To the left, the developer monitors the user's performance on the display of the laptop running the application.

4.1.2. Insights from tests

 Here, I discuss the users' impressions that tests have revealed[41]. "De Boekenkamer" was very well received overall, with a neat majority of testers finding it enjoyable and satisfying. About half of the users seemed to have very little issues getting acquainted with the system, while the other half needed some extra explanation before starting; some struggled with the interface of VIVE itself (by not feeling physically comfortable or, more commonly, by not being familiar with the controllers), while some others had a few doubts about which switches to activate in the application. Generally, though, once learned the basic workings of the system, the users were able to explore the environment quite smoothly (with users reporting being confident throughout the experience), with the one exception of a user who could never fully familiarise with the set-up, or navigate it independently. Overall, I am satisfied with this result as it appears that, with just a few corrections, these problems can be largely mitigated: users mostly reported that some extra, more detailed, instructions in the opening slides could do the job just fine – although I reckon that a brief introductory 'tutorial', to be completed before the actual exploration of the digital space, would probably be the most suitable solution.

The entirety of the test sample declared to have found the representation aesthetically pleasing and the overall majority to have found the digital image to be detailed enough. Through the comments that we

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[41] The full questionnaire's results can be found in Appendix a.5.

invited to leave at the bottom of the questionnaire, it emerged that users found the colour-coding system itself to be working, and easy to associate a colour to a class[42].

The informative panels were firstly placed over the two doors in the middle of the room, facing each other; users reported them as not being in the best position, as they were noticeable but it wasn't clear that they had priority over the rest, and in which order they ought to be read (with a couple of users not reading them at all); after hearing the feedback, the panels were moved to their final position, next to the main 'switch', so that they would be immediately visible and readable after Stage 2 has been activated. Furthermore, small text was reported to be hard to read at times, but little could be done to improve this (other than enlarging it where possible) as I believed it mostly had to do with the screen resolution of the VR headset.

There was general appreciation for the application's structure, the splitting into separate stages and the 3rd Stage in particular; the structure seemed to make sense to the users, and functioned well to organise the content, as I desired: people interacted in different ways, choosing different paths and focusing on what intrigued them the most. The results pleasingly show that the general concepts behind this prototype are valid. Some of the users wandered around the reconstruction of this small room (at Stage 1) for up to 8 minutes; some others skipped that relatively quickly and liked to spend the majority of time reading through the information panels at Stage 3. It seemed to us that the organisation we devised could effectively empower the users to search for the content that they were more interested in, leaving aside what engaged them the least. A few users reported that they would have liked a deeper level of interaction with the 3D objects themselves (by being able to manipulate, rotate, or play around with them), both in the main reconstruction space but especially in the 3rd Stage, where the object in the centre of the scene appeared too static at times; adding to this, many wished that they could somehow read through the content of the books, or open the cabinet. Users indeed showed a strong desire to interact more with the objects in their surroundings; in fact, at his moment, there is a lot to read but not really a lot to do, which is probably not making the best out of VR possibilities. Considering that the focus of this work was on an interface suited to display uncertainty, the primary issue in the field overall, I didn't put much effort in the development of 'playful' features such as a window that can be opened. I rather saw the application at this stage as a core for future CH applications that, if wanting to be successful, will need to incorporate more of those playful elements; besides attracting more users, by giving them what they really want from VR, these 'tools' can really engage users and exploit VR technology as a tool to test our hypotheses and reflect upon past customs and materiality.

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[42] The first version of the application, that we tested in the first session with 5 participants, used a different combination of colours, compared to the final one; these colours, chosen to be suitable for a colour-blind audience as well, were reported to be too difficult to immediately associate to a degree of uncertainty. After receiving the feedback, colours were changed to a more traditional green-to-red scale, which was reported to be much more recognisable at first sight.

4.2. Reflections

For me, this has been the very first project in the fields of VR and Digital Heritage. This section will summarize some of the observations I could make during the process of research and development - not only about the product described in this paper, but also on the wider context in which this project is placed.

4.2.1. Engaging with a digital materiality

Making an object and placing it into context (even a virtual one) increase the engagement with the materiality of the objects: for instance, after having created the room and having placed it coherently with the accurate sun position, it was evident that the sun was going to hit only one corner of the room. We know that, at the time, books were placed away from direct light to avoid weathering, when possible: therefore, that bright spot is where we placed our cabinet, solving this way a possible issue we had with a lack of certainty in the sources. In the activity of reconstructing and being immersed in a similar environment, one can identify oneself with the impressions and questions that someone might have had when building the real counterpart. In VR, one can evaluate how the objects might have related to each other during their use-lives. Walking around the digital library, one can put himself in De Graeff's shoes, and try to execute the same actions he would have done (like simply picking a book from the shelves and read[43] – or opening the window, for instance); if gestures seem natural, and objects are placed in places that would make sense from a daily-use perspective[44], that is a little sign in favour of the credibility of the model. In this way, the model is not meant to stand on its own, self-evident, and static, but rather it is meant to be engaged with, to be improved or disproved.

