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Study and Design of Interactive Immersive Visualization Experiences for Non Experts

Edwige Chauvergne

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THÈSE

PRÉSENTÉE POUR OBTENIR LE GRADE DE

DOCTEUR DE L'UNIVERSITÉ DE BORDEAUX

ÉCOLE DOCTORALE
DE MATHÉMATIQUES ET D'INFORMATIQUE

SPÉCIALITÉ : INFORMATIQUE

par **Edwige CHAUVERGNE**

**Etude et Conception d'Expériences Interactives de
Visualisation Immersive pour des Non Experts**

Soutenue le 26 Novembre 2024

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Résumé De nos jours, la production de connaissances et données prolifère dans de nombreux domaines afin d’analyser, comprendre et expliquer des phénomènes parfois complexes. Communiquer ces connaissances à des publics non-experts peut parfois s’avérer compliqué et les modes de transmissions classiques reposant sur des textes, représentations graphiques ou reportages audio-visuels peuvent atteindre leurs limites.

Les technologies immersives telles que la réalité virtuelle offrent de nouvelles opportunités de visualisation en permettant d’immerger les utilisateurs dans des environnements interactifs. Ainsi, la réalité virtuelle peut tirer parti de cette immersion interactive afin d’impliquer les utilisateurs dans le processus de compréhension des phénomènes au-delà des modes de transmissions de connaissances classiques.

Cependant, introduire à un public novice des expériences de réalité virtuelle éducatives pertinentes présente plusieurs défis. Ma thèse se porte ainsi sur l’étude de ces défis. Premièrement, nous nous intéressons à la façon dont des utilisateurs novices s’initient à l’utilisation d’applications de réalité virtuelle. Nous avons évalué des tutoriels immersifs et interrogé un groupe d’experts afin d’identifier les principaux défis de la prise en main de la réalité virtuelle avec et sans instructeurs. A partir de nos résultats nous avons pu réaliser un cadre conceptuel et fournir un ensemble de guidelines.

Ensuite, nous explorons un nouveau type de visualisation empathique de données dans laquelle l’utilisateur est immergé au cœur de la donnée. En nous inspirant des anthropographiques et du zoom sémantique, nous avons conçu une visualisation permettant une transition fluide entre une visualisation abstraite et une visualisation concrète et individuelle.

Finalement, nous étudions l’édition immersive d’expériences interactives afin de favoriser la démocratisation de création de contenus interactifs par des utilisateurs non-experts. Grâce à l’implémentation d’un prototype, l’étude de deux cas d’usage et le recueil de retours utilisateurs, nous avons identifié plusieurs défis à surmonter.

L’ensemble de ces travaux a pour objectif de contribuer à favoriser l’émergence de nouveaux types de visualisations à travers l’étude et la conception d’expériences interactives de visualisation immersive pour des non experts.

Mots-clés Réalité Virtuelle, Visualisation, Interaction Humain Machine

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Title Study and Design of Interactive Immersive Visualization Experiences for Non Experts

Abstract Today, the production of knowledge and data is increasing in many fields in order to analyze, comprehend, and explain phenomena that are sometimes complex. Communicating this knowledge to non-expert audiences can sometimes be complicated, and conventional modes of transmission based on text, graphics or audio-visual reports can reach their limits.

Immersive technologies such as virtual reality offer new opportunities in visualization by immersing users in interactive environments. Virtual reality can benefit from this interactive immersion to involve users in the process of understanding phenomena more easily than conventional modes of knowledge transmission could.

However, introducing relevant educational virtual reality experiences to a novice audience involves several challenges. My thesis therefore focuses on addressing these challenges. Firstly, we investigate how novice users learn how to use virtual reality applications. We evaluated immersive tutorials and interviewed a group of experts in order to identify the main challenges to VR onboarding with and without instructors. Based on our results we built a conceptual framework and provide guidelines.

Secondly, we explore a new type of empathetic data visualization in which the user is immersed in the heart of the data. We built upon anthropographics and semantic zoom to design a visualization that allows a smooth transition between an abstract visualization and a concrete and individual visualization.

Finally, we study the immersive authoring of interactive experiences to favor the democratization of the creation of interactive content by non-expert users. Based on our prototype implementation, we analyzed two use cases and conducted a user study in order to identify the main challenges to this authoring method.

Overall, this thesis aims to contribute to the emergence of new types of visualization through the study and design of immersive interactive visualization experiences for non-experts.

Keywords Virtual Reality, Visualization, Human Computer Interaction

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Résumé Etendu en Français

Introduction

Grâce aux avancées scientifiques et à la recherche permanente, nous accumulons de nombreuses données et connaissances nous permettant d'analyser et comprendre de nombreux phénomènes complexes. Afin d'éduquer et sensibiliser le grand public à de tels sujets, il n'est pas possible de présenter les données et connaissances dans leur forme brute car elles s'avèrent souvent trop complexes et abstraites. Permettre une meilleure compréhension de ces données et phénomènes au travers des représentations graphiques est au coeur des problématiques de recherche en visualisation d'information. Un des défis de cette thématique de recherche est de rendre ces données et connaissances accessibles au plus grand nombre.

Les technologies immersives telles que la réalité virtuelle présentent de nouvelles opportunités pour le domaine de la visualisation [111, 69]. Elles permettent notamment une meilleure représentation spatiale des données, offrent de nouvelles possibilités de collaboration et peuvent favoriser l'engagement des utilisateurs.

Cependant, l'introduction de nouvelles technologies immersives telles que la réalité virtuelle en visualisation s'accompagne de plusieurs défis. Au cours de cette thèse, je me suis penchée sur trois de ces défis que j'ai axé autour de trois questions de recherche.

QR1 : Comment peut-on encourager l'utilisation d'applications de réalité virtuelle par des utilisateurs novices ? Avant d'introduire de nouvelles visualisations de réalité virtuelle au grand public, il est important de s'assurer que de telles applications leur soient accessibles. La réalité virtuelle reste une technologie relativement nouvelle pour le grand public, ainsi les paradigmes d'interaction ne sont pas standardisés [127]. De plus, le port du casque de réalité virtuelle isole l'utilisateur de son environnement ce qui rend les méthodes traditionnelles d'assistance et de formation inadaptées. C'est pourquoi il est important d'étudier les méthodes actuelles d'apprentissage de la réalité virtuelle et d'explorer comment mieux soutenir ce processus d'apprentissage.

QR2 : Comment peut-on tirer profit des bénéfices de l’immersion en réalité virtuelle en comparaison à des technologies 2D traditionnelles, de manière à mieux communiquer des informations et impliquer les utilisateurs non experts ? Les recherches en visualisation immersive (*Immersive analytics*) s’intéressent principalement aux méthodes d’analyse et d’interprétation objectives des données. Cependant, lorsqu’elles sont destinées au grand public, les visualisations immersives ont en général pour objectif de transmettre un message, une interprétation préexistante. L’idée est ainsi d’éduquer et sensibiliser le public à travers une expérience plus viscérale favorisant diverses réactions émotionnelles. L’immersion du public en réalité virtuelle offre de nouvelles opportunités d’expériences viscérales, ouvrant ainsi la voie à l’exploration de nouveaux types de visualisations tirant profits des avantages de l’immersion en termes d’engagement des utilisateurs.

QR3 : Comment permettre l’édition d’expériences interactives en réalité virtuelle à des non développeurs ? De nos jours, la création de visualisations de données 2D telles que des graphiques circulaires ou en barre est facilement accessible à des non-développeurs. En revanche, la conception de visualisations immersives en réalité virtuelle est réservée aux développeurs. Ces visualisations immersives s’inscrivent dans un domaine d’application particulier (ex: biologie, histoire...). Or, les experts dans ces domaines d’application (ex: biologistes, historiens) sont parfois les mieux placés pour proposer et concevoir des visualisations adaptées et compréhensibles par le grand public. Ainsi, l’exploration de nouvelles méthodes d’édition sans code et une meilleure compréhension des défis qu’elles impliquent sont nécessaires.

Résumé des contributions

Dans leurs travaux, Ashtari et al. [7] évoquent le fait que lors des études utilisateurs, la prise en main des applications de réalité virtuelle peut s’avérer laborieuse, ce qui non seulement implique un temps supplémentaire non négligeable mais également une expérience ultérieure dégradée. Ainsi dans le Chapitre 3, nous cherchons à mieux comprendre ce processus de prise en main des applications de réalité virtuelle en étudiant les pratiques actuelles.

Pour cela, nous avons tout d’abord effectué une évaluation heuristique de 21 tutoriels intégrés à des applications en réalité virtuelle. Cette revue des tutoriels nous a permis d’identifier trois principaux défis pour les tutoriels générés informatiquement en réalité virtuelle. Premièrement, nous avons identifié un ensemble de pratiques pouvant nuire à l’intelligibilité des tutoriels. Deuxièmement, nous avons mis en avant l’importance de fournir aux utilisateurs des éléments d’anticipation

(*feedforward*) ainsi que des informations retour (*feedback*). Enfin, le dernier défi réside dans le fait que les tutoriels évalués n'étaient généralement pas conçus de manière à pouvoir s'adapter aux profils des utilisateurs, ce qui peut nuire à leur accessibilité.

Dans un second temps, nous avons interrogé 15 experts dans le rôle d'instructeurs pour la prise en main d'applications de réalité virtuelle. En nous appuyant sur une analyse thématique [29] des entretiens, nous avons identifié trois principaux obstacles lors du processus de prise en main assistée par instructeurs. Le premier obstacle est le phénomène de nouveauté de la technologie en elle-même. Le deuxième défi identifié réside dans le fait que l'instructeur manque de connaissances sur l'environnement virtuel de l'apprenti et de la même manière, l'apprenti n'a pas accès et donc conscience de l'environnement physique qui l'entoure. Le dernier obstacle identifié est une barrière de communication inhérente à la réalité virtuelle entre l'instructeur et l'apprenti.

En nous appuyant sur notre étude de la littérature, notre évaluation des tutoriels et nos entretiens avec des experts, nous avons conçu un cadre conceptuel pour la prise en main d'applications de réalité virtuelle assistée aussi bien par tutoriel que par instructeur. L'objectif de ce cadre conceptuel est de fournir une vue d'ensemble des différentes formes que peut prendre la prise en main assistée, ainsi que de soutenir l'exploration de nouvelles méthodes.

Pour finir, nous fournissons un ensemble de recommandations, d'une part pour l'assistance à la prise en main d'applications de réalité virtuelle en général, et d'autre part pour la prise en main assistée par des instructeurs.

Dans le Chapitre 4 nous explorons comment tirer parti de l'immersion en réalité virtuelle afin de concevoir et proposer les visualisations empathiques. Lorsque l'on souhaite sensibiliser le public sur un sujet tel que les crises humanitaires, une première possibilité est de s'appuyer sur des visualisations de données abstraites telles que des diagrammes. Une autre possibilité est de fournir une expérience incarnée et viscérale en partageant avec l'audience l'expérience des victimes à travers la narration d'histoires personnelles et individuelles. Par exemple, "*Clouds Over Sidra*" [196] est une vidéo 360° partageant la vie une jeune fille de 12 ans dans le camps de réfugiés de Zaatari.

Notre objectif dans ce chapitre est de concevoir et proposer une visualisation immersive permettant de faire une transition entre visualisation abstraite et expérience viscérale. Nous avons donc implémenté un prototype qui, en s'inspirant de la méthode de zoom sémantique, permet à l'utilisateur d'analyser des données à travers un diagramme en barre, puis de progressivement explorer les données individuelles dans une scène immersive dans laquelle les individus sont représentés par des avatars individuels.

Afin de mieux comprendre le potentiel et les limitations de ce type de visuali-

sation, nous avons créé trois cas d’usages. Les deux premiers cas d’usages sont une démonstration de comment la visualisation peut être utilisée pour sensibiliser le public au bien-être humain. La première visualisation représente des données sur les féminicides conjugaux en France en 2022 [71]. L’objectif de cette visualisation est notamment de rappeler que les victimes ne sont pas que des chiffres mais que derrière chaque point de donnée se trouve une vraie personne. Le deuxième cas d’usage s’appuie quant à lui sur les données des accidents de vélo répertoriés par les forces de police en Gironde en 2018 [110]. Notre troisième cas d’usage explore comment ce type de visualisation peut également être utilisé pour sensibiliser à des sujets plus vastes comme par exemple le bien-être animal. Nous avons ainsi représenté des données sur les élevages de poules pondeuses en France.

Nous avons également mené une étude utilisateurs au cours de laquelle les participants ont exploré le cas d’usage sur les féminicides. Cette phase d’exploration était ensuite suivie d’un entretien. L’analyse thématique des entretiens nous a notamment permis de montrer que l’immersion au cœur des avatars permet d’humaniser les individus et facilite la prise de conscience de la réalité du phénomène. Non seulement la visualisation a favorisé l’engagement émotionnel des participants à travers son expérience viscérale, mais son expérience abstraite de visualisation de données a également permis d’éveiller la curiosité des participants pour le sujet des féminicides.

Dans le Chapitre 5, nous cherchons à répondre à notre troisième question de recherche, permettre la création d’expériences interactives immersives à des non-développeurs. Pour cela, nous avons implémenté un prototype d’outil immersif en réalité virtuelle afin d’explorer l’utilisation de la programmation par démonstration et manipulation directe.

Afin de mieux comprendre les défis impliqués par la programmation par démonstration et manipulation directe en réalité virtuelle, nous avons conçu et analysé deux cas d’usages et nous présentons également une étude utilisateurs. Nous avons ainsi pu identifier cinq principaux défis à cette méthode. Tout d’abord, certains comportements peuvent s’avérer impossible à créer par démonstration car ils impliquent des manipulations irréalisables pour l’utilisateur. Le deuxième défi identifié correspond à la difficulté d’utiliser la démonstration et la manipulation directe pour des concepts abstraits ou intangibles. Il est donc nécessaire d’explorer des solutions pour parer ce problème. Un autre obstacle à l’édition par démonstration vient du fait qu’une démonstration peut s’avérer ambiguë. En effet, pour une même démonstration, plusieurs résultats peuvent être déduits. Le quatrième défi émane du fait que l’édition d’expériences interactives complexes implique l’utilisation de logique dont la création et la visualisation doivent être adaptées pour des utilisateurs non-développeurs. Le dernier défi identifié est le fait que malgré des méthodes plus adaptées à des non-développeurs, il est nécessaire d’assister les utilisateurs

dans le processus de création d'expériences immersives complexes.

Ainsi, ce chapitre a permis d'identifier les principaux défis à explorer afin de permettre l'édition d'expériences immersives interactives à des utilisateurs non-développeurs. Il constitue ainsi une première étape vers l'émancipation des utilisateurs non-experts dans la création de contenus immersifs.

Conclusion

Pour conclure, cette thèse contribue à l'émergence d'expériences de visualisations immersives interactives à travers l'étude de trois questions de recherche qui visent trois principaux obstacles à la popularisation de ce type de visualisation, 1) prendre en main des applications de réalité virtuelle, 2) comprendre comment tirer parti de l'immersion pour engager l'utilisateur dans des visualisations immersives, et 3) permettre la création de visualisations immersives interactives à des non-développeurs.

Les travaux composant cette thèse nous ont également permis d'identifier d'autres pistes de recherche dans le domaine de la visualisation immersive pour des non-experts.

Afin d'améliorer le processus de prise en main des applications de réalité virtuelle, il est nécessaire de créer des outils facilitant la création de tutoriels immersifs. Actuellement la conception de tutoriels requiert des connaissances importantes de développement. Des méthodes d'éditions comme la programmation par démonstration, explorée dans le Chapitre 5, permettraient à des instructeurs non-programmeurs de créer par eux-mêmes des tutoriels adaptés.

Une autre piste de recherche pour soutenir l'introduction de visualisations immersives à des non-experts est exploration d'expériences immersives de narration de données (*data-storytelling*) [165]. L'utilisation de la narration s'appuyant sur des données objectives semble prometteuse pour les domaines de l'éducation et de sensibilisation. Elle permet d'offrir une expérience objective des données tout en rendant possible une expérience subjective à travers la narration. Cependant, les travaux de recherche en narration immersive de données sont relativement récents. En plus du besoin d'explorer de nouvelles formes et techniques de narration de données, il est important d'étudier comment faciliter la création de telles expériences. Par ailleurs, ces expériences de narration de données pourraient être collaboratives, notamment en soutenant des expériences guidées par des experts dans les sujets auxquels les visualisations se rapportent.

Chapter 1

Introduction

1.1 Visualization

Educating and raising awareness is possible through the communication of knowledge. This communication is a transmission of knowledge from knowing experts to novices. Our main medium of communication is usually language as words allow us to express complex thoughts. Yet, even words have their limitations. With the rise of media and the accumulation of data and knowledge, the general public is exposed to a large quantity of information. Raw data and complex phenomena can be hard to interpret, and when communicating about them, words might become inadequate.

Therefore, it is best to pair written or oral communication with some visual support, hence introducing the domain of visualization. Visualization is a broadly used term. Visualization can be used as an umbrella term to describe *"any technique for creating images, diagrams, or animations to communicate a message"* [212]. With the emergence of visualization as a research domain, we can find more academic definitions in the literature. In their study Zhang et al [221] mention that *"visualization utilizes computer graphics and image processing techniques to visually represent forms and processes that are perceptible, cognizable, inferable, and imaginable. It employs techniques that make the content, variations, and developments tangible, simulated, and realistic."* Within this domain, researchers tend to distinguish *data visualization* and *information visualization*. On one side, Kim et al [105] extend Chen's definition of information visualization [46] and define it as *"computer generated interactive graphical representations of information. It aims to convey unclear and abstract ideas to its audience in a visually intuitive and effective way so that the users can be stimulated for new insights"*. On the other side data visualization is defined by Bikakis [21] as *"the presentation of data in a pictorial or graphical format, and a data visualization tool is the software that generates*

this presentation. Data visualization offers intuitive ways for information perception and manipulation that essentially amplify the overall cognitive performance of information processing, enabling users to effectively identify interesting patterns, infer correlations and causalities, and support sense-making activities". Kim et al [105] focused on the difference between the two and state that *"information visualization primarily deals with abstract or non-spatial data whereas [data visualization] focuses on processing and displaying numeric or statistical input"*. In this thesis, we focus on both information and data visualizations. However, although most visualizations are nowadays computer-generated, we wish to slightly modify the previous definitions as visualization is not limited to computer-generated techniques. Researchers in data visualization have lately shown interest in *data physicalization* [98] which do not always have to rely on computers. Moreover, although visualization has appeared as a research domain with the emergence of computer graphics, many visual representations of information are much older than modern computers.

The modern music staff notation is an example of visual musical representation that can be encompassed in the information visualization domain. Time is encoded through the staff and the shape of notes and pitches are defined by the key signature and the vertical position of the note on the staff. There is often more than one way of representing a piece of information depending on culture and needs. Musical representation varies a lot through time and cultures and the modern music representation is not always the best suited. Indeed, interpreting this type of visualization requires strong musical knowledge. The use and democratization of technology allow the creation of new visualizations more accessible to novices. Easy access to online video allowed the popularization of piano visualizers. These videos represent piano partitions through the vertical scrolling of rectangles above a piano keyboard. The tile that needs to be hit is encoded through the horizontal position of the rectangle, the time when the note needs to be played is indicated when the rectangle meets and highlights the tile on the keyboard, and the duration of the note is encoded through both the length of the rectangle and the duration of the tile highlighting. The emergence of immersive technologies such as augmented reality has enabled the transposition of such a visualization directly on the piano [178, 138]. These new computer-generated visualizations therefore make music accessible to novice people who do not need to learn and understand complex expert notations before being able to experience playing the piano.

One famous example of data visualization is John Snow's cholera map. According to the story, in 1854 in Soho, London, 500 people died in just a few days due to a cholera outbreak. John Snow, a physician from Soho, used a dot map (see Figure 1.1) to visualize the cholera deaths geographically which allowed him to localize the epicenter of the outbreak and identify the Broad Street water pump

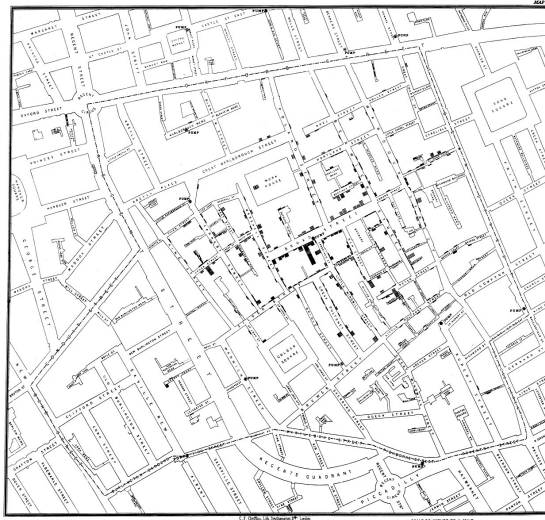


Figure 1.1: John Snow's cholera map. The high concentration of deaths around Broad Street water pump, allowed him to identify the source of contamination.

as the source of the contamination. John Snow's map provide a good example of how data visualization can be used by experts to extract information from the data.

Data visualization can also be used to communicate to the general public. Yet, some traditional charts and visualizations can remain too abstract or too complex for the general public. For instance, Charles Joseph Minard's visualization of Napoleon's Russian Campaign (see Figure 1.2) displays six types of data on a 2D chart which can make it a bit heavy and difficult to understand for the general audience.

Usually, data journalists do not only communicate facts such as quantities to the audience, they also need to provide the interpretation of the data. This interpretation is not only supported by the associated text but also by the design choices of the data visualization. For instance, Anderson and Daniels' visualization of film dialogues [189] depicts the gender dialogue duration for each film. The use of colors and layout of the films facilitates the reading of the visualization and the understanding of the message which is "men have more dialogue time than women in movies".

Researchers in visualization therefore investigate new ways of representing the information for non-experts. As seen with the music visualization example, computer-based visualization offers new possibilities for representing information. The introduction of animations and interactivity facilitates the design of evolving visualizations. An evolving visualization has several benefits, 1) the evolution of the visualization through time can be used as a new dimension, 2) it can avoid

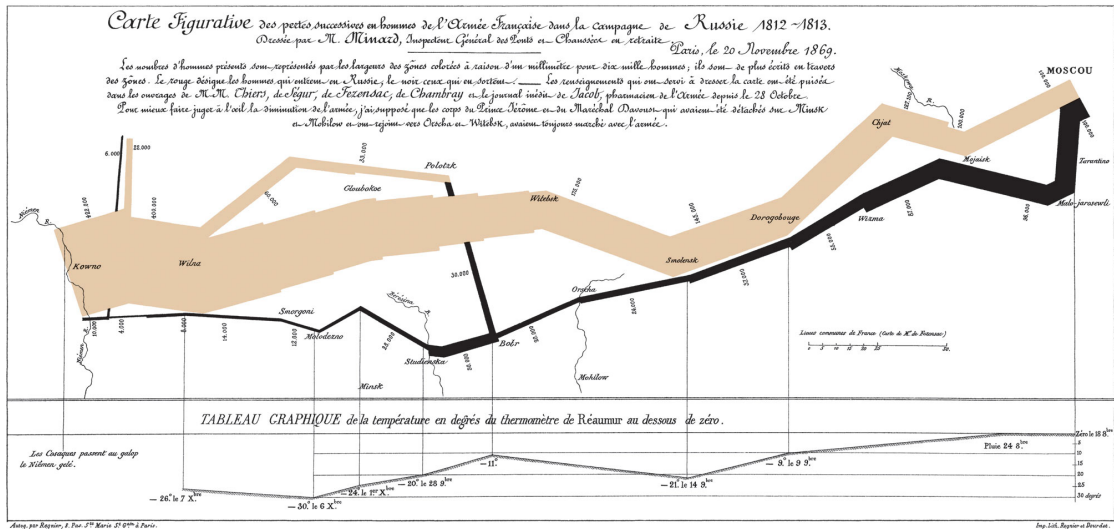


Figure 1.2: The visualization of Napoleon’s Russian campaign by Charles Joseph Minard. It displays six types of information: the army’s direction, the number of remaining soldiers, the time, the temperature, the map, and the army’s path.

clusters of information by filtering and displaying various types of information at different times, and 3) instead of facing all the information at once, the audience can gradually assimilate the information. For example, the visualization *Out of Sight, Out of Mind* [157] by Pitch Interactive depicts the drone strike deaths in Pakistan from 2004 to 2015. It gradually displays the drone attacks, starting slowly so the audience has the time to understand how the visualization works, and then it accelerates.

1.2 Using immersive technologies as a medium

The rise of new technologies offers new opportunities for visualization. Over the past decade, immersive technologies such as augmented or virtual reality have made their way into the visualization domain. In this thesis, we will focus on virtual reality although augmented reality is also an important part of immersive visualization.

Virtual reality (VR) is defined by Kumawat et al [113] as *"a simulated or spurious experience that can be identical to or utterly different from the real environment of the user. The main goal of VR is to develop a susceptible feel for the user, sometimes accompanied by sight, touch, hear, smell, or even taste"*.