The researcher should also be able to rely on the impressions of the users: those who tried the application, wished that they could have more and more direct ways of interaction with their surroundings: they wished to be able to close the gap between simply being immersed in a scenario, and being part of it. As developers, we need to empower them to research (actively and passively) and produce new knowledge by testing our hypothesis represented the 3D reconstructions. Ideally, users would spontaneously interact with objects, making natural observations around their daily use. Once a method is established to display uncertainty and accept these models as scientifically reliable, the most

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[43] My personal feeling, after having spent quite some time in its dark and tiny space, is that the room was unlikely used as a place to read, but rather as storage space.

[44] The environment of the Boekenkamer is a relatively simple one, but one can imagine how this becomes even more evident in larger and more active spaces, like a kitchen or a living room could be.

immediate next step must focus on interaction and haptic controls. This is a solid indication of the direction developers should focus on for future applications.

Being able to mediate between approximating uncertainty and perceptual vicinity – not showing more than it is known, whilst at the same time rendering an impression of the scene that is perceptually valid (even if not complete) - to the point where reliable considerations about the real object can emerge, seems to be the real challenge ahead. Perceptual vicinity appears as a very promising tool for discovery and research.

4.2.2. Need for standards

Simply by looking at the answers in the first lines of the questionnaires, something noticeable emerged pretty clearly: out of the ten participants, only three declared to have used a VR device more than five times in their lives (they were also the only ones to have used it more than twice in the previous twelve months), with two participants declaring to have never used one at all. Ten participants do not constitute a large sample but, considering their relatively young age and professional interests, the results still appear as meaningful. At the same time, the entirety of the participants (in the only question where they all casted the same vote) stated that they 'strongly disagreed' with the statement that 'these representations should have been 3D only (on a desktop monitor, for instance)'. VR technologies are obviously far from mass adoption, but it appears that, even at a niche level, they still fall far behind expectations (despite a strong interest declared by the potential users).

It is maybe worth then, once more, to reflect on why this might be; costs and technical intricacies are well-known issues but, considering how both of those elements have dropped in the last few years, I believe they are not valid reasons anymore to entirely justify the lack of adoption. The quality of gear commercially available today is sufficient to build interesting and engaging products. I reckon that the inaccessibility of content, and the dispersion of development resources into many different platforms and standards might be playing a significant role as well, when coming to the use in CH.

Especially for independent developers (such as the vast majority of those developing applications for Cultural Heritage), which do not have on the backing of a big production company to provide assets and technical support, it would be of vital importance to be able to rely, at least partially, on the work previously done by others; three-dimensional assets, very time consuming to make, are very difficult to retrieve instead. There are often projects already out there which had to produce useful assets[45], and being able to access it would be a huge time-saving resource, but this is generally not easily possible.

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[45] An example of asset complex to make, but easy to re-use, could be something as a 17th-century glass material. The most general features can be easily spent across several projects.

Between all the online stores dedicated to providing digital 3D assets, there is none specifically focused on CH. Even if a developer would want to sell his 'scientifically reliable' assets after use, it would be difficult without them being dispersed in the sea of the internet.

A solution where cultural organisations (musea, in particular), once a digital reconstruction has been accepted as scientifically valid[46], would start treating it as actual Cultural Heritage - which means storing and maintaining – would be beneficial to all parties involved. This could force standards upon developers[47], who might want their product to meet certain parameters to be accepted in a collection, and favour software maintenance by specialised staff provided by the organisation, which can organise exhibitions (both physical and web-based) with this content. This could provide a precious push towards the definition of widely accepted working standards, which could in turn help to make future-proof decisions to ensure that all the work that has been put in does not go to waste, but can rather be built upon. Furthermore, this could facilitate the development of an ecosystem of specialised services that could bring new life to the development of VR content, with a solid use case. Surely, this has costs for the cultural organisations, but I also see potential for profit, with exhibitions and sale of specialised and reliable assets. I reckon that one issue today might lie in the lack of consideration that such organisations (that could provide this services) still have towards digital Cultural Heritage, rather than in a lack of means to achieve something similar.

Today, designing a VR product that can stand the proof of time is a highly challenging task, which seems incompatible with a diffusion of the medium in the short term. Virtual Reality is a very powerful tool that is starting to show some level of maturity in its latest applications, but it seems that the market is readier to receive quality VR content than it is to produce it, at this point in time.

5. FUTURE WORK

This process is still ongoing and further developments might follow. The VR application of "De Boekenkamer" was born as a research prototype for this paper; the features implemented at this point are limited to the scope of the graduation work presented here, but they can be expanded upon. A submission[48] based on this work has been made to the Sharp 2020[49] conference, being accepted; other submissions are being planned as well.

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[46] At the scientific standards that they deem necessary, given the conventions and norms already in place.

[47] Concerning both the technical features of the 3D models, and the data notation systems adopted.

[48] Title: Reconstructing private libraries in the early modern period: A 3D virtual environment as the access point to explore the "Boekenkamer" of the Amsterdam regent Pieter de Graeff (1638 – 1707), Author(s): Piccoli, Chiara; Reuvekamp, Bart; Pantò, Alessandro; Huurdeman, Hugo.

[49] https://sharp2020.nl/, currently postponed to 2021.

If development continues on "de Boekenkamer VR", we expect the application to be deployed on at least one other platform, to better suit the multiple purposes intended for it; lighter and cheaper mobile alternatives are in the class of the "Oculus Go" or "Samsung VR". We are also planning on recording a short pre-recorded 'tour' of 'de Boekenkamer", accessible as a regular video embedded in the web. With these measures, we hope to favour content fruition for a much wider audience. It would be interesting, at that stage, to evaluate the performance of both versions next to each other, as the quality of the overall experience naturally drops.

Some additions and modifications to the application are also in the plans: tests showed that the experience was not too confusing for the users overall, but also that some fixes are needed. For instance, better guidance needs to be given to the user at the very beginning of the experience, maybe in the form of a brief introductory tutorial. Its realisation would maybe be over-kill for a simple app as the 'Boekenkamer VR' is at this stage, but it will be needed should the project become any larger in the future.

At least a few alternative reconstructive options should be made available for some objects, for the user to select in the third stage of the application; the user would be able to see the different models for the chosen object, and chose the one for the main visualization of the room. In addition, we might want to add some haptic feedback in the form of controller vibration, hopefully making navigation and object-selection more instinctive. The use of sound to provide navigation and narration could also be contemplated.

Ultimately, but most importantly, I wish to expand upon the user's way of interaction with the 3D models in the room as previously described. I expect that, once environments will get more complex and animated, with one or multiple people interacting in the same reconstructed space, new questions will arise. These places could at the same time be a workshop, to test and research, and a digital museum, to communicate and narrate. The line between this opportunity and 'simple' historical-fiction videogames will be a blurred one, and the demarcation will be the stronger as stronger will be the techniques adopted to dissipate the uncertainty of the scene. Methods will have to be devised to communicate uncertainty values of things more multifaceted and abstract than objects, such as socio-cultural aspects are[50].

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[50] Building techniques, for instance: the uncertainty relative to how something looked is a totally different matter from the uncertainty relative to how that thing was made. This becomes relevant when the digital environment re-enacts, or ask the user to re-enact, similar aspects.

6. CONCLUSION

With this endeavour, I wanted to design, implement and evaluate a trustworthy VR interface specifically tailored for the requirements of CH, where objects and data could be integrated in an interactive environment. The final design can be adopted by similar projects, hopefully providing new insight into the well-known issue of uncertainty, which has been traditionally surrounding digital 3D representations. The proposed interface is divided into three stages, where data is presented in different ways, to firstly let the user explore the reconstruction with as much perceptual vicinity to the lost original, to then visualize levels of uncertainty in an effective way with a colour-coding mechanism, and to subsequently show paradata relative to the 3D objects – whilst allowing the user to take decisions on the content they intend to consume along the way. Ultimately, we offer a tool to investigate aspects related to life at the time of the Dutch Golden Age, through the digital reconstruction of long-lost corner of that world.

With VR technology becoming more and more reliable and mature in the coming years, this field will benefit from unprecedented opportunities to attract people towards Cultural Heritage (made digital), whilst stimulating discourses around it – hence the urgent need of defining widely shared workflows. Tests showed that the outcome of the work presented here might be heading to the right direction. Surely, there is still much room for development and improvement but, already at this point, I hope to have created something the community can refer to - and take inspiration from - for future adaptations.

Fig. 25. Reconstructed corner of 'de Boekenkamer' (in Blender) next to how the same space appeared in 2019.

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8. APPENDIX

8.1. Accessing the project

The final work is previewed online at: http://boekenkamervr.pronxi.com/

At the bottom of the same web page, a 'download' button allows to download the Unreal Engine (v 4.24) project of De Boekenkamer VR; in the project folders, the reader can find all the assets described in this paper.