Virtual reality is the result of a quest to create an immersive alternative and

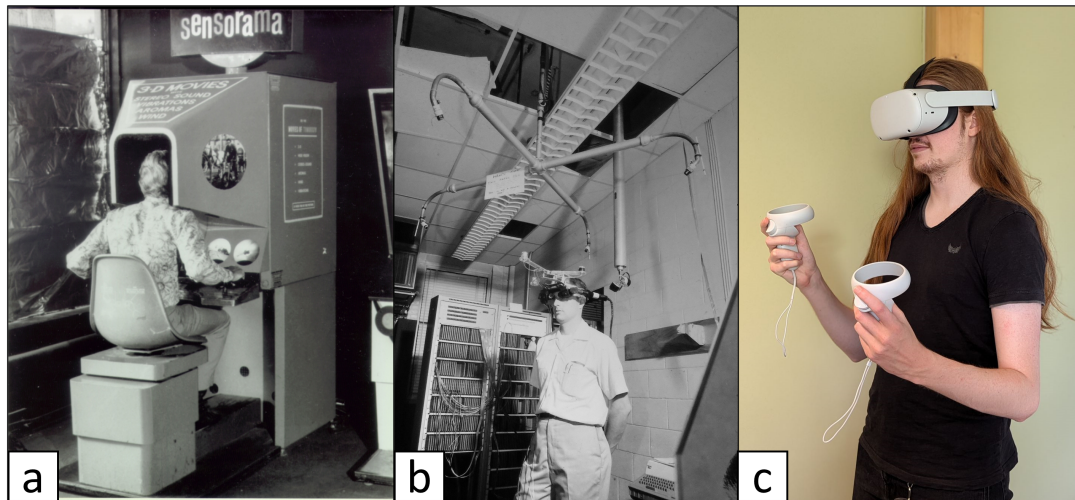


Figure 1.3: a: Morton Heilig’s immersive display called the *Sensorama* (1957). b: Sutherland’s head-mounted three-dimensional display. c: A modern virtual reality headset

virtual world. *The Sensorama* introduced by Morton Heilig [88] in 1957 (see Figure 1.3 a) was a first attempt to reach such a goal. This device simulated a motorcycle ride in New York through multi-sensory stimuli. The sight was stimulated through a stereoscopic display, hearing by stereo sound, smell by odor emitters, and touch by fans and vibrations on the seat.

In 1968, Sutherland introduced the first head-mounted three-dimensional display [186] (see Figure 1.3 b). His display called "The Ultimate Display" or also "The Sword of Damocles" offered a stereoscopic view and allowed the users to rotate their head to look around. The introduction of such a technology represents an important step for both augmented and virtual reality.

However, we have to wait for 1987 for the term *Virtual Reality* to be coined by Jaron Lanier and the years 2010s for the introduction of the first VR headsets on the public market. The availability of VR headsets in the 2010s allowed researchers to investigate new applications for VR, including in visualization, and in 2015, Chandler et al. introduced the domain of *Immersive Analytics* [43] which they defined as "*an emerging research thrust investigating how new interaction and display technologies can be used to support analytical reasoning and decision making. The aim is to provide multi-sensory interfaces that support collaboration and allow users to immerse themselves in their data in a way that supports real-world analytics tasks*".

Immersive technologies such as virtual reality offer many benefits for visualization [221]. Immersive visualizations benefit from a three-dimensional space which

allows user to get a better perception of depth and a more realistic sense of scale and proportions. Interactions in immersive environments also provide more degrees of freedom and offer the possibility for intuitive interactions using hands, gaze, movement, and voice. The immersion and equipment in virtual reality facilitate the sense of realism and presence by isolating the user from the real world which diminishes distraction and helps the user focus on the visualization.

1.3 The challenges of introducing new technologies

According to Bresnahan [31], General Purpose Technologies (GPTs) are technologies that "1) are widely used, 2) are capable of ongoing technical improvement, and 3) enable innovation in application sectors". The introduction of new technology always comes with challenges that need to be overcome to become a GPT in our society.

Let's take the Internet as an example. Nowadays the Internet can be considered as a GPT, but since its invention in the 1960s, it had to overcome several challenges to become a GPT. The "birthday" of the Internet is actually considered to only be on January 1983, with the introduction of ARPANET and a standard communication protocol. Yet, its use was still mainly restricted for governmental purposes and the introduction of the Internet to the large public came with the *World Wide Web* [19]. Since then, its use has been facilitated, with improved search engines for instance. Its content also evolved with the introduction of interactive content, images, videos, and dynamic content. The evolution of the type of content and the interfaces not only allowed the communication of more diverse information but also better accessibility to the general audience. Finally, the creation of content has been made accessible to non-developers through the design and conception of various editors. For instance, the introduction of blogs allowed users to post content without any knowledge of development. Nowadays entire websites can be created using tools such as Wix¹ or Google Sites².

Although the use of immersive technologies such as virtual reality is promising in many domains, including visualization, it still has to overcome similar challenges to potentially become a GPT.

¹<https://www.wix.com/>

²<https://sites.google.com/>

⁴<https://home.cern/science/computing/birth-web>

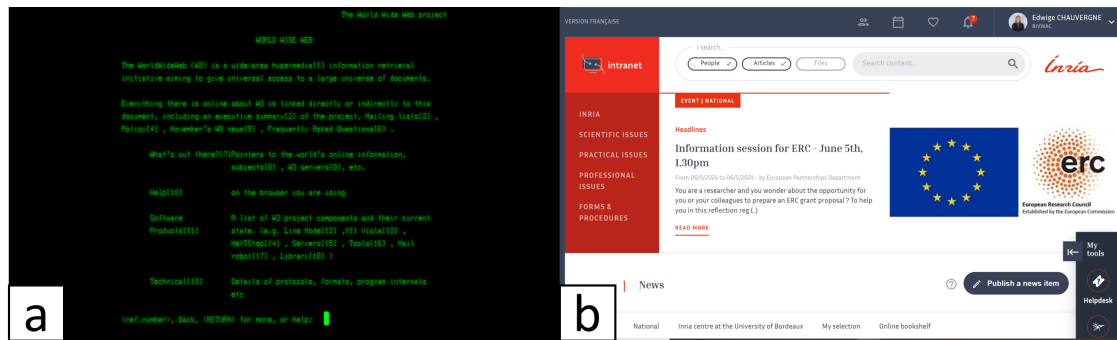


Figure 1.4: The evolution of the World Wide Web. The evolution of the interface contributed to the Internet becoming a General Purpose Technology. The World Wide Web evolved from static, plain text content, to dynamic, interactive diversified content. Figure (a) is a recreation of the first website by the CERN ⁴, and (b) is an example of a modern webpage, the Inria intranet main page.

1.4 Contributions of this Ph.D.

This Ph.D. thesis falls into the scope of both visualization and human-computer interaction. In the following sections, I will refer as *we* to include my supervisors and collaborators on these projects.

1.4.1 General motivation

Immersive technologies such as virtual reality provide new opportunities to educate and raise awareness of the large public through visualizations. They allow the exploration of new methods and show a promising potential for user engagement. Yet, immersive visualization is still a new research domain, especially when the targeted audience is the large public. Several challenges need to be studied and addressed in order to facilitate the emergence of immersive visualizations for non-experts.

1.4.2 Research axes

In this thesis, we focused on three main challenges to the use of virtual reality to support visualization which constitute our three main research questions:

- **RQ1: How can we support the use of virtual reality applications for novice users?** When providing virtual reality visualization, it is essential

that the use of such applications is accessible to novice users. Although it might vary from one culture to another, VR remains a relatively new technology for which interaction paradigms are not standardized. Due to the immersion and isolation induced by the VR headsets, traditional onboarding methods are not always suited for learning how to use VR applications. Thus, it is necessary to study and understand the current methods for VR onboarding and how we can better support this process.

- **RQ2: How can we take advantage of the benefits of immersion in virtual reality over traditional 2D technologies in order to better communicate information and engage non-expert users?** Research in traditional immersive analytics investigates how immersive technologies can best support the objective analysis and interpretation of data. Visualizations for large audiences are usually meant to communicate a pre-existing interpretation. Such communications serve a purpose (e.g.: raising awareness) and are often expected to provide a more subjective experience and arouse various emotions in the audience in order to increase engagement. The immersive property of VR offers great opportunities for subjective experiences. Thus, there is a need to design and investigate new types of visualizations that leverage the benefits of immersion in virtual reality to raise users' engagement.
- **RQ3: How can we enable the authoring of interactive experiences in virtual reality to non-developers?** Designing traditional visualizations has been made accessible to non-developers. For instance, novices can easily create charts thanks to various computer software. In virtual reality, however, the edition of new visualizations usually requires advanced development skills. These requirements prevent non-developers from creating visualizations for their own domain of expertise which hinders the creation of new immersive visualizations. It is thus necessary to empower non-developers by enabling the authoring of interactive immersive visualization for them. To do so, we take an interest in the investigation of code-free authoring methods and understand the challenges users can face during the authoring process.

1.4.3 Contributions

Chapter 3: User Onboarding in Virtual Reality: An Investigation of Current Practices In this chapter, we try to answer our first research question and investigate the current practices and challenges in virtual reality onboarding. To better understand how user learn how to use both the VR equipment and new immersive applications, we explored both tutorials and instructor-assisted

onboarding methods through a review of immersive tutorials and interviews with experts in immersive technologies. We introduce a conceptual framework for assisted VR onboarding and provide a set of guidelines. Finally, we discuss the main challenges to virtual reality onboarding.

Chapter 4: Zoomable Empathetic Visualizations In this second chapter, we focus on our second research question and explore the use of immersive technologies to raise awareness and favor the audience’s engagement. We investigate how virtual reality can be used to provide data visualizations that bridge the gap between number-centered objective visualizations and empathetic experiences. In this chapter, we introduce a zoomable empathetic visualization that transitions from a global abstract chart to a unit immersive visualization in which user can learn about individuals. In order to better understand the benefits and drawbacks of this zoomable empathetic visualization, we designed three use cases and conducted a user study. We then present our analysis of the participants’ interviews and discuss the perspectives to this type of zoomable empathetic visualization.

Chapter 5: Authoring Interactive and Immersive Experiences Using Programming by Demonstration We then investigate our third and last research question and study how to enable the authoring of immersive interactive experiences for non-developers. In this chapter, we explore the concept of immersive programming by demonstration. With such an approach, users can directly interact with the virtual content to demonstrate an interaction or a behavior. We implemented an immersive authoring prototype, and, in order to better comprehend the challenges of such a system, we designed two use cases and conducted a user study. Using our observations and the results of the study, we discuss the challenges associated with the design of such systems and provide guidelines for the development of future immersive programming-by-demonstration tools.

Chapter 2

Background

In this chapter, we summarize the general background of this thesis. More detailed and specific backgrounds are then introduced in the following chapters.

2.1 Visualization for awareness and education

As mentioned in the previous chapter, visualizations provide a great support for education and awareness. In the literature, we can find many recommendations regarding the design of traditional charts [218] in order to support a better understanding of the information and thus facilitate the learning process. Such visualizations facilitate the understanding of complex data and phenomena. They give a clear overview of the data and are easy to explore. Yet, improving the understandability of information is not necessarily the only way of enhancing the process of education or raising awareness. Promoting the user's engagement with the visualization is also an important and promising dimension.

Traditional graphs and visualizations can sometimes appear a bit daunting and thus fail to engage the users and promote interest in the visualization's topic. It is thus necessary to investigate how to engage users [135].

Data physicalization Although traditional graphs can be used to compare measures, numbers are often too abstract for the audience to comprehend them fully. This is especially the case with high numbers or unfamiliar units. As the users fail to grasp the extent of a phenomenon, their engagement with the topic is reduced.

Data physicalization and tangible visualization offer opportunities to better comprehend scales. Jansen et al. [98] introduce data physicalization as "*a physical artifact whose geometry or material properties encode data*" and present its benefits on both perceptual and cognitive levels. Figure 2.1 is a photo taken on the Skara Brae site. Skara Brae is a stone-built Neolithic settlement located in the Orkney

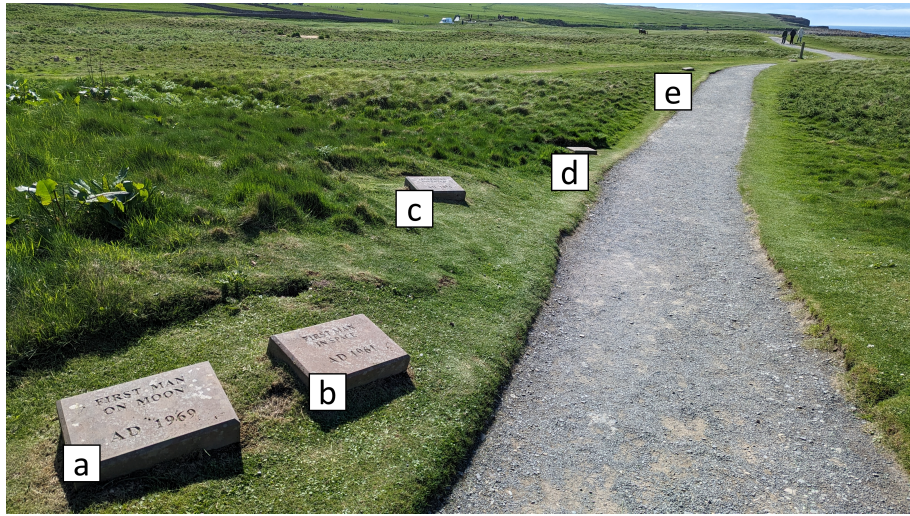


Figure 2.1: Physical representation of time on the Skara Brae site. Each stone represent an historical event and the distance between the stones is proportional to the time between each event. a) First man on moon AD 1969; b) First man in space AD 1961; c) Telephone invented AD 1876; d) American declaration of independence AD 1776; e) Inca civilization AD 1400.

in Scotland which was occupied from approximately 3180 BC to about 2500 BC. 5000 years from now is a very long time which can be difficult to comprehend. Therefore, on the path from the ticket office to the site, they laid stone plaques which represent important historical events and the distance between each plaque is proportional to the time between each event. This visualization is thus an attempt to physicalize time

Concrete scales Although data physicalization offers great opportunities, these visualizations come with physical constraints such as size limitations or the fact that they are not ubiquitous. Computer generated visualizations benefit from being ubiquitous and enable comparison with high scale elements. Research in computer generated visualization have investigated the use of concrete scales [49] which can be defined as the *"process of visually relating complex measures with familiar objects from the real world"*. One can thus represent complex measures through the use of *"magnitudes and units that are visually and kinesthetically experienceable"*. For instance, *"Drowning in plastic"* [173] is an online visualization that compares the volume of plastic bottles used in a specific amount of time, to known landmarks. We can for example see a stack of bottles next to the Eiffel Tower, which represents the amount of plastic bottles sold in a day. In their study, Kim et al. [106] introduce a tool that compares distances and area measurements

to personalized spaces. As the user enters a distance, the application represents the distance on a map of the user's location, which allows them to compare the distance with distances in a familiar environment. Their user study revealed that users had a better comprehension of distances and areas in the personalized spatial analogy condition compared to both the conditions with no analogy and generic spatial analogy.

Animated and interactive visualization Animated visualizations can be used to intuitively represent the evolution of data or phenomena through time but also to enable smooth reorganization of the data or draw attention to a specific part of the visualization. On one side their efficiency for data analysis is questioned in some contexts. For instance, a study from Robertson et al. [167] revealed that the use of animated visualizations to depict trends lead to longer completion time and less accuracy for analysis. However, the study also revealed that the animated visualization was preferred by the participants. Indeed, animated visualizations tend to be perceived as more enjoyable and exciting by the audience [72]. Thus, the use of animation offers opportunities for user' engagement, however, designers should use them carefully.

Interactive visualizations allow passive users to become active and gain control over the visualization. Yet, like animations, higher levels of interactivity do not always imply better learning. In order for the visualization to remain efficient, the design of the interaction must be made in accordance with the type of task [153]. Yet, it is important to take into consideration both effective and perceived learning as well as the user's engagement. In their study, Cervenec et al [42] focused on students' engagement and perceived learning. They found out that the condition with higher interactivity was preferred as it was perceived as the more engaging and student felt like they learned more from it.

Storytelling Another way of engaging users in visualization is the use of narratives which are often paired with the use of interactivity. Storytelling has a way of triggering fascination to its audience. Through the use of narrative, one can convey a message. Due to its structure, it facilitates the understanding of abstract concepts and helps share a vision of a system [12]. Actually, the way we convey information and structure it influences the audience's reaction to it. Morris et al.'s [142] study reveals that embedding information into a story would promote pro-environmental behaviors. By structuring the information into a story, it gives sense to it, conveys a comprehensible message, and triggers emotional responses.

When the storytelling experience is based on data, it is called data-driven storytelling. Data-driven stories (DDS) are defined by Riche et al. [165] as "*stories that are data-driven in that they start from a narrative that either is based on or*

contains data and incorporates this data evidence" Stories directly rely on the data representations. These representations can vary and support the narration by providing visual insights and context.

Explore new types of visualizations Finally, in order to improve both engagement and understanding of the information, researchers have explored new types of visualizations. For instance, Haroz et al [81] studied the use of pictographs in visualizations. Their study suggests that pictographs favor memorization for demanding tasks and promote the users' interest in the visualization. However, the use of superfluous pictographs that do not encode data is detrimental as it distracts the users.

Data comics are another example of newly explored types of data visualization. Data comics are defined by Zhao et al [222] as *"a visual storytelling method based on sequential images consisting of data-driven visual representations. Its purpose is to build engaging narratives about data"*. In their study, Wang et al [208] compared the use of data comics and infographics. Not only were data comics rated as more enjoyable and engaging, but their results also suggest that participants better understood the data with data comics.

Position of this work Exploring new types of visualization can thus lead to more efficient ways to engage the audience and explain complex data and phenomena. In Chapter 4, we inspired ourselves from the techniques mentioned above and introduce an interactive visualization to explore how concrete representations of individuals can be used to engage the audience. We also aim at supporting the exploration of new types of visualizations in Chapter 5 through the study of the authoring of interactive immersive experiences.

In the next section, we explore the use of immersive technologies, and more specifically virtual reality, to support visualization.

2.2 Immersive visualizations

Although VR presents several benefits for visualization, Kraus et al [111] suggest that the use of immersive visualization is not always recommended and they explore four scenarios in which immersion could be beneficial for visualization.

Situated visualization Situated visualizations are *"data representations whose physical presentation is located close to the data's physical referent(s)"* [213]. Such visualizations are often designed for augmented reality displayed near their physical referent. For instance, Assor et al [9] propose to visualize waste production in the environment where it was produced. Yet, the physical referent might not always

be visible [10] whether because it is occluded, inaccessible, or no longer existing. In that case, virtual reality can be used to recreate the environment and visualizing the data next to its virtual referent helps the user create a connection between the two. For instance, with *Corsican Twin* [161] Prouzeau et al propose an AR/VR system that enables in situ visualization of a building's data. The VR alternative allows distant users to visualize the data in the virtual reproduction of the room it relates to.

Spatial data and spatial task The second scenario mentioned by Kraus et al is the visualization of spatial data and execution of a spatial task. Visualizing some data on a two-dimensional display can sometimes require a transformation of the data which makes it more difficult to comprehend. The three-dimensional property of virtual reality enables 3D mapping of the data and an intuitive comprehension of it. Raja et al [163] studied the benefits of immersion in abstract information visualization and their study revealed that participants had a faster completion time of the task and felt less disorientation.

3D representation of data can be used to minimize occlusion and cluster and facilitates the adoption of multiple points of view for the user. Researchers have thus built on these properties to improve data analysis. For instance, Prouzeau et al. [160] explore how VR can be used to visualize connections between data points. Cantu et al. [35] investigated the use of a helical structure in virtual reality to represent radar signal data and assist users in signal association. They compared their system to the desktop system currently used and their evaluation revealed better performances when using the immersive visualization. In their paper, Cantu et al. mention how immersive visualizations can be used to identify noise or missing data. In their study, Kreylos et al. [112] support the use of virtual reality to analyze LiDAR data point clouds. Immersive analysis of LiDAR data allows faster and more accurate identification of subtle flaws in LiDAR data.

The 3D environment also provides opportunities for embodiment which can be defined as "*the mapping of data artifacts to 3D virtual constructs that users can directly manipulate, examine, and rearrange*" [220]. In TimeTables [220], Zhang et al. introduce how an abstract concept such as time can be represented and manipulated using virtual objects, in this case, space-time cubes.

Collaboration Virtual reality also offers the possibility for collaborators to gather around the same visualization which favors the sense of *co-presence*. Instead of each of them analyzing the data on an individual screen, they can use natural communication such as gaze, pointing at elements, and using gestures and deixis. Kraus et al [111] mention another benefit of VR for collaboration, which is the fact that it is possible to make some avatars invisible to each other and thus be co-

located which enables more people to gather around the same visualization but also to share the same point of view. Thus, immersive technologies provide great opportunities for Collaborative Immersive Analytics which is defined by Billingham et al. [22] as *"the shared use of immersive interaction and display technologies by more than one person for supporting collaborative analytical reasoning and decision making"*. Collaborative immersive analytics has been tackled as one of the main challenges in immersive analytics [69]. Two of the main challenges within this domain are awareness and communication. In co-located conditions, the use of head-mounted displays can hinder awareness and communication. Similarly, they can be hampered by asynchronous and/or distributed collaboration. Nguyen and Duval identified five elements, users need to be aware of: others (collaborators), the virtual environment, coordinating actions, the physical environment, and inconsistency due to network delay. They also identified four types of communication: audio, embodiment and nonverbal, visual metaphors, and text and 3D annotations. As each type of communication has its benefits and drawbacks, collaborative systems should support them all. For instance, with the FIESTA system, Lee et al. [120] support awareness and communication in various ways. Audio communication is supported as the participants are co-located. The use of avatars (heads and hands) facilitates awareness of others and nonverbal communication. The system also contains brush functionalities to communicate using 3D annotations.

Presentation Finally they support the use of VR for the engagement it generates although they mention the fact that part of it could be due to the Wow effect of VR. Engaging users is especially interesting in the context of education and raising awareness and the benefits of virtual reality in such a context have been investigated.

Position of this work In Chapter 3, we explore the challenges for instructor-assisted onboarding. Some of these challenges intersect with the research in immersive collaboration. In Chapter 4 we explore how immersive visualizations can support the users' engagement. We rely on virtual reality to incarnate victims and project the users into an immersive view to provide context and promote perspective-taking. In Chapter 5 we aim to facilitate the authoring of such immersive visualizations and study immersive programming by demonstration and direct manipulation.

2.3 Virtual reality for learning and raising awareness

Virtual reality appears to be a promising medium for education and raising awareness. Research in immersive technologies highlighted the impact of virtual reality on learning experiences, creativity, and engagement.

Theories In their literature analysis, Suh et al [184] mention three theories that support the use of immersive technologies including VR for education and awareness.

- **The flow theory** The state of flow is defined by Csikszentmihalyi as *"a subjective state that people report when they are completely involved in something to the point of forgetting time, fatigue, and everything else but the activity itself"* [54]. Studies have investigated the effect of VR on the state of flow [86]. Kim and Ko [104] compared VR and 2D monitors for sport spectatorship and their results revealed a higher state of flow in VR. An induced state of flow in VR can enhance the users' concentration, motivation, and sense of satisfaction and thus improve the learning or sensibilization process.
- **The presence theory** Although the sense of presence can have several definitions in the literature, most studies in VR refer to the sense of presence as *transportation, the sensations of "you are there," "it is here," and/or "we are together"* [174], in other words, the sense of presence is a sensation of being part of the virtual environment. This sense of presence can affect the learning process and a study from Ke et al [101] revealed that it can foster users' engagement.
- **The Stimuli-Organism-Response (SeOeR) framework** According to Suh et al. [184], *"the framework posits that external or environmental cues trigger a user's internal evaluation, which in turn leads to user behavior"*. The immersive technology can influence the users' affective state which in turn can lead to behavioral changes.

Although more studies are necessary to fully understand the effect of immersive technologies on users' cognitive states and learning processes, VR appears to be a promising tool for educating and raising awareness. Such use of VR has therefore been investigated in the scientific literature and education and awareness can be supported by VR through the use of various types of applications.

For instance, VR can be used to recreate realistic conditions which often prove useful when real-life training is made impossible due to limited resources or security

and health issues [215]. VR can for instance be used to train healthcare workers [169], or emergency rescue workers [155].

Virtual reality for behavioral change Virtual reality also offers opportunities to promote specific behaviors. For instance, various immersive experiences have been proposed to encourage pro-environmental behaviors. Markowitz et al [132] studied the effect of VR on educating about ocean acidification. They conducted four studies that suggested that using VR was beneficial for knowledge acquisition and to promote the users' interest in the subject. Moreover they observed some pro-environmental changes in some cases.

According to Dirksen et al [63], behavioral change can be promoted in various ways. We will enumerate the various methods in order to explore how VR can be useful to promote behavioral change.

- **Facilitate the desired behavior** Sometimes, "bad" behaviors are not motivated by a lack of willingness rather than by a lack of knowledge or capacity. If we take pro-environmental behavior as an example, people are sometimes simply ignorant of the fact that a specific behavior is environmentally harmful. For instance, the environmental impact of our dietary choices is more complex than it might appear. Although many people are aware that they should favor local food, many remain unaware that the type of food we eat has a substantial impact. The adoption of the desired behavior can also be hindered by a lack of training. In that case, virtual reality can be used to immerse the users in a simulation. The use of VR has for instance been explored to improve social skills for children with social skill deficits [206], or to train health professionals to communicate with their patients [122].
- **Empathy training** Behavioral changes can be promoted by raising the audience's empathy. Empathy can be defined as the capacity to take someone else's perspective. Such a mental exercise can sometimes prove to be difficult. Virtual reality can be used to almost literally put the user *into the other's shoes*. Researchers have explored the benefits of such simulations to fight against discrimination through embodiment. Koniou et al [108] explored the embodiment of an autistic person to better understand their experience. Similarly, Peck et al's study [154] revealed that embodying a dark-skinned avatar can reduce implicit racial bias. In the Chapter 4, we explore how immersive visualization can be used to promote empathy.
- **Experience the consequences** Experiencing the consequences of a specific behavior in virtual reality not only provides a visceral experience that can be more striking than a theoretical explanation but also allows its users to

safely experience the consequences. Morley et al [141] propose a VR system to experience the negative consequences of driving and using a phone at the same time. As the immersed user interacts with the phone, the car is involved in a head-on collision. Such an experience wouldn't be possible in a real environment. Also in the road safety domain, VR can also be used to promote pedestrian safety [114]. Beyond safety, virtual reality could be used to improve decision-making through the exploration of the various outcomes of our decisions.

- **Future projection visualization of the intangible** People can be reluctant to change their behavior as the consequences of negative behavior are too abstract. This is especially the case for delayed or intangible consequences. It can be sometimes difficult to adopt the right behavior for our health when the consequences are not expected for years. Similarly, the consequences of our actions on the environment are both far in time and intangible. Virtual reality can thus be used to visualize these consequences such as our carbon emissions or dietary choices. Plechatá et al [159] simulated the impact of our dietary choices on a national park. High ecological impact food choices would lead to the forest dying and users have the possibility to change their decisions in order to obtain better results. Wienrich et al's system [211] allows its users to calculate their CO_2 emission over a year and visualize it through floating balloons representing their carbon emission.
- **Provide feedback** Providing feedback to users allows them to know if they are performing the correct behavior. Indeed, there isn't always an obvious feedback. For instance, meditation training can be difficult as it is difficult for the users to know if they reached the right state of mind. Kosunen et al [109] created a peaceful environment in which the users get visual feedback based on neurofeedback.

Position of this work In Chapter 4, we explore how virtual reality can be used to create empathetic visualizations and support awareness raising for humanitarian crisis. Although we believe that the emergence of VR offers many opportunities for data and information visualization, according to Kraus et al [111], one of the challenges of using VR to explain complex data and phenomena is usability. Indeed, users are still unfamiliar with the interactions in immersive technologies. Therefore, this a challenge we tackle in the next chapter.

Chapter 3

User Onboarding in Virtual Reality: An Investigation of Current Practices

Immersive Virtual Reality is based on the transfer, in a synthetic world, of our sensory-motor and cognitive abilities to interact with the real world. This way, for many tasks that mimic the ones we experience from our birth, we can interact in a virtual environment in a natural way, as we would do in a physical environment, without any need for explanation or training. In particular, this is the case when moving the head or the hands around. For such basic tasks, the transfer from real to virtual is straightforward and does not require to be accompanied.

On the other hand, for more advanced tasks, interacting in VR can become much more challenging. Interactions in immersive visualization do not always rely on such intuitive interactions as they restrict the potential of interaction. Moreover, immersive visualizations are usually not a mere virtual reproduction of physical objects. Thus, interactions such as zooming or filtering have no natural equivalent in the real world. Yet, this phenomenon is not specific to immersive visualization but also applies to VR applications in general. This is for example the case for applications like Tvor¹ or Microsoft Maquette², two VR prototyping tools, which offer their users numerous functionalities. Even with simpler VR applications, novice users may have difficulty interacting with the system and, consequently, they often need to be trained first before being able to take benefit of the full potential of the VR application.

This need for training, in particular for complex and specialized software tools, is not specific to VR but common to every platform. General knowledge about

¹<https://tvori.co/>

²<https://docs.microsoft.com/en-ca/windows/mixed-reality/design/maquette>

computer software might be enough to use low-level software applications like word processing software, but hours of specific training will be required to master complex professional software like design or architecture software applications.

This initial training is often called *Onboarding*. In this chapter, we use Renz et al. [164] definition of onboarding as *the sum of methods and elements helping a new user to become familiar with a digital product*. The goal of onboarding is not just to technically train users, but to also make them discover the system’s potential and how they could benefit from it [183]. Onboarding can be done in several ways. It can be achieved by the mean of user guides and tutorials provided inside the tool or available online, or it can be done by experts in remote or colocated training sessions. The difference between the different methods has already been studied for desktop [59] and they all have their pros and cons. However, we believe that Onboarding for VR applications may differ because: (1) of the nature of VR headsets, the user is isolated from the physical world; (2) for most users, the input technology (e.g. the controllers) and interaction paradigm (e.g. teleport to move) are new and need to be taught as well; (3) there is no real interaction convention established yet (e.g. grabbing an object can be done using the trigger button in some applications and with the grip button in others). For these reasons, VR designers and experts have been trying different solutions, with varying results, to train users but also guide them to autonomously explore the functionalities of the application to use it at its full potential.

In this chapter, we focus on the current practices and challenges for user onboarding in VR. Although this thesis primarily focuses on immersive visualization, it is still an emerging domain with limited literature. Moreover, the need to study onboarding also applies to other type of VR applications. Thus, in this chapter, we chose to explore the practices beyond the realm of visualization and focus on all types of VR applications. After reviewing the literature, we explore and discuss the existing tutorial approaches, and we report the results of interviews we conducted with VR experts. Building upon this work we propose a conceptual framework for assisted VR onboarding, provide a set of guidelines, and discuss the research challenges in this domain. This work provides researchers and practitioners with an analysis of the existing techniques. It also paves the way for the design of future efficient VR onboarding systems.

Main portions of this chapter were previously published ³ in :

[45] Edwige Chauvergne, Martin Hachet, and Arnaud Prouzeau. User onboarding in virtual reality: An investigation of current practices. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems*, pages 1–15, 2023.

³Thus any use of “we” in this chapter refers to me, Martin Hachet, and Arnaud Prouzeau.

3.1 Related work

In this section, we investigate the literature on software user onboarding and VR onboarding.

3.1.1 Software onboarding

According to Nielsen [149], for a system to be usable, it should be possible for users "to reach a reasonable level of usage proficiency within a short time". As explained by Grossman et al. [79] this is first achieved by designing an easy-to-learn interface. It is, however, not enough in most complex systems, and novices benefit, in this case, from onboarding sessions. Linja-aho [126] explained that this is mostly due to the difference between the novice's mental model of the software before trying it and the actual system, assistance is then needed to adapt the novice's mental model. It is mostly done using 2 different methods: (1) with tutorials [216, 27], in this case, learners follow, without outside help, instructions given by the system or a video; (2) with instructors who directly give instructions and demonstrations to the learners [59, 131].

To our knowledge, research on user onboarding mostly focused on the first method rather than the second one. In a study, Wiedenbeck and Zila [210] showed that tutorials allowed more efficient software learning compared to a non-guided exploration of the functionalities. This can be explained by the fact that novices do not know which components are important, and thus, do not explore them efficiently. As shown by Megyeri and Szabo [136], onboarding indicates to the users on which part of the interface important functionalities are, making learning more efficient. Focusing on games, Anderson et al. [3] refined this result and showed that on low complexity games, users could manage to understand how to play, but tutorials became essential when complexity rose.

In their paper, Carroll and Van der Meij [38] provide principles and heuristics for minimalist instructions and give application examples for tutorials. They define the four major principles as (1) *Choose an action-oriented approach*, (2) *Anchor the tool in the task domain*, (3) *Support error recognition and recovery*, and (4) *Support reading to do, study and locate*.

Most tutorials are actually videos showing the steps to do a specific task using the application. Others are directly integrated into the application and ask learners to interact with the system to perform each step. Such methods allow learners to be active during the learning which helps focus the user's attention, encourages deeper processing of information, and keeps the user motivated [188]. In their work, Dong et al. [64] used games as an active form of onboarding for Adobe Photoshop and showed that it improves learning.

3.1.2 VR onboarding

The recent popularization of VR, and the decrease of the cost of the equipment, have made VR accessible to non-expert users. Yet, VR can be overwhelming for first-time users. Thus, the VR onboarding phase is then even more critical as even the devices and interaction paradigm are new [127]. In their paper Ashtari et al. [7] mention the fact that users need to go through a long and cumbersome onboarding process during user testing, which not only is time-consuming but also adds a significant cognitive charge to users, making it important to increase research in this domain.

Tutorials in VR can take different forms: (1) they can directly demonstrate how to do a task inside the virtual environment, as it is done with TutoriVR [193]; (2) they can consist of a set of written/oral instructions with a set of visual aids to attract the attention of learners to the appropriate virtual objects. Bozgeyikli et al. [26] explore four different forms of instructions, 3D animated, pictograph, written, and verbal instructions. Their results suggest that animated instructions were preferred whereas verbal instructions had the lowest ranking. Kao et al. also explore the form of instructions but focused on the controllers. They compared text instructions, text instructions combined with diagrams, and finally text combined with spatial instruction. Their results suggest that the last condition was the most favorable for learnability.

Onboarding with an instructor raises the issue of communication as the VR headset completely isolates the learner from the instructor. In TransceiVR [192], Thoravi Kumaravel et al. propose a system that allows instructors to use a tablet application to include annotation directly in the VR scene and to highlight specific buttons on the controllers. Not specific to onboarding, Wu et al. [214] compared different communication modalities for a navigation task in which the VR user was guided by a second participant using an asymmetrical setup and showed that a combination of audio and visual cues was the most effective and easiest to use. More recently, the use of Augmented Reality (AR) by instructors has been explored in systems like Loki [191], Vishnu [48], and MiniMe [158] and used avatars to allow more non-verbal communication and deixis.

Another issue is the lack of awareness of the virtual space for instructors. Most of the time, they only have access to a limited mirror view of what the person in VR sees. Many studies tried to improve this awareness. Cools et al. [53] and Ishii et al. [96] try to build the virtual environment around the user either through AR or a reversed CAVE. RoleVR [123], Dollhouse [91] and ShareVR [80] offer a bird's eye view of the environment, this method is commonly used to offer a global understanding of the environment.

In conclusion, VR user onboarding is critical to guarantee the users' understanding and complete adoption of VR applications and it is not possible to just

re-use onboarding techniques from desktops as both the type of device and the interaction paradigm are new to most users. As demonstrated here, there is research in VR on collaboration and communication in an asymmetrical context, but not focusing on onboarding. However, because VR is more and more used and accessible to the general public, onboarding has to be done for games and applications on commercial headsets, by companies selling VR products, and by researchers from various disciplines running studies using VR. It is done using tutorials directly integrated into the application or 2D videos watched on desktop. There are also examples in which it is done with an instructor, following the user in VR using a mirror view on a desktop. In this chapter, we investigate the current methods of onboarding used in the field to then propose a conceptual framework for VR onboarding and identify future interesting research directions.

3.2 A review of integrated tutorials in VR

Tutorials are extensively used to guide novice users along with new VR applications. Generally, a first generic tutorial, linked to the material itself, allows users to understand the basic features of the controllers, and guide them in the definition of the safe space around their location. Then, more advanced tutorials generally come with the applications that have been launched. Their goal is to show, step by step, how to access the functionalities of the application, and how to use them.

In this section, we aim to understand how these tutorials are designed, what functionalities they focus on, and how usable they are. For this purpose, we perform a review of a set of VR tutorials. Although non-immersed 2D videos can be useful for VR beginners to learn how to grab the controllers and install the hardware, and they are easy to make, we believe this solution to be impractical while learning how to use a VR application [193]. Indeed, it forces its users to go back and forth between the virtual environment and the video screen, removing and putting on their headset each time, which is time-consuming. In addition to that, the video provides 2D instructions and demonstrations for a three-dimensional task. Therefore, in this review, we focus on VR-integrated tutorials and do not consider standard video tutorials that are available online and watched outside of the HMDs (e.g. via desktop computers or mobile devices).

3.2.1 Methodology

The goal of this tutorials review was to get an understanding of the current practices for immersed tutorials, as well as their strengths and weaknesses. Heuristic evaluation of user interfaces based on ergonomic criteria has proved to have higher performances than expert inspection [14, 11]. This method allows the discovery

of more design flaws and is more consistent between evaluators, and when compared to user testing, their performances are similar. Thus, we adapted the criteria from Bach and Scapin’s ergonomic scale for virtual environments [172] (Bach and Scapin consider VR applications in general, thus some criteria were not relevant for tutorials). Using these criteria, we then performed a heuristic evaluation of 21 tutorials.

We chose tutorials from applications for either Vive or Oculus, two of the most used VR headsets on the market. Applications were downloaded on either Steam⁴ or the Oculus store⁵, which are two popular sites to download VR applications. Among the available applications, we selected applications that have an integrated tutorial and tried to get various types of applications. As depicted in Table 3.1, our tutorials sample covers a broad range of application domains with 11 different types of applications (some applications had several types): modeling, data visualization, collaboration, general tutorial, exploration, gaming, social VR, animation authoring, workspace, interactive movie, and divers. However, the onboarding process of complex applications is, in our opinion, more relevant to envision onboardings of future applications that are meant to become more powerful and therefore, to some extent, more complex. Immersive VR modeling tools are numerous and provide a great example of a complex application as interactions do not mimic realistic interactions and these applications include many different functionalities. This is why we particularly looked at this type of application.

One collaborator adapted the evaluation questions and each tutorial was evaluated by one coder who was trained by this collaborator to make sure that all coders had a shared interpretation of the evaluation questions. There were four coders in total, including two collaborators. Coders were not new to virtual reality, however, they were new to the VR applications the tutorials belong to. As we used a heuristic evaluation methodology, we did not measure the performance of the coders at the tutorial, their role was instead to rate the content and methods used according to the set of criteria that were provided. To focus on the tutorial themselves and avoid struggling with the usage of controllers and VR in general, we selected coders with experience with VR headsets, however, they were novices with the applications they tested.

For each evaluation, coders first had to go through the set of ergonomic criteria, so they get familiar with the questions and have in mind what they need to look for in the tutorials. Then, they went through the entire tutorial. Finally, they filled out a questionnaire about the purpose and mechanics of the tutorial, and for each criterion, they had to estimate how the tutorial fulfilled it on a 1 to 5 Likert scale. The score could, optionally, be complemented by a comment. During

⁴<https://store.steampowered.com/>

⁵<https://www.oculus.com/experiences/quest/>

this phase, the coder was free to try the tutorial again, or some parts of it. The translated questionnaire is provided in Appendix A.1.

Name [Application type]	Name [Application type]	Name [Application type]
Blocks [Modeling]	MaestroVR [Gaming]	First step for Quest2 [General tutorial]
Maquette [Modeling]	RecRoom [Gaming; Modeling; Social VR]	Demeo [Gaming]
Altar Show [Data visualization]	ShapesXR [Modeling; Collaborative]	Tvori [Animation authoring]
Noda [Data visualization; Collaborative]	AltSpace [Social VR]	Immersed [Collaborative; Workspace]
SteamVR Tutorial [General tutorial]	Arkio [Modeling; Collaborative]	Goliath [Interactive movie]
Google Earth [Exploration]	Liminal [Divers]	Elixir [Gaming]
Gravity sketch [Modeling; Collaborative]	Oculus first contact [General tutorial]	Mission: ISS [Exploration]

Table 3.1: Table of the tutorials we tested and their application type

3.2.2 Context

With the exception of three tutorials that only used videos integrated into VR as tutoring support, all of them were a combination of several modalities. Text was the most used and was present in 16 tutorials. Other visual aids were used such as images (9 tutorials), animations (8 tutorials), or 3D static virtual objects (9 tutorials). Only 5 of the 21 tutorials we tested used avatars to embody the assistance. Regarding audio, 9 tutorials used sound to transmit instructions. Finally, two tutorials used a combination of interactive content for basic functionalities and integrated videos for more complex ones.

3.2.3 Results

We then plotted the results into horizontal bar charts so we could identify the trends and main issues. As aggregating the results into the eight ergonomic criteria would not be informative regarding the tutorials' main issues, we decided to aggregate the questions around the main problems. We first identified the underlying issue for each question, then gathered these issues into three main categories

that we identify as the three main challenges in VR tutorials: (1) intelligibility, (2) feedback and feedforward, and (3) adaptability and accessibility. The results of the questions related to these 3 criteria are illustrated in Figure 3.1.

Intelligibility

To be useful, learners first need to perceive the instructions. We identified two situations in which such instructions could be missed. First of all, as learners evolve in a 3D virtual space, instructions can be anywhere around them, including behind them or too high, hence outside of their field of view. Getting instructions in front of learners, in their field of view, when they appear, guarantees that they will perceive them, it was the case in only 4 out of 21 tutorials. For 13 applications, instructions are usually fixed in the environment, sometimes attached to the objects they are related to, yet those objects are not always in the user's field of view and no indications are used to attract attention to those. In others, arrows, or other visual indications, are used to indicate the position of the current instruction. In our tests, it was the case with the *Immersed* tutorial. One benefit of such a method is to limit the occlusion of the virtual environment. Some tutorials attach instructions to the controllers, which are most of the time in the lower part of the users' field of view, and thus can be easily missed.

Only two tutorials do not provide the full instructions visually but use mainly audio: *Elixir* and *MissionISS*. Visual aids are used to complement the audio but there is a risk that the user misses one instruction that will not be repeated afterward. Such tutorials can be harder to understand for non-native speakers.

Beyond the location of the instruction, their amount is crucial to balance, as too much information can overload the learners. In cluttered environments, important instructions can get lost in the middle of useless ones. Almost all tutorials we tested (20/21) were considered as giving only relevant information. However some instructions appeared to be too minimalist, not giving enough details, thus leading to confusion, ambiguity, and frustration, it was particularly the case in 4 tutorials. For instance, some applications such as *Oculus First Contact* only proposed a minimalist image of what step to do, and others, like *Tvori*, do not show which buttons to press to perform the presented action. Regarding the instructions themselves, in most tutorials, they were considered as easy to understand and feasible (19/21) as well as easy to remember (15/21). The main reason why instructions were difficult to remember in a few tutorials was the fast pace at which they were given (5/21).

3. User Onboarding in Virtual Reality: An Investigation of Current Practices

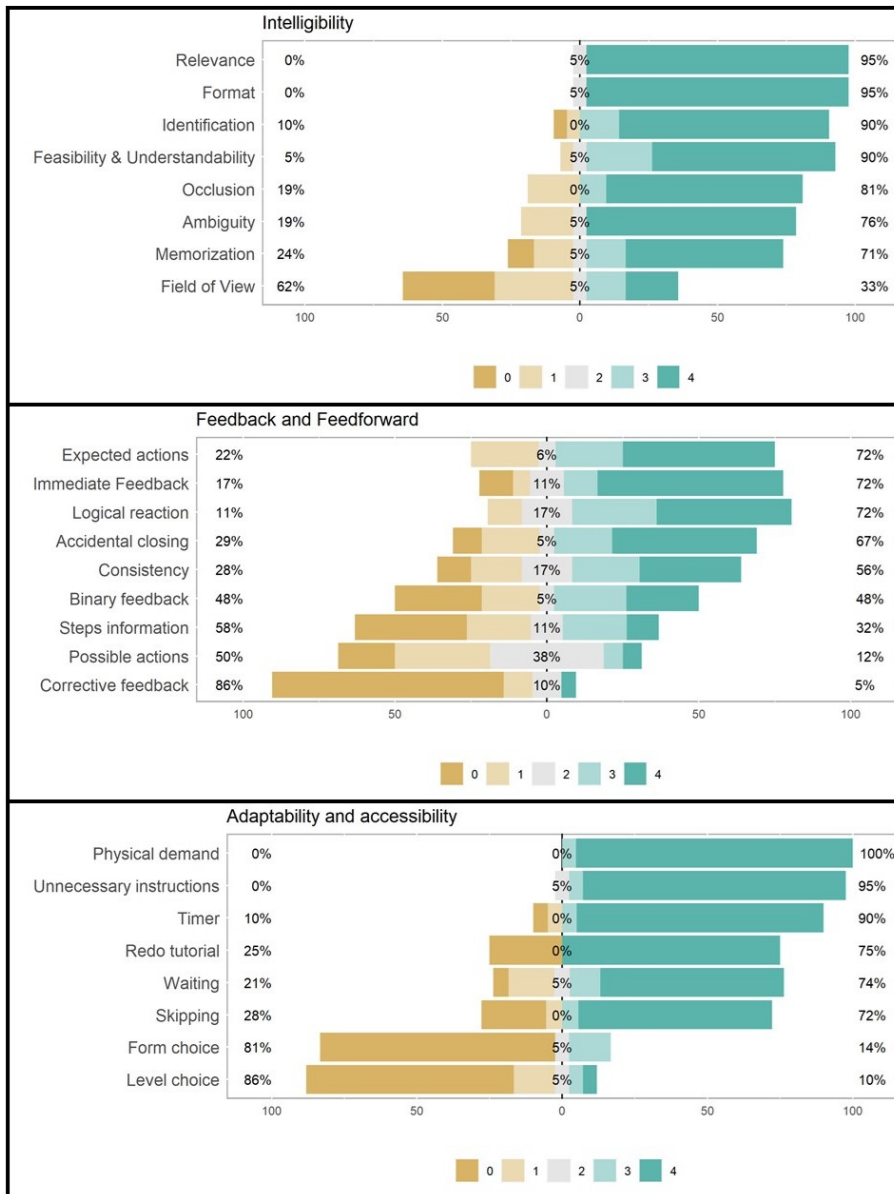


Figure 3.1: Results of the tutorial reviews, questions are organized in three main categories: Intelligibility (top), feedback and feedforward (middle), and adaptability and accessibility (bottom). To ensure the legibility of the figure, we associated each of the questionnaire's questions with keywords. An equivalence table of the bars denominations is provided in Appendix A.2.

Feedback and feedforward

Feedbacks are a crucial element in tutorials as they allow learners to make sure they perform the right action and help them to learn and progress. 10 of the tutorials we tried, give no or insufficient feedback about the correctness of the learner's action. The most common type of feedback was implicit feedback with 11 of the tutorials we tried simply moving to the next step when the right action was performed. This method raises the question of accidental success. Indeed when learners do not understand or cannot perform the instruction, they sometimes tend to frenetically move and push the controllers' buttons. Eventually, the expected action is performed and the system moves to the next step, yet the learner is usually not able to understand what was the action that unlocked the step and thus did not learn the point of the instruction. *ShapesXR* offers one possible solution to this problem. For some instructions, it asks the learner to perform the action not once but several times.

Yet, binary feedback on the correctness of the learners' actions does not inform the learners on how well they performed nor how to get better, which can hinder understanding of the different functionalities demonstrated. Regarding feedback on how to correct wrong actions, we did not find any tutorial that gives detailed instructions. In order to correct the learner, the tutorial needs to analyze the learners' actions, and understand which suggestion to make to help them understand what they have to do.

Feedforwards indicate with which objects users can interact, what actions they can do, and what would be the potential result. 13 tutorials provide insightful indications about what actions users are expected to do, for instance *Occulus First Contact* uses a robot avatar that points at the objects the learner needs to grab and use.

Another method, found in six tutorials, to provide users indication about what they are supposed to do is to propose them a final goal to reach. *Blocks*, for instance, shows the learner a model of an ice cream cone they have to imitate. This method gives cohesion to the different instructions, helps the learner have a sense of purpose, and keeps them motivated.

Plans and progress bars is a common visualisation tool to provide both feedback and feedforward as it indicates what users have done so far but also the length of the tutorials and the content of future steps. Among the tutorials we tested, six of them gave information on the user's progress. Applications with video tutorials organized in a timeline offer a global view in which the user can navigate while being aware of the order they are supposed to look at them.

Adaptability and accessibility

Learners have different capacities, they have different knowledge about VR and past experience with it, abilities, and learning styles. Some might not need a tutorial as they already feel comfortable with the device and application and others may prefer learning through trials and error. Finally, users might want to only do part of a tutorial and prefer to skip it, if it is not possible to select a specific step. Therefore it is important for them to be able to skip the tutorial or part of it. 13 of the tutorials we tried offer the possibility to skip the tutorial. Most applications let the learners choose whether they wish or not to launch the tutorial, however, once the tutorial is launched it is not always possible to leave it. Few tutorials allow skipping only parts of the tutorial, which is slightly more adaptable. Overall, most systems allow users to restart a tutorial (16/21) if needed without closing the application.