8.2. Paradata Examples

Reported here is on example of *paradata,* sheet, for one of the Reconstruction Units (Window).

Herengracht 573: Windows

1. *Provenance*

   We have no direct record of the original appearance of the window.

2. *Decisions*

   With the most likelihood, the window looked as a typical "kruiskozijn"(cross-window). The first known drawing of the house, by Caspar Philips, dates to the late 18th century (van Houten, 1962) and represents Herengracht 573 together with the neighboring houses.

   The land lots were auctioned in 1664 and bought by Nicolaes Vis (nr. 571), Cornelis de Graeff and Pieter de Graeff (nr. 573), Gerard van Papenbroeck (nrs. 575 and 577) and Pieter van Schoorel (nrs. 579 and 581); they made agreements about the common characteristics of the buildings that they were going to build. Among the agreements made at the presence of notary Vincent Swanenburgh, there was that all windows should have had the same shape and height, while the width could vary.

   We know that interventions in the early 18th century gave 573 the new Louis XIV style which we can see in the Philip's drawing, but the neighboring houses at nr. 577 and 579 still show the facades close to their original state, with "kruiskozijnen" windows in place.
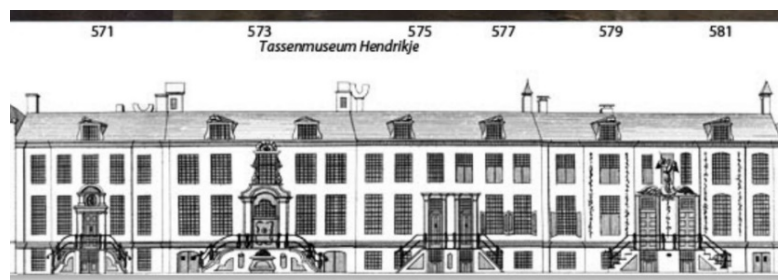
[img_BK_window0]

This was common for newly built patrician houses of contemporary Amsterdam. Most of the facades, on the same Herengracht, depicted in the painting "Gezicht op de Gouden Bocht in de Herengracht" (1671-2) by Gerrit Adriaensz. Berckheyde show kruiskozijnen and shutters.

[img_BK_window1]

3. *Evidence. Five types of evidence are provided for:*

    1. *Architectural Evidence*
        The reconstruction has been based on measures based on the present state of the building, which has been heavily modified through the centuries. We could use the cadastal plans of the house, which are conserved at the archive of the City of Amsterdam, although the current Dutch legislation doesn't allow for their publications.

[img_BK_window2]

    2. *Archaeological Evidence*

    3. *Documentary Evidence*

    4. *Precedent Evidence*

    5. *Analogy Evidence*

    A typical "kruiskozijn" would have looked similar to the example below (Monumentenwacht Nederland 2003, p. 7).

[img_BK_window3]

Examples of window shutters (Monumentenwacht Nederland 2003, p. 39).
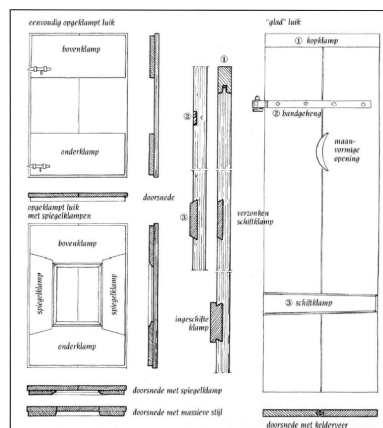
[img_BK_window4]

4. *Dependence*

We have no element to determine if the wood was painted and, if so, in what colour; the window was then left as unpainted timber. Difficulties in reproducing a believable digital version of the glass material made so that, in the model, it probably appears brighter and more transparent than it should; overall, the model is simplified in some of its details.

5. *Alternatives*

The main alternative available to us would have been the other type of window popular at the time, another type of kruikozijn with a different design. The two alternatives of 'houten kruiskozijnen' can be seen in the top right corner in the image below, as well-used from the late 16th Century until for the end of the 17th Century (Verbrugge, 2018, p.139).
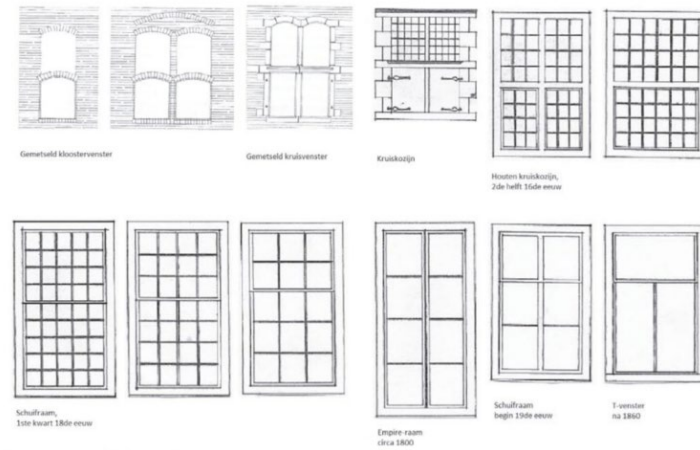
[img_BK_window5]

6. References

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La Fontaine Verwey, H. De, Eeghen, I.H. van 1976. *Vier eeuwen Herengracht. Geveltekeningen van alle huizen aan de gracht, twee historische overzichten en de beschrijving van elk pand met zijn eigenaarsen bewoners*. Genootschap Amstelodamum Amsterdam, Amsterdam Stadsdrukkerij van Amsterdam.

Verbrugge, B. D., Teunissen, M., 2018, Architectuur-en Bouwgeschiedenis in Perspectief: Bouwen En Bouwkunst in De Nederlanden En De Westerse Wereld, van Haren Publishing, Amsterdam.

All the information is then inserted, for each object, into an Excel sheet, which can then be imported into Unreal Engine.

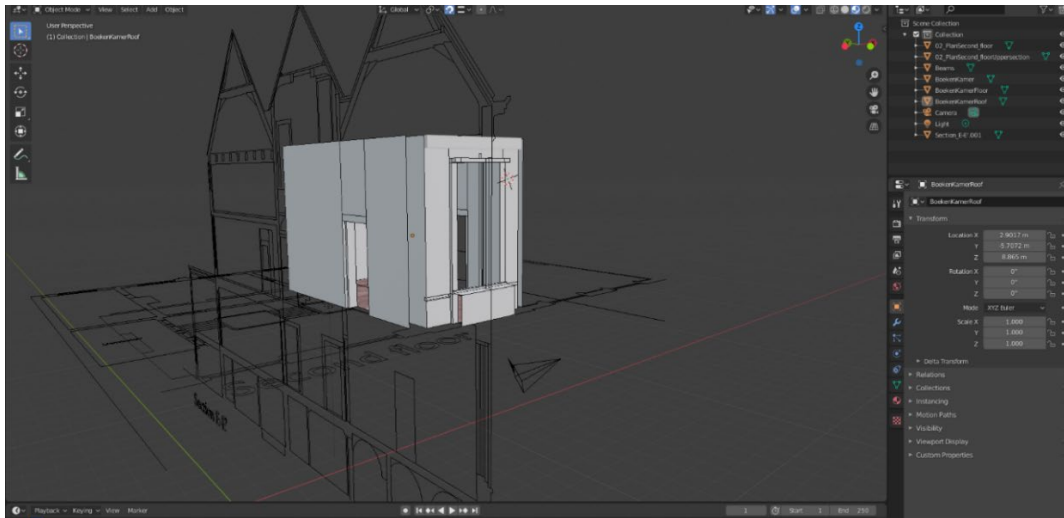*8.3. Implementing the Environment*

Fig. a1. Volumes of the Boekenkamer inside the planimetry of the building (Blender 2.80).
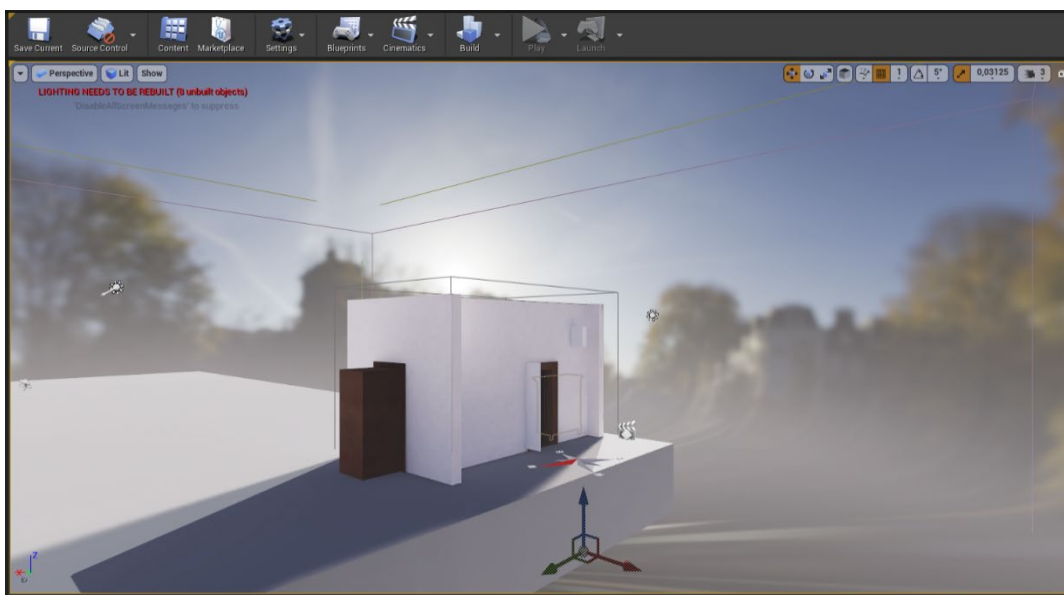