To manage the potential difference in the users' experience in VR or a VR application, some applications propose tutorials for different levels: beginners, medium, and advanced. At the beginner level, users get very basic instructions regarding the use of controllers, while at the advanced one, they get instructions on very specific complex functionalities. It was however rare in the set we reviewed as only *Arkio* proposed video tutorials for different levels.

Users also learn at different speeds, some might take more time than others to understand instructions. We identified three ways for tutorials to handle flexibility regarding the learners' pace. Most tutorials have instructions displayed until they are fulfilled. Then, some tutorials might offer instructions that have a "timer". We consider instructions with a timer, instructions that are not persistent and will disappear after a certain time whether or not users accomplished them. Tutorials in this category will still wait for users to finish one step before starting the next one.

3.3 Interviews with experts

As mentioned in the previous section, tutorials in general lack flexibility and tend to focus on basic functionalities. A solution to propose a more complete, in-depth, and targeted training is to have an instructor (i.e. an expert with the system) onboard one or a group of users. This approach is naturally more flexible and interactive. Human experts can more easily analyze and interact with the learners to help them, adapt the content of the tutorial and provide customized feedback for them. Situations, where VR experiences are guided by an expert, can be numerous. This is the case in demo sessions where novice users discover a given VR application for the first time (e.g. during an exhibition, in a scientific outreach

place, and possibly at school in the future, in a lab, and so on). It can be a way to teach collaborators how to use a new tool in a company. Application-specific trainings are also expected to increase in number as VR applications multiply and get more complex. As a matter of fact, *ShapesXR*'s ⁶ editor already organizes online onboarding sessions for their application. Another example is during user studies, part of research work, where participants need to be taught some actions to perform the experimental tasks correctly while being immersed in VR.

In order to identify the current practices and the main challenges in VR onboarding with an instructor, we conducted semi-structured interviews with VR experts with experience in VR onboarding.

3.3.1 Participants

We recruited 15 participants for the interviews via word of mouth. All participants had experience as the role of experts in VR onboarding. Participants had various levels of experience in VR, in various application domains, with various setups and onboarding contexts (See all details in Table 3.2). As we are interested in VR onboarding in general, we did not limit our focus on one specific onboarding context. Although 11 of our participants' primary experience as an expert in onboarding was in the context of research experiments, four participants were VR trainers for VR applications. Participants had between 1 and 6 years of experience with VR (on average 3.6). 2 experts, P5 and P7, had more experience with Augmented Reality (AR) using a Head Mounted Display than with VR. In their case, we counted the sum of their VR and AR experiences as they faced similar challenges.

Participants had experience with various VR onboarding setups. Onboarding can either be done co-located in the same room or remotely. It can also be done using a symmetrical setup, meaning that both the expert and the learner are in VR and they share the same virtual environment. On the contrary, it can be done using an asymmetrical setup in which one user is immersed in VR, while the other one evolves outside the virtual environment. In an asymmetrical setup, bystanders can visualize and possibly interact with the virtual environment through various devices such as desktops, smartphones and tablet applications, or projections, depending on whether or not the non-VR interface is interactive.

3.3.2 Interviews' content

Our interviews were semi-structured, therefore we relied on a set of questions and themes to guide the interviews, however, the topics addressed during the interviews

⁶<https://www.shapesxr.com/>

ID	Domain	VR # Years	Passive /Active	Collaboration	Setup	Context
1	Biology VR visualization	2	Passive	Co-located	Asymmetrical	A
2	Immersive analytics	4	Passive	Both	Asymmetrical	R
3	VR navigation	4	Passive	Both	Asymmetrical	R
4	Embodied data exploration	2	Passive	Co-located	Asymmetrical	R
5	Virtual avatars	3	Passive	Co-located	Asymmetrical	R
6	Immersive analytics	4	Both	Co-located	Both	R
7	Data visualization	1	Passive	Co-located	Asymmetrical	R
8	Embodied interaction	5	Passive	Co-located	Asymmetrical	R
9	Haptic interactions	4	Passive	Co-located	Asymmetrical	R
10	Objects manipulation	3	Passive	Co-located	Asymmetrical	R
11	Immersive visualization	5	Passive	Co-located	Asymmetrical	R
12	Hand gesture learning	2	Passive	Co-located	Asymmetrical	R
13	VR engineer	5	Both	Co-located	Both	A
14	VR teacher	4	Both	Both	Both	A
15	Immersive learning media- tor	6	Both	Both	Both	A

Table 3.2: Table of the participants’ domain of interest in VR, years of experience in VR, details on the kind of collaboration (Co-located, Remote or Both) and setup (Symmetrical or Asymmetrical), and the context of their experience (R: Research and A: Application training).

and their duration could vary between participants depending on their personal experience. The leading themes and questions of our interviews are provided in Appendix A.3.

We mainly focused the interviews on their personal experience as experts during onboarding sessions, yet we also questioned them about their potential experience as learners for other applications. We started the interviews by asking them about their profiles (e.g.: experience, domain of application, complexity of the applications...). Then we collected information regarding the onboarding conditions such as the setup and the learners' profiles. The interview was then divided into two main topics, 1) the issues they encountered, and 2) the solutions to these issues.

As we mentioned the issues they encountered, we first asked them to remind themselves of the last demonstration they did, then we asked some general and open questions such as *"What would you say are the main difficulties when teaching VR?"*. Then, we eventually asked about communication and understanding the learner's experience and feelings during the onboarding. Regarding solutions, we asked the participants about the solutions they use or wish they could use whether they already exist or not. Finally, we asked them if they sometimes used gestures while talking to the immersed learner despite the fact they can't be seen.

3.3.3 Methodology

Two of our interviews were done face-to-face and 13 were done using video conference. We recorded and transcribed them. Then, we performed a thematic analysis, based on these transcriptions, following Braun and Clarke's methodology [29] in order to identify patterns in the current practices and issues.

The thematic analysis comprises six steps. We first familiarized ourselves with the data through the interviews' transcription (step 1). Then, we coded the interviews (step 2) by extracting and associating sections of interest to codes. We first classified these extracts into two categories, problems and solutions, and added comments to the extracts (e.g.: "Touch user", "Non-immersed expert").

Then, we identified patterns and aggregated these codes together to generate themes. For instance, we first merged "Limits of the mirror view" and "Onboarding without the mirrored view" into "Understanding the VR environment". At the end of this step, we had four main themes. We then reviewed these themes (step 4) and decided to discard one theme as its extracts could individually be merged with one of the other themes, and this theme did not have enough content to be strongly supported. We then defined and named our three remaining themes (step 5): (1) The novelty of virtual reality, (2) The lack of awareness, and (3) Communication barrier in virtual reality.

The last step consisted in presenting both the challenges encountered and so-

lutions implemented by participants⁷.

3.3.4 Novelty of virtual reality

As VR is not mainstream outside of specific communities, most novice users to a specific application are also novices regarding VR itself, they do not know how to use the hardware nor how to behave in the virtual environment. As P15 explained to us, just correctly adjusting the headset requires assistance: *"Properly adjust their headset, people don't know how to do that. It is too tight, not correctly positioned, it's blurred because their eyes aren't aligned"*.

Learn to use the controllers

Before learning how to use the application, novices need to know how to use the controllers. They are, most of the time, unaware of their shape and layout, and sometimes do not get to see them before being immersed in VR. P1 mentioned that *"they came into VR too fast without seeing the complete device before. Therefore, they ended up with the controllers in the hands but they had no idea what it looked like"*. Controllers are meant to be held a certain way in order for fingers to be placed on top of specific buttons and therefore facilitate pressing them. Yet, as novices do not know what they look like, they often hold the controllers improperly which hinders the understanding of the experts' instructions as the latter often use the name of fingers to indicate which button to press. Moreover, this issue does not only target VR novices but also all experts using a new type of headset. P14 shared his own experience using a Vive for the first time, *"I never used a Vive before, and I had to do a presentation. [...] I was about halfway through the presentation before I realized where the buttons were."* Some applications render a realistic virtual 3D representation of the controllers, yet it is not always the case and some applications render virtual hands instead of controllers meaning that the visual feedback they get does not match the haptic feedback they have, which makes figuring out the controllers more difficult.

Users also need to learn the functionalities linked to each controller's inputs. These associations tend to vary a lot between applications due to the lack of fully defined conventions in VR and the diversity of application domains. The controllers are not used the same way in a realistic application in which controllers are used to control virtual hands, and in a modeling application in which controllers are meant to be complex tools allowing the user to navigate between functionalities. P13 mentioned that *"You need to keep it simple. New users, they really only like one or two buttons. They can't handle five buttons they need to remember and even"*

⁷Some interviews were performed in French, quotes from those are translated to English for the purpose of this chapter.

two controllers like... for me two controllers are awesome. But for new users, they really don't.". Commands associated with the different controller buttons should be gradually presented.

Get used to the virtual environment

Most users are used to virtually navigate in a 3D environment on desktop using a keyboard and mouse. VR introduces the potential of physically moving to navigate in the virtual environment, but at least 4 participants mentioned that users tend to stay static in VR and encouragements from the experts are most of the time needed to remind the users that they can physically walk and move their heads (P5, P6, P11 and P13). Virtual navigation is also necessary in VR to move on large distances (Virtual workspaces tend to be larger than the physical room) and is, for now, mostly done using teleportation. To be fully functional, users then need to learn to combine both physical (for short, complex and accurate moves) and virtual (for faster and longer moves) navigation. However, most novices at first struggle to master this combination and end up trying to reach everything with physical movements (at the risk of hitting the boundary of the safe physical space or stretching the cable) or trying to do very short and accurate movements with teleportation.

The wow effect

Two participants (P7, P14) reported that just going through the basics, the hardware, and how to navigate in the environment, can take quite a bit of time that is not spent on the core functionalities of the application. This can be exacerbated by the excitement of users due to the novelty of VR and its "wow" effect. This led to some users wanting to rush to wear the headset and not really paying attention to instructions. For instance, P13 tried in some sessions to show the controllers to users before they put on the headset but stopped because *"I think they just glazed over and they just weren't really attentive to it"*. P7 had a similar experience: *"Most people trying VR for the first time, they cannot wait to press the buttons, so they won't take time to stop, look at you, let you do the demo"*. Finally, during the session itself, novices can be tempted to interact with every virtual object without following the instructions and can be disengaged: *"I usually start the session by just asking people not to look ahead, but you always have that one person who just goes crazy, aren't doing things"* (P14).

3.3.5 The lack of awareness

By definition, a VR headset isolates its wearers from the physical environment and bystanders in it, and vice versa. Such lack of awareness is not a problem in general when someone uses VR, mechanisms are included to warn the user of potential physical obstacles like walls. However, in an onboarding context, it becomes important for instructors to be able to communicate with their learners and to be aware of the environment they evolve in.

In symmetrical setups

In a symmetrical setup, learners and instructors should be both in the same VR environment, thus there should be no issue regarding communication and awareness. However, in many multi-user applications, like *ShapesXR*, only actions that impact the shared environment are visible to everyone. It means that if a user opens a menu, the others will not see it. Similarly, detailed models of controllers and which buttons are pressed are only visible to the owner. This design choice is made to limit visually overloading the workspace but can be a handicap in onboarding, as explained by P14: *"That's been the biggest challenge is just knowing they can't see what I see. Even though we're in the same space, they can't see my controllers and they can't see my menus and just slowly talking them through things"*. It is then harder to guide them through the interface and between the different buttons of the controllers. In addition, as learners and instructors are in the same virtual environment, they can move around and wander far from each other leading to situations in which the instructor actually loses the learners. Such a situation happened to P13: *"if you're in a multi-user space, you could actually lose sight of where they are"*. To limit this, P13 remembered a functionality they had on one of their collaborative tool that allow the instructor to automatically gather the other participants.

When in VR, the instructor also cannot check for the learners' handling of the equipment itself. As previously mentioned, VR is still new for most users and while in VR they can forget their headset is actually wired to a computer or forget about any potential tripping issue in the physical room: *"the downsides of being in VR with the person is definitely going to be making sure that they're actually safe"* (P6). P15 actually explained that for this reason, they do not do onboarding sessions alone, they are in VR with learners but another instructor is in the room monitoring the learners' movements and interaction in the physical world, and potentially assisting them with any technical issues.

In asymmetrical setups

In an asymmetrical setup, the situation is actually more complicated as instructors and learners are not in the same "space". It can be an instructor doing a demonstration in VR with learners watching it on a screen or, on the contrary, one or several learners trying the tool in VR and the instructor monitoring and assisting them. The people in VR evolve in a virtual space completely isolated from the physical space they are in, while the people in the room have most of the time a mirror view of what the people in VR see on a screen, like a window from the room to the virtual space. Five participants mentioned not having a view at all to the virtual space when they were onboarding users in VR, mostly due to the fact that they used self-contained headset⁸. As P5 explained, in such a situation: *"You had to memorize what you had seen when you were using it. [...] You had to imagine what they were seeing"*. Without any common ground at all, communication can be quite difficult and both P6 and P7 explained that at times the learner could get stuck and they had to ask the learner to take off the headset and go into VR themselves to understand and solve the situation. P15 partially solved this issue by using *augmented virtuality* which consists in adding physical elements into a virtual scene. It is used by gamers to show a third-person perspective of their gaming session⁹ using tools like Liv¹⁰. P15 implemented the same setup and can then follow learners evolve in the virtual environment from an external point of view, see the surroundings, their controllers, all of these without the shakiness due to the user's head moving.

Having a mirrored view of the learner's experience greatly facilitates expert assistance. Not only the expert can see what the learner sees but also any other bystander, therefore, in an onboarding session with one headset and several, non-immersed learners, they can learn from the mirrored view. However, viewers in the room are constrained to the VR user's view which is often shaky and does not show the surrounding environment making it hard for the instructor to guide the attention of learners to an object or a location outside of their field of view: *"I've sometimes asked the person can you just look around for me? [...] I'm trying to direct your attention to something that's outside the field of view. I then don't really know what's there or not."* (P6). P15 also explained that hands and controllers were most of the time too low to be seen on screen, making it hard sometimes to see what learners do with their hands.

On the virtual side, users in VR cannot see who is in the room. In the case of instructors demonstrating in VR, it is very hard for them to know if learners are listening, or even watching what they are doing. P2 actually shared not being

⁸Headsets that do not need to be wired to a computer to run.

⁹Examples can be found here: <https://www.youtube.com/watch?v=jBLl6n7tRQE>

¹⁰<https://www.liv.tv/>

aware of the number of people surrounding him: *"[There were] three or four people and they want me to show my work, and I put on my headset and do it. And when I take off my headset, I see a crowd of people"*. In the case in which learners are in VR, the situation of being observed without being able to observe in return can be uncomfortable and some learners can feel vulnerable and refrain themselves from moving too much, fearing looking ridiculous. About this, P14 told us about having a no photo and filming rule when he was teaching VR in a class.

Only 3 participants reported doing onboarding sessions with several learners at the same time. This situation can be challenging as all of them need to be monitored, and they should follow the session at the same pace. P15 actually mentioned a tool developed by his team which displays on a large screen a mosaic of all the mirrored views of the learners and provides controls to the instructor to start and pause the experience for all of them.

3.3.6 Communication barrier in virtual reality

VR headsets isolate their users, which keeps them from directly sharing their environment and seeing each other. In the context of onboarding, these constraints can greatly hinder communication.

Non-verbal communication

In symmetrical setups, even if everyone wears a headset and can be in the same virtual space, a large range of non-verbal cues cannot really be used when communicating in VR like facial expressions and subtle gestures. P2 and P13 explained that it can then be hard to make sure learners are actually listening to him or if they are having difficulties understanding instructions. Relying only on body language is then not really possible and everything has to be verbalized, making the collaboration cognitively costly and less smooth. This was confirmed by P14 explaining that it differs from a regular classroom experience: *"My favorite thing about the classroom experience is reading people. You know, when I'm giving a lecture, I can tell very quickly if they're getting bored. I can tell very quickly if they are not understanding. And as soon as I see that, I can respond to it and I can change my message. [...] That was probably the biggest challenge with teaching in VR is just you don't have the same feedback loop that you would have in the classroom."*

In asymmetrical setups, communication gets harder as users in VR do not see the people outside VR, making it impossible to use facial expressions, gestures, spatial referencing, and deixis. As we rely so much on such communication means, several of our participants mentioned still using them unintentionally, even if they are useless in this context, and for instance point at virtual objects on the screen

to indicate to the VR user to look at them: *"It's just your natural habit to start pointing and things. Yeah, that menu right there when you realize, oh, they can't see what I'm pointing."* (P14).

The limits of verbal communication

Yet, verbal communication has its limits and all the experts we interviewed faced them at some point. First of all, despite trying to use precise vocabulary, some ideas are difficult to convey like distance: *"they don't know how far to go and how much to turn"*(P6). It can also be difficult for learners to describe what they see in VR or a specific issue they are facing as they don't necessarily know the right vocabulary to use and the environment can be quite complex: *"they described things, but you wouldn't understand what it was, what it corresponded to"* (P10). This makes it hard for instructors to understand the problem and sometimes can make them misidentify the issue. P7 shared with us a misunderstanding that happened in AR, yet it could most likely happen in VR, *"you should have a menu in front of you." and the person would say 'yes I have a menu', and actually he opened the Hololens' menu and not the application's one"*.

In order to counterbalance the lack of visual communication and still have effective communication, participants developed a precise and visual vocabulary, that can be easily understood by learners, and avoid unfamiliar technical terms. For instance, instructors often use the names of fingers to guide learners through using controllers instead of naming the controllers' buttons. Participants also used a lot of visual descriptions and invoked mental images to convey information: *"With my voice, I give gestural indications"* (P7). Finally, P1 mentioned describing virtual objects of interest using references from movies. To describe the interface he designed, he said *"It looks like typically Iron Man"*, hoping learners would see the similarities with Iron Man's wrist interface.

Communicating through touch

An interesting behavior due to the difficulty to communicate was reported by at least eight of the participants we interviewed. They touch the user to guide him. Most contacts occurred in order to help the user with the controllers like: *"I directly move their hand, move their finger onto the button"* (P4). In some case the experts also touch the learner to make him face a specific direction: *"I kind of grab onto their shoulders"* (P6). The expert explained to us that this second scenario occurs because of the difficulty to precisely orient the learner. Touching users can rise several issues. First of all, it disregards social distances, especially as experts are often likely not to know the learner. Beyond proxemics, as learners cannot see the experts, they cannot foresee the contact which, in addition to be unpleasant,

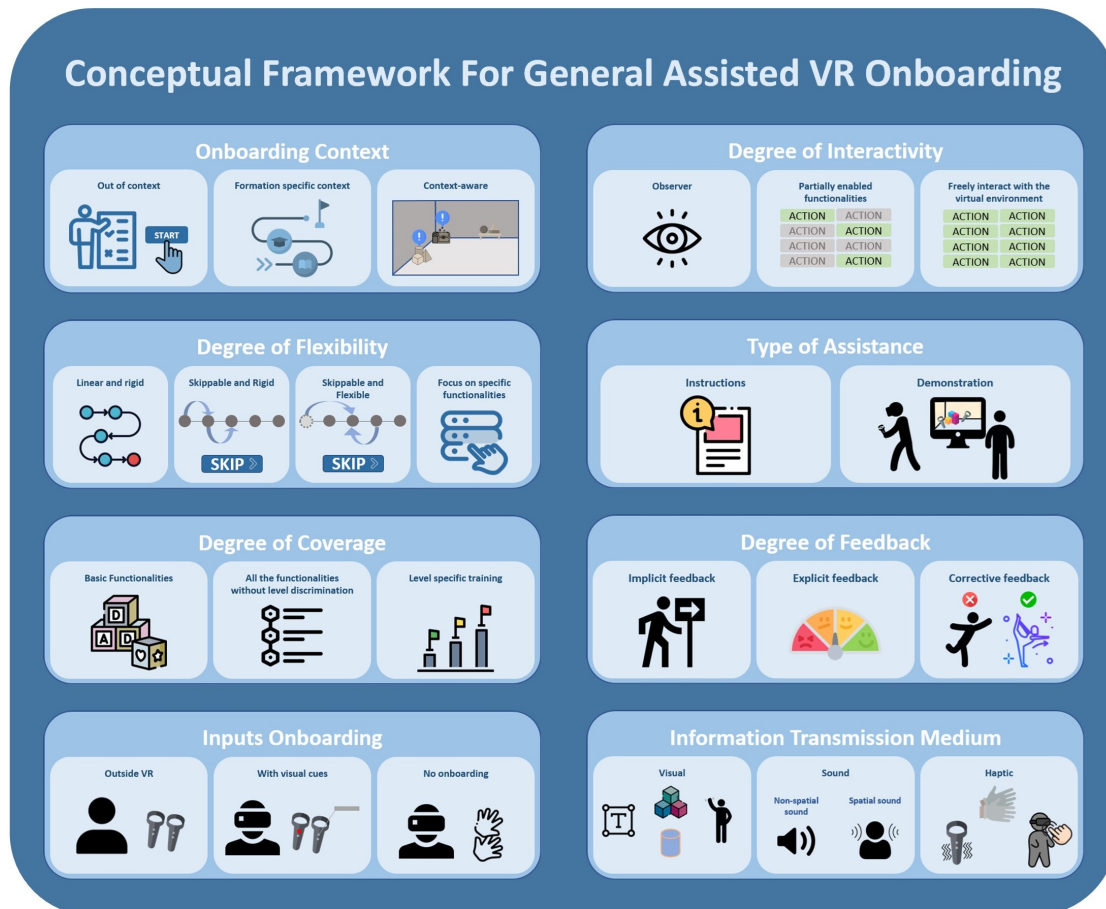


Figure 3.2: Conceptual framework of assisted virtual reality onboarding

could break the sense of immersion for the learners and scare them. As a matter of fact two of the experts we interviewed refuse to touch the learners. P7 mentioned social reasons and P10 based his choice on his personal experience *“I find it very confusing when I have an interaction which is not visible in the virtual world”*.

3.4 Designing VR onboarding

Based on our knowledge from our personal experience, our related work, our tutorial review and our interviews, we created a conceptual framework for general assisted onboarding, illustrated in figure 3.2. The morphological analysis from Zwicky [166] can be used to both generate and exploit a framework [37]. The creation of our conceptual framework is based on the first two steps of the Zwicky

box method. The first step consisted of brainstorming to find the main categories in onboarding practices which were inspired by our tutorials review and thematic analysis of the interviews. The second step consisted in adding values to these categories. These values could either be a continuum (e.g. Degree of flexibility) or a set of different modalities (e.g. Type of assistance). We then used an iterative process during which we detailed, modified, split and merged the different categories. Finally, we refined the names and concepts of our dimensions and sub-dimensions. The last step of the Zwicky box method will be explored in section 3.4.2.

This conceptual framework describes both computer-assisted and human-assisted onboarding of VR applications and aims at giving a better understanding of the multiple forms VR onboarding can take and the contexts in which each form can be found or necessary. Our interviews also revealed that there is a broad range of designs and methods for instructor-based onboarding. Similarly to general onboarding, the design choices depend on the context, and we believe there are still unexplored designs. Thus, future research could benefit from a conceptual framework that focuses on instructor-based onboarding. However, in this chapter, we focus on general onboarding.

3.4.1 Conceptual framework

Onboarding context

It defines the moment when the onboarding is done in relation to the moment when it can be used in the application. When onboarding is done **out of context**, it means that it is done when the learner is not using the application at all. This happens when a learner is watching an online video tutorial, or when the different buttons of the controllers are shown to the learner before going into VR. Then it can be done in a **formation-specific context**, a specific part of the application dedicated to learning. Most tutorials we tried (see section 3.2) are in this case, most of the time, a specific tutorial is proposed the first time the application starts, but in some cases, it is accessible from the main menu anytime. Finally, onboarding can be **context-aware** which means that instructions on how to use a functionality are given when users need it inside the application. To have automatically context-sensitive instructions given to users requires detecting with high precision the users' intentions, which is complicated to put in place. However, it is used when onboarding is done by an instructor (See section 3.3). This particular kind of onboarding is useful when there are a lot of functionalities to learn which makes it impossible to be taught all at once. Games are often suitable for context-sensitive onboardings as the goal given to users is known which help predicts their actions and needs. Frommel and al. [77] studied the effects of context-sensitive tutorials

in VR games and found higher valence, joy, and motivation, and lower frustration and boredom.