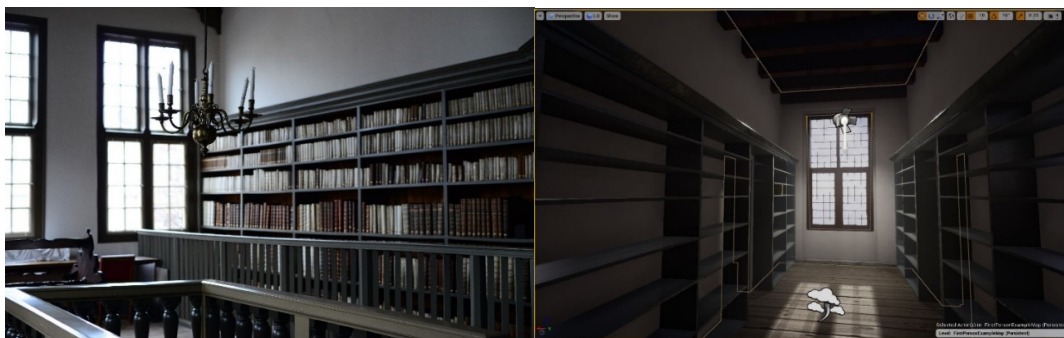Fig. a2. View of the room in its Unreal Engine setting and HDRI.

Fig. a3. Tests with lighting referenced pictures of surviving examples (left, the Thysian library in Leiden; right, UE4).

Fig. a4. Test were also made to evaluate how many books would fit the space available in the room.
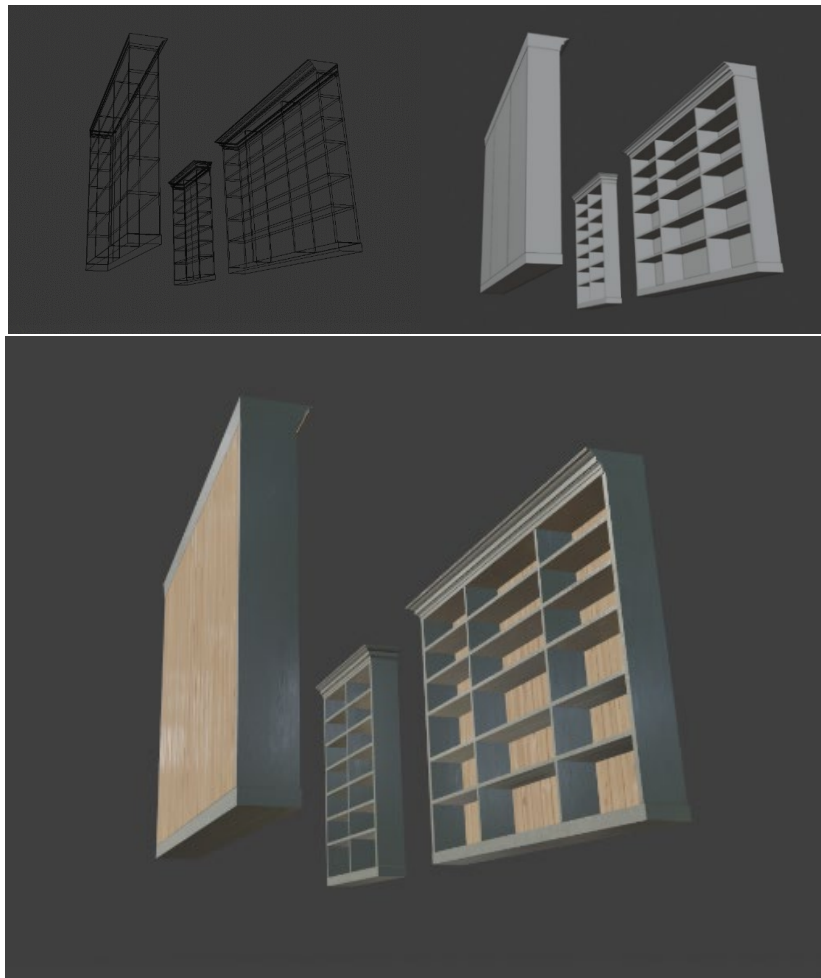

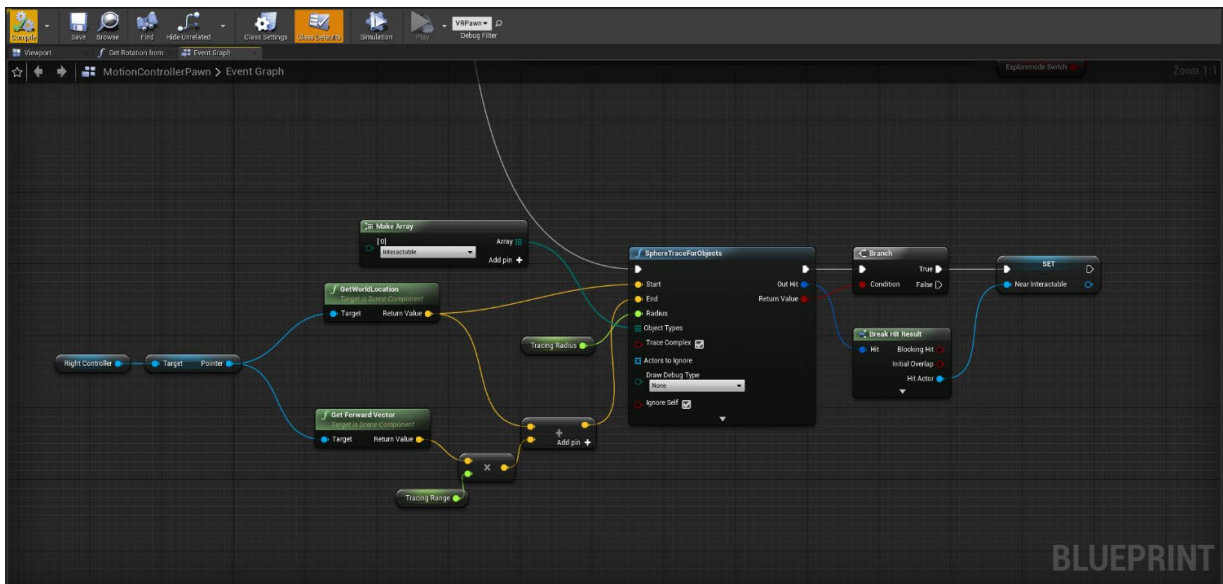Fig. a5. Realisation of the models (blender 2.80)