Degree of flexibility

It represents the degree to which learners can choose which part and in which order to follow the training. It can be, of course, considered a spectrum but we present here 4 situations we encounter in our investigation. First, onboarding can be **linear and rigid**, and learners have to go through all the steps in a fixed order. Then it can be **skippable and rigid**, meaning that some steps can be skipped by learners if they feel they are already comfortable with a functionality, however, they have to follow the steps in a specific order. It can be **skippable and flexible**, meaning that in addition to being able to skip a step, learners can also replay previous steps, or even start the tutorial at a specific step (to skip the first steps that may be too basic for them), this is done in *AltarShow*. Finally, some applications do not propose a linear onboarding but training that **focuses on specific functionalities** that can be done in any order. This is interesting for advanced users looking for a specific functionality so they do not have to go through the entire tutorial before finding what they are interested in. Immersed video tutorials for applications like *Gravity Sketch* and *Tvori* are organized per functionality.

Degree of coverage

This dimension focuses on the amount of functionality covered by the onboarding. Some onboardings only demonstrate the most **basic functionalities** to allow a low-level use of the application, mostly targeting first-time users. In complex applications such as *Microsoft Maquette* and *ShapesXR*, the tutorials only target the basics like creating a shape and moving it around. Other onboardings propose training for **all the functionalities without level discrimination**, meaning that all learners should go through all functionalities. Finally, **level-specific training** allows users to choose a training that is appropriate for their level of experience. This is the case of onboarding with an instructor as it can be tailor-made and adapted to individual and personal training.

Inputs onboarding

This dimension focuses on the way inputs are taught to learners. These inputs are most of the time VR controllers or hand gestures but we could also imagine the system using other inputs such as a keyboard, gamepads, or full body tracking. It is possible to teach the inputs **outside VR**, before learners put the headset on. Depending on the functionality, it is possible for users to get feedback from

the system on a 2D screen. For instance, P1 mentioned that they developed an additional 2D application on Unity to facilitate inputs training. As learners do not wear the headset yet, they are not isolated which means that on one hand the expert can more easily demonstrate and show them, and on the other learners directly see the inputs. Input can also be introduced when learners are in VR, which happens in most cases. In such cases, it can be **with visual cues**, like a virtual model of the controllers, with or without labels, that allow learners to get familiar with the different buttons, and even sometimes ghost hands showing how to perform a specific functionality, as it is done in *Elixir*. Finally, in some cases, **no onboarding** is done for inputs.

Degree of interactivity

It focuses on how much learners can interact with the virtual environment during onboarding compared to the regular use of the application. In some cases, learners can only **observe** how a task is done and cannot interact at all. This is the case in tutorials that propose only videos, or in demonstrations done by an instructor for learners outside VR. Then, some onboarding environments propose **partially enabled functionalities**, most of the time, only the ones that were already demonstrated. It was used in six of the tutorials we tried, probably to avoid unexpected behaviors that could disturb the learning. Finally, some onboardings allow users to **freely interact with the virtual environment**. This method encourages discovery learning that can be more motivating and allows a better understanding of information[188].

Type of assistance

Assistance can be provided to the user in different forms. It can come as **instructions** of either a practical action to do or a goal to attain as we observed in *Block*. Instructions can be simple and direct to closely supervise onboarding or open-ended to encourage learners to be creative and encourage discovery-based learning. The onboarding can also provide a **demonstration** of what learners are expected to do. It gives them a model to follow and helps them visualize not only the expected behavior but also the expected feedback from the application. The tutorial of *Immersed* contains an avatar that demos the hand gestures the learners have to learn to interact with the application.

Degree of feedback

It is essential for learners to know, at least, whether the performed action is correct or not, and if possible, how to correct it. The lowest level of feedback is **implicit feedback**, meaning that the training simply moves on to the next step when

learners do the correct action, even if it was an accident, which means that there is no guarantee that they understood and learned the task. This was the case of 11 of the tutorials. **Explicit feedback** can also be given about the success or failure of their attempts. Not only it informs learners if the action is incorrect but it can also detail how well they performed in case of success, as it is done in *MaestroVR* with a color code. Finally, it is possible to use **corrective feedback**, feedback that indicates what to fix and how, when learners do a mistake. We did not see any tutorial giving this level of feedback, but it happens when the onboarding is done by an instructor.

Instruction modalities

Instructions can be given using different modalities: visual, audio, or haptic which can be used concurrently and even combined. The most used modality is the **visual** one, which is present in all the tutorials we tested. It can be persistent and always accessible to the learners to allow them to go at their own pace. Visual aids can be static, such as text or highlighting around objects, or dynamic as avatar or animated aids mainly used to attract attention. **Sound** is the second most used modality as it was found in half of the tutorials we tried. It can be verbal instruction or sound effects to indicate the success or failure of an action. **Haptic** is for now rarely present for onboarding in tutorials. Controllers' vibration can indicate that the learners collided with an object with which they can interact. In session with an instructor, we can consider physical contact with learners as haptic instruction, although it is more a by-product of the lack of awareness than a design choice.

3.4.2 How to use the framework

This framework has three main purposes [15], (1) it has descriptive power, (2) it can be used to compare designs, and (3) it is a support to generate new designs.

First, this framework aims at providing an overview of the wide range of onboarding designs. It also provides a set of dimensions that can be used to describe a specific system.

This framework can also be used to compare onboarding-specific methods. There is not one perfect design for onboarding, and the ideal one varies depending on the context. Thus, it can sometimes be intricate to understand which design better fits a specific context. In order to do so, users can rely on this framework to compare each of the designs' dimensions and identify the strengths and weaknesses of each design. It is important to notice that this framework is not meant to be prescriptive and cannot advocate the use of one method over another. Its purpose is to be descriptive. Users can rely on it to better understand how two systems

differ. Then, based on further research they can conclude which design method better fits their situation.

To generate new designs, researchers can use this framework to first describe the state of the art, which allows them to identify gaps in it. This generation process actually corresponds to the third step of the Zwicky box method mentioned in section 3.4.

For example, a first system that could answer some gaps in our related work and tutorials review would be a tutoring system that could provide adapted feedback. If we take the example of The Beat Saber game, the system could distinguish users who did not understand what to do, from users who could improve their gestures or have improper game settings. The tutoring system could accordingly either reexplain the rules or suggest swinging more or less smoothly or adapt the height settings.

3.5 Guidelines

In this section we provide some guidelines for VR onboarding. However, this list is not exhaustive as many guidelines would depend on the context. For instance, adjusting the content and speed of the onboarding to the learner would be desired for one-to-one training, however, it would be inadequate for a controlled experiment, or laborious while training a group.

These guidelines are lessons learned from our tutorials review and our interviews. They are meant to encourage other researchers to explore the use of these methods as they appeared to us as promising or part of a gap in the conceptual framework. However, further research is required to ascertain the efficiency of each method.

3.5.1 General onboarding

Some of the following guidelines might appear as being more tutorial oriented, yet, they also apply to instructor-assisted onboarding although their application does not necessarily involve a technical implementation.

G1 - Instructions need to remain available. Instructions are first provided before the learner performs the task. Not only learners might misunderstand it for various reasons, but the time between the instruction and the resolution of the task might be long which increases the risk of memory lapse. Thus, it is necessary for the user to have access to the instructions at all times. This guideline stems from our tutorial review. Some coders missed some audio instructions as they were focusing on another task when it was given.

G2 - Provide corrective feedback. This guideline correspond to a gap identified in the *Degree of feedback* dimension of our framework. It was also discussed with P12 during the interviews. Feedback is essential for efficient onboarding, it informs the users whether they understood and performed well the task. However, binary feedback only provides limited help. Not only it classifies the users' actions simply as success or failure instead of being part of a continuum, but it also doesn't inform them of why they failed, and more importantly, how to improve. Although corrective feedback is common and one of the main benefits of one-to-one instructor-based onboardings, it is a point that should not be overlooked by onboarding designers for tutorials and instructor-based onboardings with multiple learners.

G3 - Support the use of visual cues. Virtual reality environments are mostly visual environments. Whether instructions come from a computer or an instructor, it is essential that a significant part of communication relies on visual cues. Visual elements benefit from being more persistent and, as they are incorporated inside the VR environment, they are better spatial indicators. We encourage here the exploration of the visual modality that is part of the last dimension of our framework. This modality appeared to be well explored in our tutorials review, however, our interviews revealed that it is not the case with instructor guidance.

G4 - Use multiple instruction modalities. We noticed during our tutorials review that many onboardings would combine several modalities. Combining visual, audio, and potentially haptic modalities to transmit instruction has two main benefits. It provides redundant information which limits the risk of missing a piece of information and makes it more adaptable as learners can prefer one modality over the other. Thus, we advise onboarding designers not to limit themselves to only one category of the *Instruction modalities* dimension. Although we encourage the exploration of the use of haptics in boarding, we advise designers to be careful. Haptic signals need to be consistent with the perceived virtual environment. Moreover, we advise against using a person touching the novice, whether they are real or virtual, as it breaks social boundaries.

G5 - Favor context-based onboarding. Situated learning is a learning theory first introduced by Lave and Wenger [116] that supports the incorporation of knowledge acquisition in the context it will be applied. Beyond situated onboarding, we encourage onboarding designers to incorporate the instructions into a bigger task. Thus, it gives a purpose to learners, as well as an insight into upcoming tasks. Not only it supports the learners' engagement, but it also helps them better understand the functionalities' usefulness and their application context. This guideline encourages the exploration of the categories *Formation specific context* and *Context-aware* of the dimension *Onboarding context* of our framework. It is motivated by both our related work [77] and our observations

during the tutorials review.

3.5.2 Instructor-assisted onboarding

Through our interviews and their thematic analysis, we were able to elaborate a first set of guidelines specific to instructor-assisted onboarding. This set of guidelines is not exhaustive but is intended to serve as a basis when designing instructor-assisted onboardings.

G6 - Do not rush the hardware and inputs onboarding. The use of controllers and how to wear the headset are often perceived as obvious by expert users. Moreover, although learning how to use the hardware is a necessary step to use the application, it does not directly tackle the application's functionalities and thus the core interest of the onboarding. Thus, it is often overlooked by instructors, especially in controlled research experiments. Yet, rushing this step weakens the necessary basis for a VR experience. During interviews P8 mentioned how rushing this step could hinder the experience later. This will to rush can also come from the novice (P7), it is then necessary to help them slow down. Thus, we advise experts to take some time to show the controllers before the learners put the headset on, and then introduce the inputs to them before going deeply into the application's special features and functionalities.

G7 - Experts need at least a mirrored view. Wireless VR headsets complicate the replication of the user's view. Although there are solutions, users are not always aware of them, do not have the technical knowledge to use them, or the headset does not have the capacity to both correctly transmit the visual and run the application. Not only the absence of mirrored view prevents experts from doing a demonstration, but they can only rely on their memory and the learners' reports, to understand the learners' experience and guide them. As neither are reliable, the onboarding ends up greatly unsatisfying. During our interviews several participants (P5, 6, 7, 10, 14) mentioned struggling with the onboarding without a mirrored view. Thus, we consider the use of a mirrored view as the strict minimum required for instructor-based onboarding.

G8 - Instruction is not collaboration. In a collaborative context, participants focus on the result of their collaborators' actions. During onboarding, the result of an action helps the expert understand if the learner succeeded, however, it does not explain why he succeeded or failed. Similarly, when learners see the result of the expert's actions, it helps them understand the utility and power of a feature, but not how it was done. To answer the "why" and "how" questions, experts and learners need to focus on the execution stages of the action [150]. Thus, unlike collaborative tools, onboarding tools need to support sharing the details of the execution stages. This guideline is supported by the interview of P14 who supervises onboardings using a collaborative tool and shared that it is not always

easy to explain how to proceed or understand what the novices see.

3.6 Challenges and discussion

Although there are recurring methods and patterns in VR onboarding, there is no conventional practice for virtual reality software learning. Developers and experts need to find solutions on their own. In this chapter, we make an attempt to investigate them and define a general conceptual framework for VR onboarding, and discuss the future challenges and research directions.

3.6.1 Combining tutorial and onboarding with instructors

One of the findings from our investigation is that onboarding with tutorials and with an instructor can be complementary. A tutorial brings instructions directly accessible in the virtual space and an environment in which learners can focus on the different functionalities to learn. On the other hand, an instructor brings flexibility and adaptability to the learners' characteristics and experience and can provide corrective feedback. A first step to propose more efficient onboarding would probably be to provide tutorials that can be monitored and supervised by an instructor outside of the virtual environment. We can easily imagine a regular tutorial in VR, with a dashboard that can be controlled from a desktop or a tablet to allow for an instructor to control the level of training and which functionality to train the learners on. The tutorial would provide enough visual and audio instructions to the learner to understand what needs to be done, and a basic mirror view could allow the instructor to give live feedback. This represents a low-hanging fruit for VR onboarding, in the future, tutorials should tend to have more and more flexibility.

3.6.2 Toward more flexibility and adaptability in tutorials

As shown in our framework, flexibility and adaptability are the two main issues in current tutorials for applications. Editors should provide users with tutorials, directly integrated into VR, that will show them the basics functionalities, but also the more advanced ones. Users should be able to select a difficulty level or a specific functionality they would like to be trained on and get corrective feedback if they don't succeed. Similarly to tutorials on desktops, it should also be possible for a user to choose a formal and pre-configured training pathway or, on the contrary, choose a more discovery-based approach in which a user would get information while using the application. With the development of learning analytics and the numerous information regarding the users' behavior VR can get (hand and head

movement, gaze, etc.), it becomes possible to better understand users' intents and thus provide the appropriate information, when they need it. But it becomes also possible to assess how users understand instructions and to propose corrections. Future research could for instance build upon Asish et al's work [8] which presents a system capable of detecting students' distraction based on eye gaze data.

3.6.3 Exploring the creation of tutorials

As shown by our conceptual framework, demonstrating is a powerful tool for onboarding, especially when it is combined with instructions. If tutorials are developed at the same time as applications, they can be complicated to put in place. An interesting research direction would be to explore the design of specific tools to create tutorials by demonstrating and recording the different actions and gestures directly in the applications. Such an approach has already been investigated to prototype interaction techniques in AR [205] and can fit well into the VR onboarding agenda. Similarly, the authoring of tutorials for education and training has previously been explored in various domains such as medical [117], welding [94], and office [198] training. This would allow expert users to easily propose tutorials that feature their own demonstrations of the tool usage. However, this should not replace, in some situations, the need for VR onboarding with an instructor.

3.6.4 Developing appropriate tools to manage VR onboarding with instructors

Our interviews and conceptual framework highlight the fact that VR onboarding with instructors is still important and that there is a true lack of appropriate tools. The main point to address is the lack of awareness of the virtual environment for the instructor and the difficulty to communicate almost without non-verbal communication and common ground, especially because collaboration is a lot about what to do in the virtual environment. These issues are multiplied with a group of users instead of just one user in VR. To provide a better awareness of the virtual scene for the people outside VR, P15 mentioned using LIV, a tool that provides a third-person view of the user. To improve communication in VR, Kumaravel et al. [192] developed a tablet interface that allows an instructor to add annotations in the VR scene and highlight buttons on controllers. This is promising and a necessary first step, however, its impact is limited to non-verbal communication and the demonstration of complex gestures in 3D. Future work should focus on such outcomes using for instance Leap Motion or Kinect. These issues are very typical of asymmetrical systems, the most used for onboarding. However, they could be solved by using a symmetrical system, as it has been suggested by a few

participants. Symmetrical setups are also affected by awareness issues as teachers cannot check on all learners' attention and actions. In response to this problem, Broussard et al. [32] implemented a system integrating information on learners inside the teacher's field of view.

3.6.5 Investigating symmetrical versus asymmetrical setups

To have both the instructor and the learner in VR in the same virtual environment can ease the communication and allow for a limited non-verbal communication (using for instance gestures and deixis). The instructor can also have a complete view of the virtual scene and easily attract the attention of learners on specific part of it, even outside of their field of view. It is important to make sure that every elements of the VR interfaces, like menus and controllers, are visible for everyone to allow the instructor to demonstrate their usage. Participants in our interviews however mentioned that being in VR with the learners could make it more complicated to what they are doing and manage them, especially with a group of learners. It is also an issue if there is an audience which is outside VR as the instructors is completely isolated from it. There are then situations in which a asymmetrical setup might be a better solution (with improvement as previously discussed), and more research is needed to understand in which one. It would be interesting to take inspiration from setups with large projection similar to Ishii et al. [96] or Kamei et al.'s [100] works, which allow to share the virtual experience with large audiences of non-immersed learners.

3.6.6 Limitations

We hope this work will guide future developers, trainers, and designers while conceiving their onboarding sessions. Yet, we are aware of the limitations of this study and discuss them in this section.

We could only evaluate a set of tutorials. There are, of course, more already available (probably as many as there are applications), and many more are going to be created in the coming years. We surely missed a few atypical tutorials that would perform better on our evaluation. However, both the tutorials we tried and our personal experience in general highlight the challenges we mentioned and confirm the framework we proposed. We believe a more thorough and systematic review would give a more complete vision of the current state of VR tutorials, but it would also confirm our findings.

Regarding the interviews, around two third of our participants came from a research background. We don't believe this invalidates our findings, but a more balanced set of participants between research and industry could definitely bring very interesting findings. We are not the first study to mention a need to include

more participants with an industry background in research, but considering the importance for industry to make VR accessible for everyone, their insights is more than crucial. Future work should continue our investigation but focused more on the VR industry. Our study is a first step toward a better understanding of VR onboarding in general, and more work is necessary to complete it.

3.7 Conclusion

In this chapter, we investigated VR onboarding through a tutorials review and interviews with experts who have supervised VR onboarding sessions. Building upon literature, our tutorials review, and our interviews, we defined a conceptual framework and proposed an overview of current practices. Finally, we provided guidelines for general and instructor-based onboarding, and discussed challenges and future research questions that need to be explored to answer the challenges we identified. We expect this work to become an aid that designers can build upon while conceiving onboarding assistance.

We focus here on VR onboarding, a context close to the one of education with one or several students with a teacher and using tutorials [162, 99]. The use of VR is more and more explored in such context to immerse students in new experiences (e.g. visiting the bottom of the ocean to understand the acidification process and its impacts [70]), and to provide practical activities that can be complex and expensive to put in place in the physical world (e.g. training in veterinary schools which requires a large number of living animals [74]). Self-adaptability [201] and lack of awareness [24] among the participants have been already identified as important research challenges for these systems. We believe that it would be possible to generalize our framework to such context and then guide the design of efficient systems for VR education.

Providing a good and effective onboarding experience is essential for a positive user experience. When introducing a new visualization experience to users, inadequate or nonexistent onboarding could hinder the user's experience, preventing him from correctly interacting with the system and thus correctly understanding and exploring the visualization. Moreover, a negative user experience can be detrimental to the user's engagement. Thus, onboarding represents the first step to engaging users. Although it is necessary, it is not sufficient and in the next chapter, we investigate how we can leverage immersion to promote the users' engagement.

Chapter 4

Zoomable Empathetic Visualizations

Visualizations for non-experts usually don't serve the same purpose as immersive analytic visualizations. Unlike immersive analytic visualizations, information and data in visualization for non-experts have already been analyzed and interpreted. Visualizations are thus designed based on the interpretation and message the authors wish to communicate. These visualizations are rarely neutral and although they are based on facts, the goal is to engage the audience through a subjective concrete experience. In this chapter, we qualify as subjective the emotional and visceral response of the audience during the visualization experience.

Immersing the user in virtual reality allows us to explore new subjective experiences. It offers for instance opportunities for embodiment where users get to experience evolving in a different body through the use of avatars. Users can impersonate real individuals [134], but also less realistic scenarios such as being a superhero [85], or embodying an animal such as a cow and a coral reef [2]. Beyond embodiment, virtual reality offers opportunities for realistic experiences that leave a more visceral impression.

Thus, immersive virtual reality offers new opportunities for both objective and subjective analysis and experience of data. In this chapter, we try to answer our second research question and investigate how to leverage virtual reality to create visualizations to engage the audience through both convincing and persuasion.

Many human tragedies are unfolding around the world, and effectively communicating about these tragedies can be a first step towards improvement. Behind many tragedies are numbers worth communicating to help people build an understanding. For example, in 2020, 726 elderly people died from the flu in France, whereas in 2017, they were 2327 [93]. With a simple data visualization like a bar chart, one can immediately see that the flu killed three times more elderly people in 2017 than in 2020. Using visualizations, it is possible to convey much richer data

and help people understand complex patterns and trends [144]. Visualizations are effective at giving a quantitative understanding of complex issues, and can help gain the audience’s trust by highlighting facts. However, most visualizations are inadequate for conveying the reality of people’s lives, and for helping the audience relate on a visceral and emotional level. For example, although 726 is three times less than 2327, it is very still a large number of lives. When looking at abstract representations such as bar charts, it is hard to see the human suffering behind. As Jacob Harris [82] mentions “*From a distance, it’s easy to forget the dots are people*”. Dragga and Voss [65] go as far as stating that conveying human tragedies using abstract visualizations is unethical.

To help people understand other people’s lives, humanity has long used stories and narratives, now shared through media such as news articles, books, and documentaries. Narratives are very effective at giving a detailed understanding of human tragedies and can help the audience relate to people’s plights at a deep level. Charities often rely on documentaries to bring out the common humanity between the audience and the victims [90]. Recently, new media have started to be explored ; Immersive documentaries based on 360-degree videos and virtual reality displays offer realistic reconstructions of human tragedies, and sometimes let the user take the perspective of protagonists [168], such as a young teenager in a refugee camp [196]. Narratives, immersive or otherwise, help understand human experiences on a visceral level and are more effective at making people care than numbers. For example, a large body of work in psychology has shown that people are more likely to give to a charity after having seen a photo of a victim than if they have been told the number of victims [124]. However, news articles, books, TV documentaries, and immersive experiences rarely try to promote a quantitative understanding of human tragedies – they typically do not convey how many people are affected, whether the situation is getting better or worse, or whether it varies across countries. This provides an incomplete – potentially distorted [197] – picture of reality, which can impair understanding and fair decision making, for example when deciding how to allocate helping resources [202].

We therefore have on one side quantitative information that provides a crucial type of information (e.g., the extent of a humanitarian crisis), and on the other side qualitative information that provides some other type of crucial information (e.g., a visceral understanding of the personal experience of the victims). Recently, there has been research on trying to combine the best of both worlds. In particular, there has been a surge of interest in *narrative visualization*, where data visualizations are combined with conventional storytelling techniques and media such as newspaper articles and videos [175, 194]. Meanwhile, there have been efforts at trying to design data visualizations that emphasize individuals [139, 140] – a research area that is promising but still nascent, without clear empirical evidence

for a benefit so far [140]. In both narrative visualizations and anthropographics, the two facets (story and data) are intertwined, but they are rarely blended in a smooth manner: many existing approaches maintain a divide between the world of stories and the world of data. In addition, many narrative visualizations and anthropographics are data-oriented – in particular, we are not aware of any anthropographic visualization that conveys rich information about individuals, as news articles or documentaries do. To summarize, we are still missing interactive systems that really break the divide between stories and numbers, where people can understand the two facets of human tragedies in a holistic manner.

As a step in this direction, we introduce *zoomable empathetic visualizations*, or ZEVs. In this chapter, we describe a novel type of immersive visualization system that allows its users to smoothly explore the continuum between data and individual stories. This visualization aims to bridge the gap between the quantitative and qualitative worlds. To do so, users start with an abstract visualization of humanitarian data and use a zooming metaphor to get progressively more information about individuals, until being immersed into a first-person view.

In this chapter, we explore the visualization’s potential through a qualitative study. We introduce three use cases and present a user study. Our results suggest that progressively immersing the audience in an individual representation of the victims promotes emotional engagement while displaying quantitative abstract data visualization helps satisfy the audience’s curiosity regarding the facts and numbers.

Main portions of this chapter will be submitted to ACM CHI 2025 ¹.

4.1 Background

We provide a broad survey of related work, covering a variety of work in visualization, storytelling, and virtual reality.

4.1.1 Conveying human tragedies

We first survey general strategies for conveying the quantitative and qualitative aspects of human tragedies.

Conveying humanitarian crises: Data vs. Stories

Humanitarian crises are large-scale events or phenomena that negatively affect impact welfare, such as pandemics, extreme weather events, or wars. As already

¹Thus any use of “we” in this chapter refers to me, Martin Hachet, Arnaud Prouzeau, and Pierre Dragicevic.

discussed in the introduction, sharing data is one way of informing people about humanitarian crises. This type of data is called humanitarian data, which the Center of Humanitarian Data defines as “*data about the context in which a humanitarian crisis is occurring (e.g. baseline/development data, damage assessments, geospatial data); about the people affected by the crisis and their needs; or about the response by organizations and people seeking to help those who need assistance*” [73]. Data visualizations can provide a good understanding of the quantitative aspects of a humanitarian crisis, both to decision makers and to general audiences.

For general audiences, a more common strategy for communicating about humanitarian crises is by sharing stories – especially stories of individual victims. The audience becomes a direct witness of an individual’s suffering, which can promote empathy for the victims. Stories can be either real or hypothetical. As an example, the short movie “Most Shocking Second-a-Day Video” [1], also called “If London Were Syria” follows a young Londonian girl going through an imaginary war. This video tries to show how the Syrian war would feel if it took place in the UK, in order to help the audience relate to war refugees. Such narrations give very little to no information regarding the number of victims affected by the event, but they can provide a visceral and emotional experience that is often stronger and more impactful than plain numbers [124].