Fig. a6. Unreal Engine's blueprints allow to code with a visual scripting language. For instance, this 'block', part of the 'motion controller' object, checks if the red pointer is overlapping any Interactable-class object (such as a button, or a switch).
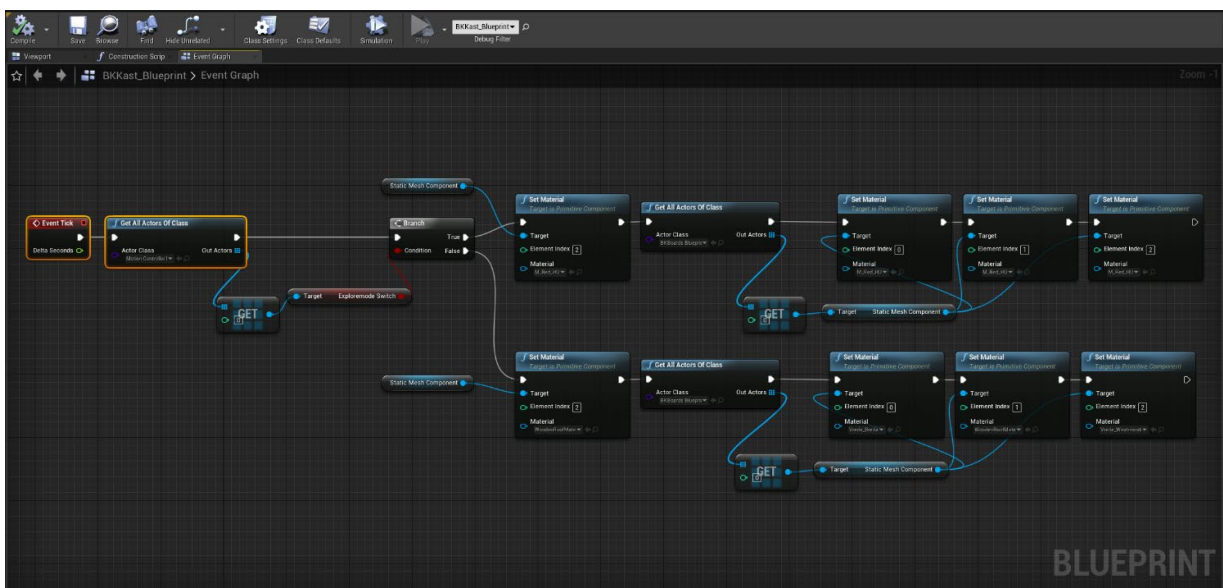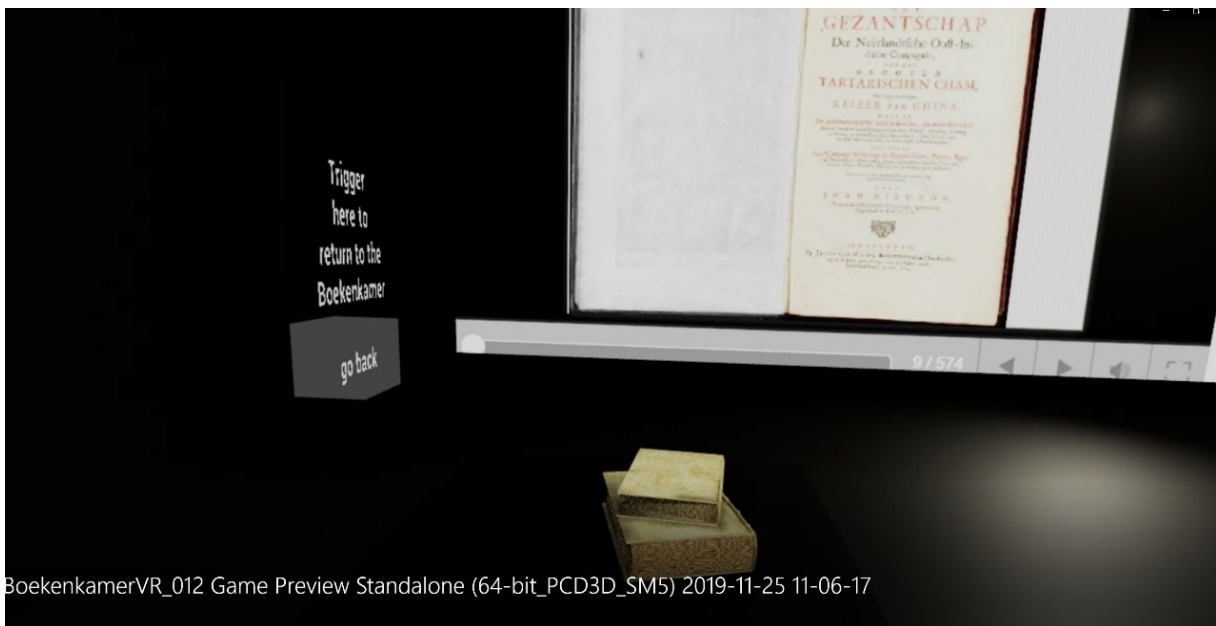

Fig. a7. This 'block', part of the 'cabinet' object, changes the material of its 'static mesh component' when Stage 2 is active, to reveal the uncertainty colour coding.

Fig. a8. A different colour coding was adopted at first, with complementary colours. This was confusing for the users, who preferred a conventional red-orange-yellow-green scheme.

Fig. a9. I tried to implement a pdf reader to allow the user to go through the content of the book, using the red pointer of his controller to navigate. Unfortunately, this didn't work as expected in VR.

8.4. Test Results

	Strongly disagree				Strongly agree
	1	2	3	4	5
1. I think that I would like to use this system frequently			2	6	2
2. I found the system unnecessarily complex	5	3	1	1	
3. I thought the system was easy to use		1	2	4	3
4. I think that I would need the support of a technical person to be able to use this system	3	1	2	4	
5. I found the various functions in this system were well integrated				6	4
6. I thought there was too much inconsistency in this system	7	2	1		
7. I would imagine that most people would learn to use this system very quickly		2	2	3	3
8. I found the system very cumbersome to use	6	3	1		
9. I felt very confident using the system		1		7	2
10. I needed to learn a lot of things before I could get going with this system	4	3	3		
11. I am satisfied with the aesthetics representation overall.				5	5
12. I think representations should have been 2D only (on a desktop pc, for instance)	10				
13. I think the picture had enough detail.	1		2	5	2
14. I think that the 3D representation provides significantly more information than a 2D picture would.				3	7
15. I think that exploring the representation was fun.				1	9
16. The environment was easy to look at.				7	3
17. The picture did not have enough detail.	2	6	2		
18. The widgets provided me with enough information on the task I needed to do.		1	1	7	1
19. I found it easy to move around in the reconstruction space.		1	2	4	3
20. I felt lost when using the system, and did not know what to do	6	3		1	

Table a1.