Both visualizations and stories can be used to educate audiences and raise their awareness about social issues that are on a smaller and possibly more local scale than humanitarian crises but are still important, such as social inequalities, diseases, crime, and poverty in a specific country, region, or city.

Anthropographics: Visualizing data about people

In the recent years, researchers have explored how to design data visualizations in a way that helps the audience relate to the individuals whose data is represented [25, 139, 140]. This area of research has been sometimes called *anthropographics*, which Morais et al. [139] broadly define as “*visualizations that represent data about people in a way that is intended to promote prosocial feelings (e.g., compassion or empathy) or prosocial behavior (e.g., donating or helping)*”. Although multiple design strategies exist for anthropographics, a common strategy that is routinely applied to online infographics is to “de-aggregate” visualizations so that each individual is represented by a separate symbol [139]. Such visualizations are also called *unit charts* [152]. Similar strategies have been used in the area of data physicalization [98] – as an example, one installation uses more than 800,000 ceramic poppies to represent WWI victims [56].

Several studies were conducted to evaluate anthropographic design strategies such as de-aggregation in regular 2D visualizations, but with mostly inconclusive results [25, 140]. However, studies simply assigned a different visual symbol to dif-

ferent individuals, without conveying information (or only fictitious information) about individuals. Therefore, one new direction has been to convey actual information about the victims, such as their gender, approximate age, and location and cause of death for migrant deaths [140]. Similarly, Dhawka et al. [60] argued for representing sociodemographic diversity (e.g., race) in visualizations about people. Although there is presently no strong evidence that conveying basic information about individuals can help the audience relate [140], there has been no study so far on conveying rich information.

Conveying large-scale tragedies

Stories can be used to raise empathy but they typically focus on single victims or small groups. Raising empathy for a large number of victims appears to be more challenging. A number of studies have found that empathy decreases as the number of victims increases, a phenomenon known as *compassion fade* [180, 200] or *scope neglect* [41]. A related psychological phenomenon is the *identifiable victim effect*, whereby people donate more to victims whom they can identify (e.g., with a photo or a name) than to anonymous victims [181]. Compassion fade and the identifiable victim effect can lead people to direct their emotional energy and resources to small causes, ignoring issues causing large amounts of suffering. Although there is no simple solution to this problem, it may be partly alleviated by conveying both the scope of a crisis (with data visualizations) and personal details about the victims themselves (with qualitative information displays and stories). However, compassion fade can partly cancel the benefits brought by conveying information about victims, as people donate more to a single identified victim than to a group of identified victims [107].

Ethical arguments for showing individual victims

Ethical arguments can be made for showing information about individual victims, regardless of whether doing so is effective at promoting compassion. The opposite practice of anonymizing victims has often been pointed out as ethically problematic. For example, a study analyzed the representation of refugees in Australian media, and revealed that photos often depict overcrowded boats of migrants [23]. By not showing individual pictures of refugees, the authors argued that refugees are dehumanized and perceived as a threat rather than human beings seeking safety and stability. Some data journalists similarly advocate for showing the people behind the data [82, 179]. In their paper “*Cruel pies: The inhumanity of technical illustrations*”, Dragga and Voss [65] argue that conventional visualizations are inhuman because they look the same whether they refer to the number of dead children in war or the number of cars sold by a company. Of course, the possible

benefits brought by sharing information about individual victims must be traded off against risks of invasion of privacy: it is important that potentially identifiable information is shared with the consent of the victims or their family, and in accordance with privacy protection laws.

4.1.2 Virtual reality as an alternative medium

In this section, we survey what can virtual reality bring to the problem of conveying human tragedies.

Virtual reality for visualizing data

Virtual reality has been explored as an alternative information medium, both in data visualization and in traditional storytelling. In visualization, *immersive analytics* is a growing research area aiming at facilitating the analysis of complex datasets using immersive displays [69]. As an example, Datahop [87] is a system that lets the audience explore data by spatially arranging one’s data analysis steps in a virtual environment. More recently, researchers have proposed to use familiar objects in virtual reality to represent data, in order to give people a more visceral sense of numbers and quantities [119, 9]. However, most virtual-reality visualization systems proposed so far do not focus on conveying data about human tragedies. One exception is the immersive visualization of mass shooting victims by Ivanov et al. [97], where each victim is represented by an avatar and the user can walk among the avatars. This work shares similarities with the avatar step in our visualization (see Section 4.2.2). However, our work distinguishes itself from Ivanov’s work as it proposes a transition from an abstract visualization to an immersive scene, the avatar representation is only an intermediate stage of the visualization. Moreover, our visualization aims to humanize the victims and highlight their individuality through sharing individual data but also personalized avatars which was only slightly explored by Ivanov et al.

Virtual reality for telling stories

There is a longer history of virtual reality being used to tell stories, including about human tragedies. Immersive journalism was introduced about 15 years ago as a new form of journalism, and defined by Peña et al. [57] as “*the production of news in a form in which people can gain first-person experiences of the events or situation described in news stories*”. Immersive documentaries taken on various formats ; a common one being 360° videos where the audience takes a first-person perspective. Although such experiences are generally not interactive, they benefit from a high level of visual realism. The United Nations have produced several immersive videos

to raise awareness of humanitarian crises such as the living conditions in Syrian refugee camps [196] or children suffering poverty and violence in Haiti [195].

Immersive experiences can also rely on fully virtual environments. For example, Titanic VR [128] is a virtual-reality simulation of the sinking of the Titanic where the audience embodies a passenger of the Titanic and boards on a lifeboat while watching the Titanic sink. In some virtual experiences, the user can move and interact with the virtual content [204] – they become an agent [5]. Although the level of visual realism of such experiences is typically lower than 360° videos, they can be made more interactive and can be used to recreate events that have not been captured, or are hypothetical. In addition, virtual reality can give people the illusion that they inhabit other bodies [103].

Virtual reality for promoting empathy

Because of the sense of immersion and embodiment it can create, about ten years ago many envisioned virtual reality as a technology with unprecedented capacity at promoting perspective-taking and empathy [137]. A recent review of studies however paints a more nuanced picture [50]: when comparing the power of empathy in virtual reality to other technologies, only three articles out of the eight comparative studies they reviewed found a reliably positive effect of virtual reality on empathy. Meanwhile, a recent study [55] found that presence has a mediating effect on different dimensions of empathy (i.e., cognitive, affective, and associative empathy), which can possibly explain the conflicting findings in previous studies, where presence was not controlled for and the different dimensions of empathy generally not accounted for. A study also found that the participants perceived immersive storytelling as more trustworthy, and exhibited more sharing intentions [185].

Virtual reality for telling stories about data

So far there is little work combining immersive data visualization with immersive stories. Some recent work has started to extend the concept of narrative visualization (i.e., data visualizations with narrative structures) [175] to immersive displays. For example, Flow Immersive [61] is an immersive and interactive data visualization tool that integrates storytelling components into the visualizations to make the data more accessible to a large audience. However, there is very little work looking at how such techniques could be used to communicate about human tragedies specifically, with the exception of a position paper introducing *immersive humanitarian visualization* as an underexplored but potentially promising area of research [66].

4.1.3 Semantic zoom

Zoomable User Interfaces (ZUIs) are defined by Bederson [16] as "systems that support the multi-scale and spatial organisation of and magnification-based navigation among multiple documents or visual objects". First introduced by Perlin and Fox [156], the use of ZUIs have been broadly explored on desktop interfaces and many current desktop applications rely on them.

Semantic zooming is a subcategory of ZUIs. In their study [209], Chris Weaver defines the semantic zoom as *"a form of details on demand that lets the user see different amounts of detail in a view by zooming in and out"*. Although the term was coined by Perlin and Fox in 1993 [156], semantic zooming was really explored by Bederson and Hollan with Pad++ [17] and has since then been used in various domains not only in research studies [67, 51, 78] but also in applications available to the general public such as Google Maps ².

In this chapter, we inspired ourselves with semantic zooming to allow the exploration of humanitarian data. The visualization first enables the analysis of global data through traditional and abstract charts and then allows the users to zoom and get closer to the individuals through the visualization of individual data and the immersion of users in a realistic representation of victims.

4.2 Zoomable Empathetic Visualizations

4.2.1 Concept

In this section, we define the concept of Zoomable Empathetic Visualizations (ZEVs) in general and do not restrict ourselves to the limits of our implemented prototype. Indeed, the implementation process involves making choices based on various factors such as time and resource constraints, therefore our prototype only shows one possible implementation of this concept.

We inspired ourselves with the concept of semantic zoom to transition from an abstract visualization to a more individualized and concrete visualization which would bring the human back into the visualization.

First, it is necessary to define the type of data suitable for this kind of visualization. As one of our goals is to bring the human back into the visualization, it is necessary to gather data on individuals. Concretely, for each dot that constitutes an abstract visualization (e.g. bar chart) we associate individual and personal data (e.g.: age, gender, name...).

The first level of the visualization is an abstract aggregated visualization that would show the proportions of individuals depending on a variable (e.g.: the pro-

²<https://www.google.com/maps/>

portion of women vs men). This visualization can look like any traditional graph such as a bar or pie chart.

As the user zooms into the visualization, it becomes granularized. Each person in the data is represented by an individual element. This second step introduces new information, the number of individuals for a variable (e.g.: the number of women and men). This individual graphical representation can either be abstract such as a geometrical shape or introduce some concrete meaning with a specific shape (e.g.: a low-poly human shape).

In the next zoom level, each individual is embodied by a personalized representation. The level of personalization can vary. It can be non-specific and depend on one or several variables (e.g.: only gender or gender and age). In this case, the level provides qualitative codable information on the subject. The embodied representation can also be specific to the subject. In this case, the representation can provide qualitative non-codable data. Some data are difficult to code. It is for instance the case for visual information. A lot of information can be lost in the coding process. For instance, we could implement a visualization with the data of the exhibit *What were you wearing?* [52] which shows the clothes victims were wearing when they got raped or sexually assaulted. The name of the exhibit refers to the famous question that is too often asked to the victims. The purpose is thus to *"to challenge the idea that provocative clothing is the cause of the sexual assault, a stereotype used for victim blaming"*. If the clothes were coded based on predefined categories and the exhibit did not show the real clothes, we can easily imagine that the impact of the exhibit would not be as strong. Thus, we believe that this concept of visualization can also be used to depict non-codable data. Yet, it is also possible to use specific representation for another purpose such as improving the credibility or sense of realism of the visualization.

In the next state, the user is projected into the granularized representations and can wander in it. In this state, the user can fully benefit from the virtual immersive nature of the visualization. We consider that getting closer to an avatar is a form of zooming as its visual representation appears bigger to the user. Thus, as the user gets closer, personal information on the subject can appear. The form of this type of information can vary depending on the designer's choices. It can be text, sound, pictures, or videos. We could imagine the avatar coming alive, interacting with the user, and narrating their story.

In the final state of this visualization, the user is immersed in a scene personalized to a subject (the avatar they got close to). This immersive scene can either be a 360° picture such as a Google Street View image, a 360° video, or an entire 3D environment with which the user can evolve and possibly interact with. This immersive state serves three possible purposes which can be inclusive or exclusive. 1) Similarly to the visual representation of the individuals, the immersive scene can

provide information on non-codable data. For instance, the visualization *Dollar Street* [4] documents the incomes, everyday life, and housing environments of families around the world. For each family, the user has access to several photos and videos that depict their way of living. These photos and videos share information that would be hard if not impossible to code otherwise. The use case presented below on femicides in Section 4.3.1 provides such an example. 2) The immersive scene can also provide some context to the user. This is especially relevant when the data relates to events such as accidents. Getting immersed into the location where an accident took place, might help the user better understand the factors that led to the accident (e.g.: use case on bike accidents in Section 4.3.2). For instance for a car accident, by getting on the spot of the accident, it is possible to identify a blind spot, a source of distraction for drivers, or a danger. This can also be perceived as a form of 3) embodiment which is the third purpose we identified for the final immersive scene. The user can embody the victim and put themselves into the victim's shoes. This scene could for instance be similar to the one used in Seinfeld et al.'s study [176]. They immersed a group of males with a history of domestic violence into the body of a female avatar. The participants then experienced a scene of abuse in the first-person perspective.

4.2.2 The prototype

In this section, we describe our design choices for the prototype. As mentioned before, it is not the only design possible. Our choices were guided by our knowledge of interaction and virtual reality and by resources and technical constraints. We provide a demonstration video of our prototype in the supplementary material ³.

State 1 - Abstract visualization

In the first step of our implemented visualization, the user faces a vertical bar chart (see Figure 4.1 a). On top of this bar chart, a title is displayed and at the bottom of each bar, a text label indicates the value associated with this bar. The bar chart only shows the proportions of individuals for each value. On the left side of the bar chart, a series of buttons is displayed in order to change the sort variable (e.g.: age, date, gender). These buttons only appear at this zoom level.

State 2 - Granularized visualization

In the next zoom level, each bar is split into cubes. Each cube represents one individual data point. We chose to keep an abstract presentation (a cube) for

³https://osf.io/awqgc/?view_only=33bcae0227ee4926b00cc1f32ddaaca6

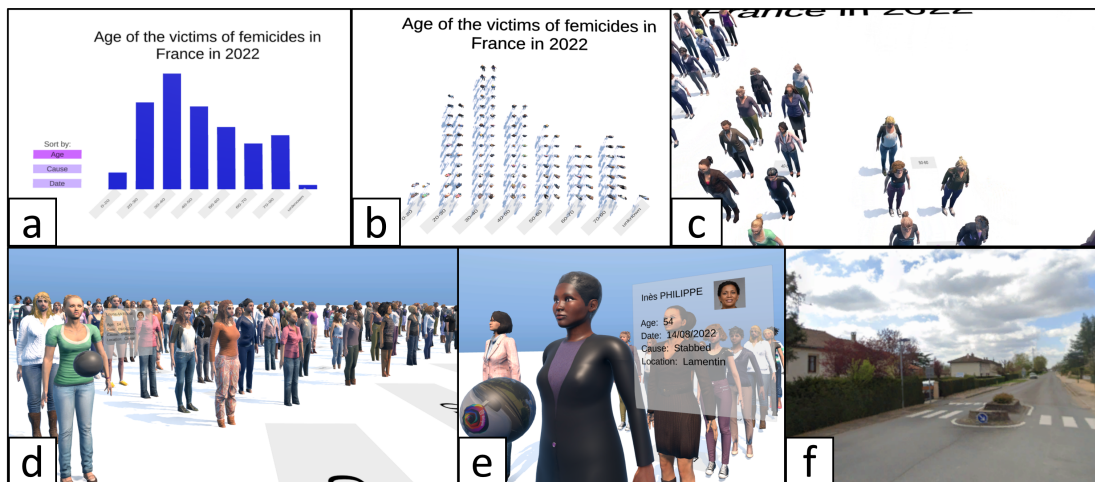


Figure 4.1: Captures of the femicide use case. **a:** Abstract chart with the data displayed based on the victims' age, **b:** Unit visualization with avatars, **c:** As the user keeps zooming, the visualization tips over, **d:** The user is immersed in a human-scale individualized visualization in which an avatar represents each victim, **e:** When the user get closer to an avatar, individual data are displayed and a sphere appears to dive into the 360° view, **f:** 360° view of the address where the femicide took place.

this step as we believe it makes the transition from a bar to an individual cube smoother.

State 3 - Avatars

As the user keeps zooming, each cube turns into a personalized prefab (see Figure 4.1 b). In this thesis, we will call it an avatar, yet it does not have to be human-shaped, it could be just any prefab. When the visualization reaches a certain level of zoom, the visualization tips over to a horizontal plane (see Figure 4.1 c), and the user can wander among 1:1-sized avatars (see Figure 4.1 d). Our prototype allows the authors to personalize the avatar either depending on the value of a variable (e.g.: male or female, age range) or to specify a path (in the csv file) to a prefab in the Resource file.

State 4 - Information panel

As the user gets closer to the avatar, a panel appears on its right (see Figure 4.1 e). The panel contains personalized text and displays the individual's data. It is also possible to display a picture at the top right of the panel. It is for instance possible to display a profile photo of a victim which makes the victim more identifiable and tends to trigger more emotional reactions [124].

State 5 - 360° view

A sphere also appears in front of the avatar (see Figure 4.1 e). The user can grab it and dive their head into it to get immersed into a 360° picture (see Figure 4.1 f). The interaction is similar to the street view immersion in Google Earth VR ⁴. The user can then leave the 360° view by grabbing the sphere again and exploring more of the visualization.

4.2.3 Implementation

Editing the visualization

Data format Our prototype is more suitable for non-aggregated data as our main purpose is to humanize back the victims and show them as individuals instead of a group of numbers. Yet, Section 4.3.3 shows an example of how we could use this visualization with aggregated data.

The visualization reads a csv file in which each row contains information about a subject. Each column is then associated with a variable. The CSV file can contain

⁴https://store.steampowered.com/app/348250/Google_Earth_VR/?l=french

qualitative data (string), quantitative data (float or int), time format (the following formats are accepted: mm/yy OR mm/yyyy OR dd/mm//yy OR dd/mm//yyyy), or a string path referencing to either a Resources folder or a web URL referencing a picture. CSV files of our three use cases introduced Section 4.3 are provided as examples in the supplementary material ⁵ (we however anonymized the data for the use case introduced in Section 4.3.1).

Configure the visualization The implemented prototype allows its users to edit the visualization based on the provided dataset. The authors can configure the visualization through the Unity inspector. A video example of the visualization configuration is available as supplementary material.

Implementation details

The prototype was implemented with Unity 2022.3.1f1 using C# and SteamVR⁶. The prototype runs on an Oculus Quest 2 and a laptop computer MSI GT63 Titan 10SF with an Intel Processor Core i7-10750H CPU 2.59 GHz, 16Go RAM and a Nvidia GTX 2070 graphic card.

The avatar models in the pictures and videos come from Mixamo⁷, Microsoft Rocketbox⁸ and the Inria avatars gallery⁹. Each model was processed through Blender to create Levels Of Details on Unity. All animations were downloaded on Mixamo.

The code is publicly available and open source¹⁰.

4.3 Use cases

In this section, we introduce three use cases for our visualization. Although the use cases may visually look alike, we wish to emphasize that the avatar and immersive states serve different purposes. For each use case, we describe the data then the application and share some possible takeaways. These takeaways were extracted by the collaborators in this project and do not result from a user study. We simply share them as an illustration of the visualization's interests at each state.

⁵https://osf.io/awqgc/?view_only=33bcae0227ee4926b00cc1f32ddaaca6

⁶<https://store.steampowered.com/app/250820/SteamVR/?l=french>

⁷<https://www.mixamo.com/>

⁸<https://github.com/microsoft/Microsoft-Rocketbox>

⁹<https://avatar.inria.fr/>

¹⁰<https://gitlab.inria.fr/egros/zoomintodata>

4.3.1 Femicides

About the data

In a CSV file, we gathered the data collected by the collective "*Féminicides par compagnons ou ex*" on the femicides by partners or ex-partners in France in 2022 [71].

For the year 2022, the collective kept a record of 113 conjugal femicides. When the information was known, the collective shared the first and last name of the victim, her age, the presumed cause of death, a profile picture, a link to a press article, and an explanation text from which we extracted the date and place of death.

The visualization

For the first state of the visualization, the bar chart can be sorted depending on three variables, the age of the victims, the cause of death and the month the femicide happened. The main takeaway from this abstract visualization is that femicides happen at all ages but it is at its highest between 30 and 40 years old. The two main causes of death are getting stabbed or shot, yet there are many causes of death listed (15) including four which are a combination of causes. However, there is no obvious information that can be extracted from sorting the data by month.

For the avatar, we chose to associate a specific avatar to each victim. Based on the collection of avatars we had access to, we tried to match the victims' profile picture (when we had one) to the most resembling avatar. When we had no profile picture available, we chose an avatar based on the age of the victim and tried to limit the redundancy of avatars. We chose to associate a specific avatar to each victim to avoid inconsistencies with the profile picture that is displayed on the avatar's panel. As the data were first collected by an external collective and are not anonymized, we chose not to share identifying data or pictures in the figures and supplementary material. Choosing a specific avatar for each victim allows us to highlight the individuality and uniqueness of each woman.

For the immersive view, we chose to immerse the users into a 360° Google Street View picture of the place of death. As we believed that displaying a picture of a random position in the city wasn't relevant, we skimmed the press articles looking for a more precise location (the neighborhood or exact address). By getting a more precise location, we were able to notice that femicides happen in all types of environments (cities, countryside, suburbs, council estates...).

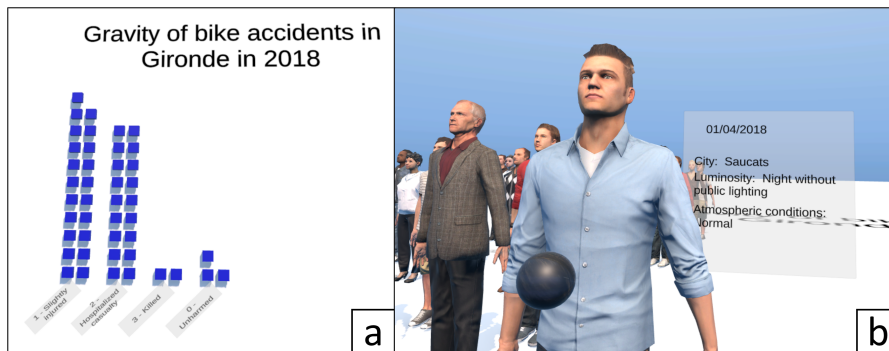


Figure 4.2: Captures of the bike accident use case. **a:** Abstract unit chart with the data displayed based on the gravity of the accident, **b:** Immersive individualized visualization of a victim of an accident, the avatar is based on the victim’s gender.

4.3.2 Bike accidents

About the data

We downloaded a dataset of all bike accidents registered by law enforcement in France from January 2005 to December 2018 [110]. From this dataset, we extracted all bike accidents in the region of Gironde in 2018. We ended up with 44 bike accident for this period in this region.

The visualization

For the bar chart visualization, we enabled four different sorts, depending the seriousness of the accident, the luminosity, the victims’ age and the date of the accident. We were able to extract some takeaways from the bar chart visualization. For instance, there were nearly as many hospitalized victims as slightly injured victims. We however hypothesize that law enforcement is not always involved in accidents with only slight injuries.

For the incarnated state with avatars, we chose to associate avatars based on the victims’ gender. We provided several models for each gender in order to avoid too much redundancy between the victims. The main takeaway for this state is that hospitalized victims were mostly men which tends to suggest that men are involved in more severe accidents. Of course this is not a real statistical analysis and just an hint users can get from watching the visualization. On the avatar’s panel, we chose to share the date of the accident, the victim’s age, the city where it occurred, and the atmospheric conditions. The conditions are most likely to provide context to users regarding the accident, whereas the date and city can intrigue the users and help them identify with the victims (e.g.: they live in or

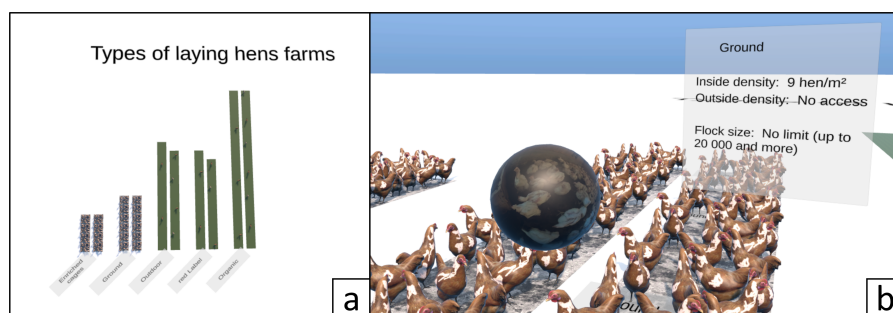


Figure 4.3: Captures of the laying hens farms use case. **a**: The vertical avatar visualization gives an overview of the hens’ density and living conditions for each type of farm. On the left, we have hens clumped together on a concrete-like background to remind the audience that they do not have access to outdoor space. On the right, we have scattered hens on a grass-like floor. **b**: By getting closer to an group of hens, the user can observe and realize the density of hens on each type of farm, read the information on the farms, and immerse themselves into a 360° view of a farm.

know the city where it happened).

For the immersive view, we downloaded the Google Street 360° picture of the exact location of the accident based on the given latitude and longitude in the dataset. This immersive view provides context on the location and circumstances of the accident. For instance, for one of the two people killed the panel indicates that it happened by night without public lighting. By getting immersed in the Google Street View, we realize that it is a long road in the forest where cars are probably going fast. For the second person killed, it happened during the day but under heavy rain. The 360° view shows that it happened on a parking lot, we can thus imagine the traffic, the possibly reduced visibility and eventually cars, bikes, and people being hidden by parked cars.

4.3.3 Beyond humans: the case of animal welfare

Through this use case, we wish to provide an alternative use of this type of visualization. This example can be defined as alternative because 1) it extends the concept beyond humanitarian data, and demonstrates how it can be used to raise awareness of other topics such as animal welfare, and 2) it shows how it can be used with aggregated data. Although we believe this concept best fits non-aggregated data, we are aware that it is not always possible to use individual data. The two main reasons are that such data are not always known and datasets can be too big to render for the computer.

About the data

We collected on the internet various data on laying hens farming. For each of the five types of farming (configured cage, barn, free-range, red label, and organic), we gathered the percentage of farms, the legal indoor density, the legal outdoor density, the maximum size of the herd, the average price of eggs and the code of the egg. We then created a CSV file for 100 farms respecting the proportions of the five types of farming.

The visualization

The barchart state shows the distribution of farms either by type of farming, or indoor density. We could argue that aggregating the data by proportions of farms instead of hens tends to make the users underestimate the proportion of hens that live in "bad" conditions (eg: configured cages). Indeed, in France there are for instance more organic farms than configured cage farms for laying hens, however as the size of the herd is significantly smaller for organic farms, it only represents 16% of the laying hens (against 33% for configured cages).

Yet, our choice to organize the CSV file by farms instead of hens is motivated by the avatar phase. Indeed, it allowed us to convey more information through the avatar representation. Instead of displaying the avatar of a single hen, each farm is represented by a group of avatars. The avatars contain the density of hens per meter square either indoors (if the hens do not have outdoor access), or outdoors (e.g.: 13 hens in one-meter square for the enriched cages farms).

Finally, for the last phase, the user is immersed in a 360° photo of a hen farm. The goal of this phase is to embody the hen and get a visceral feeling of the density and living conditions of hens in these farms.

4.4 User study

In order to get feedback and insights on this new type of visualization, we conducted an exploratory user study. The goal of this user study was to get qualitative feedback rather than quantitative results. We decided not to conduct a comparative study. However, we did collect some qualitative feedback after presenting an extract of a governmental report.

4.4.1 Participants

We recruited 12 participants (6 females, 6 males) through professional and personal networks. Participants were aged from 22 to 43 (mean=30, sd=6.9). Regarding their experience in virtual reality, three participants reported none, seven qualified

it as low (has already used a VR headset but does not consider having any experience), two as average (knows VR but does not use it on a regular basis), and none as high (use VR daily or weekly). In this chapter, we will mention the participants with F or M to encode their gender combined with their participant’s number. Table 4.1 summarizes the participants’ answers to the demographic questionnaire.

#	XP in VR	Domain of study or work	Took the report
F1	Low	Psychology	Yes
M2	Low	Master student in computer science	No
M3	Low	Computer science - information visualization	Yes
M4	Low	Scientific mediation	No
M5	Average	Robotic	No
M6	Low	Computer science	Yes
F7	None	Research team assistant	Yes
F8	None	Research engineer	Yes
F9	Low	Innovation	Yes
F10	None	Administration	Yes
F11	Average	Mathematics, computer science	Yes
M12	Low	Engineering in airport planning	Yes

Table 4.1: Demographic profile of the participants

4.4.2 Study design and procedure

After introducing the study to the participants, they signed a consent form and filled out a demographic questionnaire. This was followed by a training session. We chose to incorporate a separate training phase to our user study as many people are still new to this type of technology and universal conventions of interaction are not yet established in VR [45].

The goal of this training session was to familiarize the participant with the interaction techniques and objects’ behaviors before the exploration of the data visualization. To do so we created a Unity scene that had the same interaction techniques and objects’ behavior as the data visualization but did not include any data-related content. We then included a short break between the training and the exploration phase in order to avoid eye strain and limit cyber-sickness.

For this user study, we used the femicide use case introduced in Section 4.3.1. We chose this use case because its dataset contained non-anonymized data. Therefore, we believe it to be the use case that best serves our initial goal which is to show the human behind the data.

During the exploration phase, we guided the participants through the different steps of the visualization. During the process, we asked them some questions to motivate data analysis and exploration. For instance, during the avatar exploration, we asked them to find a specific individual. Once we introduced the participants to all the visualization’s steps, they were free to explore the visualization as long as they wanted to. The guidance support for the user study is provided in Appendix B.1.

This exploration phase was followed by a semi-structured interview for which we recorded the audio. The goal of this semi-structured interview was to gather qualitative feedback from the participants regarding 1) their insights, 2) their feelings (especially hints of empathy), and 3) their opinions regarding this type of visualization. At the end of the interview, we showed the participants an extract from a governmental report on violent deaths among couples in France in 2022 [76]. Due to its length, we chose not to show the entire report, thus we selected the summary visualization it contains, as well as the graphs that shared data that our visualization shared too (eg: cause of death or the average age of the victims). We then asked the participants about their insights on the report and to compare it with the immersive visualization they just explored. At the end of the interview we mentioned that we had a printed version of the complete report from the government. Participants were free to take it and leave with it if they wanted to. The main questions for the semi-structured interview are provided in Appendix B.2 and the extract from the governmental report is available in Appendix B.3.

4.4.3 Methodology

We performed a thematic analysis of the interviews based on Braun and Clarke’s methodology [29]. To do so we analyzed the transcriptions of the audio recordings.

The thematic analysis comprises six steps that we followed. First, we familiarized ourselves with the data through the recordings’ transcription (step 1). We then coded the transcriptions (step 2). To do so, we extracted 767 sections of interest that we associated with 78 codes. The next step consisted of aggregating the codes into patterns (step 3) which gave us themes. We then reviewed those themes (step 4). Finally, we named and defined our final themes (step 5) and we present them in Section 4.5.

4.5 Thematic analysis of the interviews

All the extracts shared in this chapter were translated from French. The extracts, results, and support for the thematic analysis are available as supplementary ma-

terial¹¹, however, they have not been translated.

4.5.1 Learning with the interactive experience

Awareness can be raised in two ways, through teaching facts and making the audience care. Our interviews revealed that our visualization can be used to teach the facts. Before exploring the visualization, several participants had little or partial knowledge on the subject. If most of them had in mind the order of magnitude of the subject, this was the all extent of their knowledge for most of them. 10 of the 12 participants we interviewed explicitly mentioned learning something during the study. They often expressed their surprise when exploring the data, they often had beliefs or preconceptions that were dismantled by the data. For instance, F9 declared *"I imagined the younger ones, like 20 to 30 years old, which are more emotional but it happens in all age classes"* and F10 admitted that *"we imagine that not much happens to the elderly"*.

Learning with the graph

Of course, the first phase of the visualization, the abstract and traditional graphs, allows us to introduce the data to the audience and provide them with a clear quantitative understanding of the data. Traditional visualizations such as graphs benefit from being concise and providing a good overview of the data. Our interviews revealed that the participants made several discoveries in this first exploration stage. F9 *"[realized] that it can happen at any age"*, F10 *"was surprised that there were so many femicides of old women"*, and F11 *"was surprised to see so many femicides"*.

Learning from non-codable data

Although most discoveries happened during the graphs' exploration, the immersive scenes with the avatar and the 360° view, offer the possibility to represent non-codable data and provide additional context and information to the audience. We mentioned earlier that some data are hard to code. It is for instance the case of the locations where the victims were killed. We could code the place as "urban", "suburban" and "rural" yet, we believe there is an important loss of information as there are very different areas inside each category. It might not be impossible to code if we crossed codes (e.g.: rural, not isolated, middle class), however, it would be much harder to read and there would be a loss of information.

Some participants actually learned from the immersive scenes, especially the sphere which allowed them to see that femicides happen anywhere. F7 acknowl-

¹¹https://osf.io/awqgc/?view_only=33bcae0227ee4926b00cc1f32ddaaca6

edged that *"the 360 view really shows that it happens in very ordinary locations"*. M3 and F9 had opposite preconceptions, the first thought that femicides mostly happened in big cities and the second that it would happen in isolated locations. After exploring the 360° views M3 *"thought it was surprising that there were so many in the countryside"* and F9 told us *"It's in the countryside so it is rural. So it confirms my preconception and my first vision of it. [...] I find Nice. It was a big surprise according to what I just said. It was really in a residential area, in quite a chic neighborhood."*

Generate interest

Of course, the discoveries participants could make while exploring the visualization were limited to the data we actually presented. Yet, we believe the visualization can support learning on a subject beyond the data it contains. Indeed, it can be used as a way of promoting the audience's interest in a topic.

Traditional visualizations can be perceived as boring or overloaded by the readers and therefore poorly engaging. Several participants shared the limitations of this type of visualization during the interviews. For example, F1 mentioned that *"it's really cold. I mean, we can write whatever we want on a graph. We don't even realize what's behind the numbers."*, M2 admitted after reading the government's report that *"when we look at the figures, we don't really want to look because it's a lot [of information]"*, and M3 described these traditional visualizations as *"generic information. You don't see the people"*.

On one side, we believe that the first stage of the visualization should not be complexified with additional data beyond reason, otherwise, it might repel the audience. M3 illustrated this phenomenon by sharing *"when I see a graph, so yes it a plot, again. There are a thousand of those a day. I don't want to [look at it]"*.

On the other side, we noticed a lot of curiosity and a need to get more information from the participants as they explored the visualization. Exploring the visualization raised a lot of interrogations and all participants mentioned wanting more information or manifested their need to explain the data through personal interpretation of it. Moreover, the fact that 75% of the participants (9 over 12) took the government report with them at the end of the interview suggests an interest in the subject.

We are therefore confident to say that our immersive visualization managed to raise our participants' interest in the matter of femicides and we believe that it could be complementary with a more traditional visualization. The immersive visualization could be first used to engage the audience on a subject, then the audience could get more thorough information through traditional visualization. Indeed, these traditional visualizations require fewer resources to be created and shared, which was mentioned by F10 and M12. M12 pointed out that *"the point*

is that it holds in a double-sided A4 page. It can easily be distributed, on a web page, anywhere, or on some sort of flyer".

Four participants (M2, M4, F8 and F10) mentioned that the report and the immersive visualization could be complementary. M4 explained how exploring the visualization before reading the report changed their perception of it, *"I would have read that, fine, I would have taken it into account. But after [the visualization], it is as if I knew someone that got killed"*. M2 emphasized the importance of introducing the immersive visualization first, *"as [the report] is more detailed, it is certain that it has to come after the visualization"*.

4.5.2 Creating empathy and affect

Through the interviews, the participants shared signs of affect and empathy for the victims depicted by the visualization.

Generating a wide range of emotions

Most participants were affected by the experience. M4 explicitly mentioned being shaken by the experience and confessed *"I did not expect to feel like this, I'm not well. I did not expect to feel unwell"* and also said feeling "feverish". Although it could vary in intensity, all participants showed signs of affect during the interviews. We were able to identify a wide range of emotions.

A range of expected emotions As people face data about femicides, it is expected to witness some specific emotions such as shock, dismay, inability to understand, sadness, and anger. We were able to extract the lexical fields of these various emotions and integrated them into Table 4.2.

Unfairness Several participants also expressed a feeling of unfairness which was often paired with anger. M2 mentioned *"all those wasted lives"* and F9 said that *"people are exterminated for absurd reasons"*. F7 also expressed this feeling while questioning *"it's not fair, why? why so many?"* and claiming that the victims *"got unfairly killed, because in any case, it is unfair"*.

Helplessness Two participants (M5, F11) also mentioned feeling helpless while exploring the visualization, which could induce a feeling of frustration. M5 said *"I can't do anything about it"* and F11 shared that they *"felt like being a spectator and not being able to do anything to help"*.

Emotion	Lexical field
Horror and shock	"shocking" (F1, M2, M12), "dreadful" (F10), "horrifying" (F1, M2), "leave a mark" (M2), "atrocious" (F10), "terrible" (F7), "chills to the bones" (M12), "harsh" (M4), "it shakes up" (F10), "suffocating" (F11), "speechless" (F11), "striking" (M3)
Sadness	"moving" (F11), "sad" (F7, F9), "emptiness" (F9), "harrowing" (F7)
Feeling of dismay, Inability to understand	"staggering" (F10), "disturbing" (F10), "hard to imagine" (M4), "not conceivable" (F7), "it makes no sense" (M2), "feeling of incomprehension" (M2), "insane" (M2)
Anger	"disdain" (M12), "disgust" (M12), "degenerate" (M5), "It irritates me" (F7) "It gets on my nerves" (F7)

Table 4.2: Lexical fields of expected emotions extracted from the interviews

Regret and guilt One interesting reaction we noticed from two participants was a feeling of regret or guilt. M5 felt relieved knowing that there wasn't any femicide near the place they lived, yet they felt guilty about it and claimed *"I'm so selfish! [...] My first reaction is to check if it's near my home. Phew! It isn't."* F1 regretted not being able to look at all the victims one by one, their feelings reminded us of the process of paying tribute, or pilgrimage mentioned by M12. F1 said *"I wish I stayed longer to look at them all. [...] They all equally deserved that I look at them."* This feeling of equal importance for all victims was actually shared by several participants (F1, M3, F10, M12). For instance, as M3 explained why he explored the graph sorted by date rather than age or cause, he shared that he would not *"sort people by age like this one is important and this one isn't important"*.

Facilitating perspective-taking

As the participants were immersed among the avatars, some of them felt closer to the victims and the subject of femicide despite the fact that they did not feel directly concerned with their personal lives. M12 used the expression *"Out*

of sight, our of mind" to explain the phenomenon. While looking at a graph, they do not see the victims, however, looking at avatars and individuals reminded them of the humans behind the graph. For instance, M3 explained *"considering that I and my entourage are not really affected by the subject, it makes it more real"* and it reminded him that *"It is not a distant issue, we need to be aware of that"*. M4 shared how exploring the visualization influenced his perception of the government's report and explained *"I understand a bit better the numbers in my flesh, rather than if I had just read [the report]. If I had just read the report, well it would have been a report because I do not know any femicide in my entourage"*.

As the participants got emotionally closer to the victims, they were able to project themselves. However, the way the participants would project themselves would vary. Some participants would put themselves in the victims' shoes or connect through the similarities they identified between the victims and their personal life or their relatives. Participants would mostly compare with the age of the victims or the city they died in. F1 for instance said *"She was 23, I thought it's my age"* and M5 explained that while he explored the visualization, *"Every time I really wanted to check if these were cities I knew"*. F7 also compared the age indicator and explained that *"of all age you can think of your mother, your grandmother, a cousin"*, and that *"the ages are really harrowing because there are people who are my age so inevitably you put yourself in their shoes"*.

Yet, adopting such a personal point of view was not always the case and some participants rather adopted a third-person point of view, becoming a spectator to the scene that appeared in their mind. M12 explained that he *"imagines the murder"*, and F11 shared her feeling about the 360° view, *"we were where they got killed, it really felt like being part of the scene"*. M4's testimony shows that adopting a third-person point of view can be just as striking, *"we always see the man from above with a knife and the woman, scared and tiny below. It's really graphic"*.

A third point of view was sometimes adopted by the participants. Some of them actually projected themselves in place of the femicides' authors. This phenomenon usually indicated an attempt to understand what happened, mostly because it seemed inconceivable to them as M3 explained *"I did put myself a little bit into the killer's mind, to try to better understand"*. M2 imagined the killer's actions and shared *"we really imagine their partner or ex-partner going to the kitchen to get a knife"*. M3 tried to imagine the authors' state of mind and thought that for some causes of death, *"It means you really want to make her suffer"*. This projection could sometimes be really graphic, M4 tried to imagine and said *"It takes a long time, you see the person burn, I don't know... Do you have the reflex to try to extinguish the fire, or do you watch her burn?"*. Two participants actually wondered if they could actually become the author of a femicide, M4 shared *"I*

think, wait, would I be capable of doing that in 40 years? And I think no, it's not me" and F7 explained that "you try to imagine yourself in this situation and you think to yourself would I also be able, in a fit of rage, to catch a knife and actually kill someone? But it's really hard".

4.5.3 The impact of immersion

Although the feelings and empathy that the participants felt cannot entirely be imputed to the effect of immersion, we believed that being immersed among the avatars and the 360° view contributed to these feelings. Some other effects of the visualization can be more easily related to immersion.

Beyond numbers

We believe the effects mentioned in the section below to be the result of combining both immersion and individualized data.

The sense of reality and concreteness As the participants are immersed in the avatars and the 360° view, they get a feeling of reality. These immersive scenes bring concreteness to the data and the humanitarian phenomenon depicted, the femicides in this case. It therefore helps the audience grasp the reality of the phenomenon. The sense of reality was emphasized by several participants, F1 claimed that *"we better realize when it is real people rather than cubes"*, M4 felt like *"the 3D effect puts you in the middle of them"*, and M6 mentioned the effect of the 360° view, *"It settles us even more into reality. We really are in a real place in France where it happened"* and said that this stage was *"the more concrete"*.

Humanizing the data Adding personal information on the victims can also contribute to adding concreteness to the data. F1 shared that *"It is worse when we know her age and see where she died, it feels like we get a little into her life for two seconds. We realize more."* Moreover, as the immersion amplifies the sense of reality, it also humanizes the data, which actually are not only data but victims. The participants feel like watching humans rather than numbers, or data points. As M12 mentioned *"It no longer is a statistic, it is an individual"*. Some participants really emphasized this feeling of walking among real people. M4 said *"I really was among these women who got murdered"* and F7 shared *"I saw the avatars, I saw people. I was able to imagine the life they had. Well, the life that they had or won't have."*

Interestingly, M12 shared that humanizing the data can also compensate for the lack of consideration we could have for outliers: *"On one side, when they are in little on the graph, well, there are outliers. And indeed that's what it is. But*

when we suddenly transpose ourselves with an individual [...] we do not perceive it the same way. On the contrary, it is almost a person we have a bond with." He shared that being alone with the victim's avatar as they are alone in a column, made them even more real and important.

Four participants (F1, M2, M4, M5) also mentioned the fact that seeing real photos of the victims next to the avatars emphasized the sense of reality. For instance, F1 said that *"These are real women. To see their faces of 25 years old, it's terrible"*.

A reminder of death As the avatars impersonate dead women, the visualization can also be perceived as macabre. Three participants (M2, F9, M12) made explicit and striking comparisons. For M12, this feeling of death started even before being immersed in the avatars as he compared the vertical avatar visualization to a "stack of cadavers". M2 and M12 compared walking among the avatar to a walk in a cemetery. M2 claimed that *"You literally feel like being in a cemetery"* and M12 shared that he *"felt a little like being in a cemetery and you pay tribute to each person"* and M12 also felt like *"You shouldn't make noise"*. When exploring the 360° views, M12 had a slightly different feeling and rather compared it to *"a pilgrimage, you come to commemorate on the place"*. F9 also shared *"I felt like when I visited a concentration camp, in a place of death"*.

The benefits of virtual reality beyond empathy

The points above, mostly praise the use of immersion to raise empathy, however, the capacity of VR to better raise empathy is still discussed [50] and since we did not compare our visualization with a 2D desktop version, we cannot be certain that the same effect would not be observed. However, participants mentioned several other benefits that virtual reality has to offer.

The novelty effect First of all, virtual reality still benefits from a novelty effect. Therefore, its innovative aspect can make it more attractive to the audience than traditional visualizations. This was pointed out by M2, *"It could be a good experience because we think a VR headset, it's not common [...] and since it's surprising, people are curious and they could come"*. Moreover, beyond the interest in the technology itself, it allows us, designers, to introduce new ways of representing the data. The audience can be more eager to explore a type of visualization that is new to them rather than something they have already seen a thousand times. F11 stated *"it brings the graphs up-to-date"*. Yet, this novelty effect is meant to fade over time and thus we should not praise the use of virtual reality based on this only benefit.

An environment deprived of distraction Some participants mentioned the fact that being fully immersed in the visualization helped them fully dive into the data. F10 and M3 explained how being in virtual reality made them forget about the external world. F10 shared feeling *"like being submerged by the avatars, the visualization"* and told us *"I kind of lost the sense of reality, that I was in a scientific VR study"*. Similarly, M3 said *"being isolated in your space. Every time I took off the headset I thought oh yes, true, I'm in this box"*. F7 and M4 also explained how being in VR helped them stay focused on the visualization. Indeed the immersion provided by virtual reality tends to block out distractions. F7 explained *"we're really in immersion so it's great because you're focused on what you do, what you're looking at"*. M4 actually compared this experience to the context in which one usually looks at information and data on a subject, *"You're not in front of a screen, or an article on your phone in the streetcar with the ads above where you can swipe. Here you're in the middle of people"*.

The perception of number As the participants get immersed in the middle of the avatars, they get a visceral understanding of the number of victims. 100 points is different from 100 people. They no longer perceive a cloud of points but a crowd of people. F11 explained that with *"the crowd at the end makes you realize the extent of the number of femicides"*, and F8 shared having a *"feeling of droves when you get in the middle [of the avatars]"*.

Memorization Three participants (M6, F8, F11) mentioned that this immersive visualization can help better remember the data. For instance, F11 claimed that they *"remembered almost everything that happened [in the visualization]"*. Although the interviews seem to show that participants do not especially remember specific data such as names, we believe that being immersed in the data can make a bigger impression on the participants than more traditional visualization. Therefore, even if they do not better remember precise data, they are probably more likely to remember the order of magnitude as well as the experience itself.

4.5.4 The benefits of using semantic zoom

This visualization concept is inspired by the concept of semantic zoom. We did not explain the concept of semantic zoom to the participants and did not use this term during the interviews, however, we used the term "zoom" for the interviews. Thus, several participants shared with us the benefits they perceived from this zooming interaction.

From an overview to the individual

First of all, the semantic zoom allows the participants to transition from an overview of the data to a detailed and immersive view of each individual. The overview allows the participants to get global knowledge on the topic, and get a quantitative and rational understanding of the data. The individual view helps them comprehend on a more visceral level, the human behind the data and get more information on specific parts of the visualization. F7 *"found it well done, starting from a large scale and then scaling down progressively"*. F10 shared that the graph *"allows you to comprehend the information as a whole and then you can easily target where you want to go"*. According to M12, starting from the overview also influenced his perception of the individual level, as *"you end up next to one, two or a few people. But you know there are more around. Since you zoomed before, you know a little, you're aware of how many people are around"*.

A gradual process

The immersion is gradual which not only prepares and warns the participants about getting closer to the individual. F1 explained that she *"didn't directly go from a big graph to the avatars, like being directly immersed in the avatars [...] I was prepared progressively"*. M4 shared his impression on this gradual process, *"First you prepared me, you gave me numbers like a rational man who reads an article. [...] and progressively you immersed me, and you talked to my emotions"*. He actually used a striking analogy and compared the experience to *"[putting] a frog in warm water and you slowly heat it"*. Moreover, this participant believed that *"if [we] had brought the avatars first, it wouldn't have worked. Here, [we] brought it progressively"*.

The freedom of exploration

This gradual process has another benefit which is that it allows the participants to stop whenever they get too close. Participants appreciated the fact that they could explore further the section of interest for them. They can choose to explore a section of the visualization rather than another. F10 explained *"We go directly where we want to. I mean, we see a piece of information we find interesting, we can directly target where to go and then move to look at something else, the information next to it."* Moreover, they can also choose not to explore a specific section if it is too emotionally heavy for them which is a point F8 elaborated on, *"You can look at what you want. If there is something that you don't want to see, you can choose not to go look at it. [...] You can keep your distance which allows you not to look at the photos, not to look at the age"*, and she explained that it allows her to *"have various reading levels and get more or less involved"*.

4.5.5 Positive impact and feedback

Using the visualization to raise awareness

Participants thought this kind of visualization was a good way of raising awareness. F9 stated that *"it's a great way to raise awareness. It speaks for itself. It humanizes the acts"* and F10 shared that *"if we want people to react, and if we want them to be fully aware of what's happening and of the extent of the issue, I think it's perfect because it shakes us to see that"*. M2 and F7 thought that *"more people should do this kind of experience"* (F7). F10 thought we *"should give it to the family planning for whenever they speak in middle schools or high schools"* and asked if the project was meant to be used outside the scope of research.

This kind of visualization could also have a direct impact on possible victims. During the interview, F9 shared that she would talk about this experience to a friend she is worried about and said *it moves me a lot because she could become another statistic*. She also took the government's report and planned to share it with a friend who she thought tended to diminish the extent of the issue.

A good experience for the participants

We got many positive feedback on various aspects of the visualization. M6, F10 and M12 explicitly expressed that they were pleased with this visualization experience and five participants (F1, M3, F7, F9, M12) shared that they thought it was important or good to create and provide this kind of visualization.

Regarding the content and choice of representation in the visualization, F1 felt like the visualization had the right balance in terms of shock for the participants and explained that *"we are shocked in the sense that we think that this person really died and it's horrible, but not shocked in the sense that we did not see any atrocious picture and are about to have nightmares about it"*. M3 also thought that despite the fact that the visualization can be somehow morbid, *"it might be necessary"*. And he compared it to war documentaries, *"it's a little bit like when you are shown pictures of a conflict or cities that got bombed for instance. It feels a little bit the same. You don't want to see it but maybe it is necessary."*

4.5.6 Limitations

The concept's limitations

The limit with the morbid and voyeurism Although participants did not think that the visualization was inappropriate, they used adjectives such as *"gloomy"* (F1, M4, M5), *"macabre"* (M12), *"morbid"* (M3), *"intrusive"* (F10), and *"voyeurism"* (M4, M5) to describe their feeling during the visualization. As mentioned be-

fore, this kind of feeling can be perceived as normal and necessary when raising awareness about human crisis, yet it is important to keep in mind that there is a thin ethical line that should not be crossed. We believe it is important to always evaluate the relevance of each piece of information and representations in the visualization. In our case, the 360° view was probably perceived as the most intrusive by our participants. We chose to share this scene because we believe that it shows the participants that it can happen anywhere. Yet, it might actually be right before the ethical limit we mentioned and we would not recommend to go further. Indeed, we caught a glimpse of a possible negative impact of going too far in voyeurism through M4's interview. M4 shared that the immersive 360° view felt somehow entertaining, *"I changed from [...] it's horrible, to something more entertaining, voyeuristic. [...] Will I be able to watch a video of the murder, a replication? [...] I turned to the playful, entertaining aspects and it could be nice to see how they got killed. You enter a game where the scientific police come to exchange with you"*. M4 projected to this possible scenario as he anticipated how to possibly zoom further into the data. We thus believe that while designing such a visualization it is important not to slip into entertaining morbidity. Yet, from one person to another, the boundary might be different. For instance, F10 did not explore 360° views other than the one we asked them to look at, because she *"felt intrusive to look at where these women died"*.

The drawbacks of freedom of exploration Therefore, as the audience's sensibility can vary from one person to another, we believe that exploring this kind of visualization should be based on willingness and the exploration itself should observe the user's personal boundaries. Yet, such freedom has drawbacks.

Although the theme of femicides is used as an example, this visualization is meant for humanitarian data and thus sensitive and often violent subjects that can scare the audience. Some participants confided that they were apprehensive about what they were about to see. F1 *"did not know how [we] could handle it so it is shocking but not too violent for the user"*. M2, F7 and F9 also admitted being anxious before their participation. One participant also mentioned that some people around him chose not to volunteer to the experiment because they were worried about the content of the visualization.

Even among the people who choose to explore the visualization, the exploration will most likely not be exhaustive. First, some participants chose not to explore certain sections of the visualization either because they wouldn't see an interest in it, or because they wanted to protect themselves from the data and the emotional impact it could have on them. At first, M12 chose not to explore the graph exposing the causes of death because it felt *"too violent"* to begin with. M5 chose not to look too much at the victims' pictures because *"it reminded me of someone"*.

So I was like stop [...] let's stop making associations". Similarly, he chose not to explore the 360° views as he was worried he could recognize some locations and thought that *"it's just a piece of information which is just about to create some sort of [emotional] overload, and there's nothing you can do"*. Similarly, M6 and F10 chose not to explore the 360° views for the same reasons. Another possible effect is an anticipated end to the exploration. F9 chose to stop the exploration when she saw a 14-year-old victim which is her daughter's age.

Even though the audience would not consciously choose to avoid a section of the visualization, exploring each avatar one by one and all the filters takes a long time. Thus the exploration will most likely not be exhaustive which means that it can have a very different impact from one participant to another. The two main purposes of the visualization are to have an emotional impact and to learn from the data. Although the emotional responses might vary from one participant to another, avoidance behavior and early exit might not be such an inconvenience as we could consider that these behaviors are indicators of an already existing emotional response to the subject.

Regarding the learning benefits of this visualization, such freedom involves that the learning experience of each participant can be different. Storytelling could eventually be used as a solution, to better guide the participants through the data. Actually, M3 perceived a story through the zooming experience and *"liked the fact that it tells a story"*. Storytelling could also help with some of the participants' frustration who wish to learn more and get more explanation. M12 also saw a story through the data, *"when you zoom in, you end up in front of a person and next to them you have information on the cause of death [...] it creates a story"* and he really insisted on the importance of stories for him, *"I think that data visualization graphs only have an interest as part of a story. And [the graph by date] lack a story so I look for stories to tell myself"*.

VR limitations

The first limitation to the use of virtual reality is the physical and mental fatigue it induces. The most common side effect is motion sickness, yet headaches and eye strain should also be taken into consideration. M6 and M12 admitted feeling a bit nauseous at the end of the experience and F1 had a bit of a headache, probably due to the weight or pressure of the headset on the head. Thus, we should keep in mind that such virtual experiences should not be meant to last too long. Moreover, beyond the physical and mental fatigue due to the technology itself, a long-lasting experience might be emotionally too overwhelming for the participants.

A second limitation of this kind of visualization is the lack of accessibility of the technology. Although it might vary from one country to another, people are unlikely to own a VR headset at home. This kind of visualization can thus

only be experienced during specific events like awareness-raising actions. This accessibility disadvantage was mentioned by four participants (M2, M6, F10, M12). F10 explained that "the visualization is interesting provided that you have the equipment and know how to use it, etc. And it is costly and therefore not accessible to all".

Our design's limitations

Finally, we here share some of our design's limitations. These limitations are presented in a separate section as they are not inherent to the concept we introduce but rather to our design choices.

The lack of ordinate axis First of all, we chose not to include an ordinate axis in the first step of our visualization so the first phase to provide information about the proportions and distribution and the second step, with the cubes, would provide a piece of additional information which is the number of individuals. Retrospectively, we would advise including an ordinate axis from the beginning, as several participants had difficulties extracting meaningful information from the graph without knowing the approximate number of individuals. For instance, M2 explained that *"it wasn't really indicative because you didn't have the numbers"*. Moreover, this ordinate axis could also prove itself useful in the cube stage as it would help the participants estimate the total number of cubes. We asked the participant to roughly estimate the number of cubes and noticed a great variability in the answers. There were 113 cubes in total, and the participants' estimations varied from 50 to 200 (Mean=125; SD=54).

Transition inducing motion sickness To transition from a graphical view to a human-sized immersive view in the middle of the avatars, we chose to make the visualization tip over in a horizontal position and translate under the user's feet. For this transition, we inspired ourselves from one of the Google Earth VR's transition ¹². We favored this transition over teleportation to avoid confusion and disorientation. Although we made sure to have gradual acceleration and deceleration, it did induce some motion sickness or slight imbalance in some participants which might have been an impediment to going back and forth between the graph and the immersive stages. Although it might not stem from this motion sickness effect, we noticed that only seven of the 12 participants went back at least once to the first stage of the visualization during the free exploration stage or the experiment.

¹²https://store.steampowered.com/app/348250/Google_Earth_VR/

The impact of limited resources We noticed that the limitations of our resources had some impact on the participants' experience. The avatars we used were not created from the victims' pictures. They came from various libraries and were manually paired with the victims' pictures to make them match as much as possible. Moreover, we weren't able to have a unique avatar for each victim and some redundancy could appear. If the participants asked about the avatars during the experiment, we chose to be honest regarding our process and as a result M3 completely lost interest in the avatars, *"knowing that the avatars weren't representative, it made me stop looking at them. If I had seen the real face, I think it would have been a lot more striking"*.

4.6 Discussion

4.6.1 Introducing the human behind the data

The main purpose of the visualization we introduce today is to introduce the human beings behind the data. We wish to help the audience realize that behind every single data point, there is a human being, a whole person just like them. As a proof of concept, we introduced two use cases on two human crises in Section 4.3. However, our proof of concept is limited by the data available to us. The data we used did not include a lot of details on the individuals themselves. In the case of the femicides, we used the data shared by the collective *Féminicide par compagnons ou ex*. Besides the name and age of the victims, the data we have is mostly related to the femicide itself (date, cause of death, and place). Although our visualization tries to make sure they are not *"just a number"*, we should also make sure that they do not become *"a number of stab wounds"* as Sarah Barukh mentioned in a radio interview ¹³. Sarah Barukh is a writer who wrote the book *125 et des milliers* [13] (*125 and thousands*) in which she asked 125 women to write and tell the story of 125 women who died from femicides. The purpose of this book is to tell who the victims were, as women, beyond their status of victim. Thus, we believe it would be interesting to investigate the impact of our visualization with more personal data on the victims. In the first steps of the visualization, we could depict general data on the crisis (here the femicides), and as the audience zooms in, the information on the victims becomes more personal (e.g.: their job, what they liked, how many children they had...).

¹³https://www.francetvinfo.fr/replay-radio/info-medias/vivante-s-sur-canal-un-mode-d-emploi-pour-les-victimes-de-violences-conjugales_6376186.html

4.6.2 Collecting meaningful and humanizing data

Telling the story of each victim implies an important and thorough data collection process. As we explored various topics to introduce our use cases, we noticed that the anonymization, aggregation, and invisibilization of the victims obstruct the process of humanizing the victims.

In their study, D’Ignazio et al. [62] explain how official organizations tend not to keep count of femicides or underestimate the extent of the phenomenon. In their paper, they introduce the challenges faced by collectives and organizations to collect data on femicides.

The challenge of collecting missing data is not specific to the issue of femicides and data collection often falls to collectives or artists. Through collaborations, the data presented in the visualization could gain in relevance and power. For instance, we believe that the data collected by Sarah Barukh or Jen Brockman and Dr. Mary Wyandt-Hiebert (the *What were you wearing* exhibit) required a lot of investigation but would be really relevant for the visualization we introduce in this chapter.

4.6.3 Evaluating the impact of the visualization

In this study, we collected qualitative feedback from 12 participants through semi-structured interviews. The goal of these interviews was to highlight the strengths and weaknesses of our visualization.

However, we chose not to conduct a quantitative or a comparative study for this first stage. One possible comparative study would be to compare the impact of a traditional visualization (such as the government report on femicides), a documentary on the topic and our visualization. To do so, participants could be split into three groups and introduced to one of the three conditions. We could then measure right after the exposure the emotional impact as well as the rational understanding and memorization of the data. Yet, the nature of each condition is quite different and could somehow bias the results. Indeed, when reading graphs about a subject in a scientific experiment, the participants are more likely to expect to be interrogated on the data later and after watching a documentary, they are more likely to know that an emotional response is expected from them. Therefore, we believe that a posterior study, several weeks after exploring the conditions could be relevant. We could then not only measure the information they memorized but also ask them if the participants feel like they are paying more attention to the subject in the media (for instance the femicides related in the press).

4.6.4 The visualization as a way to learn

We also introduced this visualization as a way to learn about a human crisis, not only from the graphical visualization in the first stage but also from the context the immersive scenes can provide. For instance, we believe this kind of visualization can help fight against the audience's bias (e.g.: femicides only happen in specific areas).

The third use case (Section 4.3.3) illustrated the fact that this visualization could be used beyond the scope of humanitarian data. We also believe that it could be used for the sole purpose of understanding and learning from contextualized immersive data. The data depicted could for instance be the data of video games, more specifically failures. In the immersive scene, the users could be projected in the exact spot where the player of a game lost which could help them better understand and analyze the context and the potential hazards of the scene. Through the exploration of the immersive scene, they could also identify some similarities in the contexts of failures, such as a distraction in the scene.

However, we shall remain aware of the possible misconceptions and misinterpretations that the audience could build out of this visualization. As mentioned in Section 4.5.6, if the audience does not explore all the immersive visualization, they might only visualize a non-representative sub-group and thus draw the wrong conclusions.

Misinterpretations of data can arise from various issues [34]. Of course, a bad design or non-representative data can mislead the audience. Misinterpretation can also stem from a lack of expertise in data analysis, which is likely to happen as the public we target is the general public. One issue with data, is that *"we read too much into them or see in them what we want to believe"* [34]. As we face data that we do not understand, we often feel the need to explain the data [102], even though it might only be speculations. This phenomenon appeared during our user study, the participants felt the need to explain the variation in the distribution of femicides over time, age, or cause.

4.6.5 Using storytelling

In Chapter 2, we mentioned the benefits of storytelling for educating and raising awareness. Adding storytelling components to the visualization could not only decrease the risks of misinterpretations of the data, but also favor the audience's engagement.

Data-driven storytelling is a technique used to help non-experts make sense of data and convey an interpretation of these data. Data-driven storytelling thus appears appealing for our visualization as it not only prevents the audience from misinterpreting the data as the story is based on data, but the story-telling com-

ponent also engages the users in the topic of humanitarian data and favors an emotional response.

4.6.6 Our prototype’s limitations

We mentioned in our results, in Section 4.5.6 some of our design’s limitations. We here wish to discuss one limitation we had to face when implementing the prototype and designing use cases, which is the required processing power to generate all avatars. Indeed, generating dozens of avatars required a lot of processing power, especially with avatars which can be very complex. Although we used levels of detail to render the avatars, it did not allow us to display large samples of avatars (e.g.: 500 avatars).

A first possible solution would be to only render the avatar of the targeted section during the zoom process. For instance, as the user zooms in on the category of the 20-30-year-old victims, only this bar will be rendered. This solution has both benefits and drawbacks. On one side, it could help the user focus on the victims they targeted and help individualize the victims as they would not be lost in a mass of avatars. On the other side, we would lose this effect of mass, and visceral comprehension of the extent of the phenomenon.

A second avenue to explore is the use of Unity’s Data Oriented Technology Stack¹⁴ (DOTS). The use of an Entity Component System (ECS) seems promising to allow high performances and the rendering of large amounts of avatars. Yet, this is a new paradigm of writing code that requires entirely redesigning the code.

4.7 Conclusion

In this chapter, we investigated how virtual reality can be used in data visualization to engage the audience. We propose a new type of visualization that bridges the gap between quantitative abstract visualization and qualitative individual stories. Our user study suggests that our visualization managed to both engage participants on an emotional level and arouse their curiosity on the subject.

The edition of the visualization for a new dataset is made possible for non-developers through a customized inspector. Although they can personalize the content such as the filters, the text, and the avatars, we consider this visualization as lowly customizable. Indeed, the structure of the visualization remains the same. Enabling a higher level of customization, especially in the more immersed stages of the visualization might lead to more engaging experiences.

¹⁴<https://unity.com/dots>

Chapter 5

Authoring Interactive and Immersive Experiences Using Programming by Demonstration

The use of immersive technologies in educational and cultural contexts is rising [39, 190]. Thanks to virtual reality, users can live experiences that would be too far in space or time, or too abstract to be experienced in reality. Such technology also supports active learning and engagement [75].

In Chapter 4, we demonstrate how immersive visualizations can be used to educate and raise awareness. Such visualizations are often designed by HCI experts and developers and involving experts on the topic in the design process is not always an option. When experts on the topic are actually involved, it is often limited to feedback sessions and they are rarely primary decision-makers in the design process. Yet, educators and cultural mediators benefit from their expertise in their own domain to design relevant VR experiences. In 2019, the Louvre's curators team and VR developers collaborated to create "Mona Lisa: Beyond the Glass"¹, an immersive and interactive scene in which the Louvre's visitors get the opportunity to closer analyze the painting, explore it through different angles and vision techniques. Strengthened by the cultural and artistic knowledge of curators and the coding skills of developers, they proposed a unique experience by giving life to the painting.

To create such immersive VR experiences, non-technical experts need to rely on developers in the early stages of prototyping. This dependency can hinder the design process and slows the emergence of new projects [7]. Enabling VR authoring to non-developers is therefore an opportunity to support the expansion

¹https://store.steampowered.com/app/1172310/Mona_Lisa_Beyond_The_Glass/?l=french

of VR. Although many tools are available for static immersive prototyping and animation editing [115], authoring tools for interactive experiences are not yet available to end-users.

Interactive prototypes help designers envision the type of interactions that would work in a specific context, and they support the discovery of design flaws through unexpected behaviors from users. However, to author such interactive prototypes without code is still an open research question. Various methods have been investigated such as simplified desktop interfaces [217], visual programming [219], and authoring by demonstration [205, 18, 148].

Immersive authoring by demonstration appears as a promising way of creation as users directly visualize the outcome of their actions and create the interaction with the first-person point of view inside the context. However, it raises several design challenges that have not been studied yet. Such investigation would help in the design of more adapted and more accessible authoring tools.

Such tools would support the edition of visualizations by non-experts. As a first step toward this direction, we focus in this chapter on general interactive experiences rather than (data) visualizations and propose a tool for the interactive creation of immersive experiences to investigate the challenges in this domain. Building upon two interactive experiences authored using our tool, and a user study, we introduce five challenges and future research questions for immersive VR authoring by demonstration. The goal of this chapter is not to compare and promote the use of programming by demonstration over other methods such as visual programming, but rather to explore its use and identify its challenges in both the conception and use stages.

Main portions of this chapter were previously published ² in:

[44] Edwige Chauvergne, Martin Hachet, and Arnaud Prouzeau. Authoring interactive and immersive experiences using programming by demonstration. In *Proceedings of the 34th Conference on l'Interaction Humain-Machine*, pages 1–13, 2023.

5.1 Related work

In their study, Ashtari et al. [7] interviewed end-user developers to tackle the current practices and challenges of AR/VR authoring. They noticed that many non-developer AR/VR creators use complex authoring tools such as Unity³ and therefore face many challenges including searching for resources, debugging, and testing. Nebeling et al. [147] studied augmented and virtual reality authoring

²Thus any use of “we” in this chapter refers to me, Martin Hachet, and Arnaud Prouzeau.

³<https://unity.com/>

tools, and they identified a gap in high-fidelity tools requiring a low level of technical skills. Enabling programming to non-developers is a common concern in research and several methods have been explored to make it more graphical and less abstract.

5.1.1 Authoring immersive application

To allow end-users to participate in the authoring of immersive applications throughout the design phase is essential to identify design flaws in an early stage, get feedback for an iterative design process and improve the design before reaching the costly implementation stage. A common basic prototyping technique is paper prototyping. This technique is fast and efficient for 2D interactions. Yet, as AR and VR evolve in a three-dimensional space and are usually dynamic, conveying ideas through paper is more challenging. With 360Proto [145], Nebeling and Madier generate a 360° AR/VR prototype from paper which gives a more realistic preview of the final experience.

To help users get a better understanding of the final product, it is possible to use videos that are more dynamic or technologies closer to the final product. Burns et al. [33] suggest combining informance design and video prototyping. This method allowed them to identify design flaws during the prototype creation and get feedback from a large audience as they shared the video. Researchers also focused on solutions that rely on technologies similar to the final device, and explore the use of real AR and VR for prototyping. DART [130] is a desktop AR prototyping tool that allows 3D dynamic storyboarding. With VREUD [217], Yigitbas et al. proposed a desktop authoring interface with a low entry barrier. Using VREUD users can edit the scene, event-based interactions, and tasks. Such a solution benefits from the accuracy of the desktop, yet, it forces users to code out of context and to go back and forth between the desktop and the HMD while testing and debugging. With ProtoAR [146], Nebeling et al. facilitate the creation of virtual props using tangible Play-Doh props. Similarly, SpatialProto [143] enables immersive spatial prototyping by recording animation using physical props.

5.1.2 Authoring in immersive environments

Oulasvirta et al. [151] discuss the benefits of designing in the original context or an environment similar to it. Such practice helps designers better understand the context and be aware of it during the design phase. As designers do not rely on their memory, their mental model of the context is more reliable. With Reality Editor [89], users can edit the behavior of smart tangible objects in AR. MARVist [47] and DXR [177] allow their users to edit visualization directly in the context it will be experienced which facilitates previewing the final result. Ens

et al. implemented Ivy [68] a VR spatially situated visual programming tool for understanding data flows and connections between smart objects. As the original context is not always accessible or available, the authoring can also occur in a reproduction of the original context. It allows in-context remote authoring. Using CAVE-AR [40], users can simulate and debug AR experiences from a VR CAVE. In DistanciAR [207] and Corsican Twin [161] users author the AR experience in a virtual scan of the place. Thus, authoring in context supports the users' awareness of the final environment during the authoring process. Beyond being in context, in this chapter we investigate how the user can interact with this context to author interactions.

In immersive environments, users can more naturally interact with virtual objects thanks to direct manipulation. Lee et al. introduce this concept as WYXI-WYG (*What You eXperience Is What You Get*) [121] which describes the benefits of immersive authoring. With VR Safari Park [92], Ichikawa et al. illustrate the ease with which users can edit a virtual environment using direct manipulation. Suzuki et al. introduce RealitySketch [187], an authoring tool for AR interactive graphics and visualizations. Interactions can be created by manipulating the virtual objects and directly linking triggers and actions attached to these objects as demonstrated by Vargas González et al. [199]. LevelEd VR [18] is a VR level editor in which users can create and edit virtual objects and visually script the game conditions. VRFromX [?] and Ng et al.'s system [148] enable the edition of virtual objects and making them interactive by creating and connecting triggers and actions.

Most of the examples previously mentioned allow users to author using direct manipulation, however, it only allows, most of the time, to design applications with simple interactions. To prototype more complex interactions, some researchers proposed to use *Visual Scripting*, a programming method allowing its users to code by manipulating and assembling graphical programming elements instead of textual coding. It is used in FlowMatic [219], an immersed visual scripting tool. It allows its users to directly script interaction in the virtual environment and to benefit from authoring in context. Another method, more accessible to non-programmers, is to use demonstration to define an interaction.

5.1.3 Authoring by demonstration

Programming by demonstration has been developed to allow end-users to easily specify an expected behavior to the machine (robot or computer) by simply demonstrating it. Programming by demonstration differs from other programming methods during the authoring phase rather than during its visualization. While programming by demonstration users directly manipulate objects, they need less fundamental knowledge and do not have to learn and use the textual primitives

that are usually used with classical visual programming, which decreases the accessibility level. However, its visualization can either be textual with the demonstration being translated to code, or it can be more visual. In that case, after the authoring phase, the results of programming by demonstration can be considered as visual programming.

Saket et al.'s system [171] analyses the users' actions to extract their intent and deduce the expected behavior. The analysis can either rely on one example of the event like AREDA [20], an authoring tool for AR assembly instructions, or on several examples of the expected behavior. Relying on several demonstrations helps the system generalize a behavior and manage individual variations. Gesture Studio [129] as well as Hartmann et al.'s system [84] rely on multiple examples to generalize an interaction.

The rising availability of VR and AR equipment, as well as the increasing power of such devices, has allowed the exploration of VR/AR authoring by demonstration. Immersive VR demonstration has been explored for intuitive animation editing. In their paper, Arora et al. [6] study the use of mid-air hand gestures for the authoring of complex animations like particle behavior. Tvor⁴ is a commercialized tool that allows VR film-making through demonstration. Rapido [125] uses a similar combination of demonstration and interfaces comparable to video editing interfaces to turn video prototypes of AR experience into executable state machines that simulate interactions on tablet.

Demonstration is not only meant to specify the users' behavior but also the elements they interact with. In GhostAR [36], a human-robot interaction authoring tool, users not only demonstrate the users' actions but also the robot's reaction. Lécuyer et al. [118] explore the use of demonstration for authoring a scenario-based training experience. The scenario is demonstrated directly in VR and is then edited on a desktop interface. With AffordIt! [133], Masnadi et al. fully immersed the authoring of affordances. Users directly cut into the virtual meshes and manipulate them to specify the affordances, for instance, users can cut a circle into the mesh of a washing machine to make a door that can be opened. With GesturAR [205], Wang et al. introduce a freehand interaction authoring tool. Users can create either dynamic or static interactions and behaviors that can also be either discrete or continuous. However, the system only allows linking triggers and actions and does not support more complex authoring such as chains or delays.

Through this state of the art, we notice that authoring by demonstration has been explored before, yet the expressivity and power of the tools remain limited. They do not enable the authoring of complex interactions. The studies mentioned above focus on specific issues such as the use of hand gestures for demonstra-

⁴<https://tvori.co/>

tion [205, 6]. As they do not investigate the authoring of complex interactive experiences, they do not discuss the main challenges that need to be studied and overcome to allow immersive authoring by demonstration of complex interactions. Thus, we decided to design, implement and test an authoring tool for interactive experiences in order to better identify the challenges in both the design phase and the tool adoption.

5.2 System overview

In order to identify the challenges while designing and using interaction authoring tools, we implemented and tested a VR authoring tool based on demonstration. In this section, we introduce a simple framework for authoring interactions, present our prototype and share the implementation details of our prototype.

5.2.1 Framework

To illustrate the different concepts exposed here, we will consider a very simple interactive system: a virtual room with a white cube floating in the air at eyes level. There is a table in the middle of the room with a big button on top of it with the label "Change color" on it. Our user, Alice, is at the beginning standing idle in front of the table.

In an interactive system, users can act on the virtual scene and modify some of its entities using interactions. It means that, for our scene to be interactive, Alice should be able to modify the cubes around her: move them, remove them, change their color, etc. According to Yigitbas et al. [217], an interaction can be defined as an event that acts as the trigger and an effect that defines the modification done on the virtual scene. A basic interaction in our scene could be that when Alice presses the big button (**trigger**), the cube becomes blue (**effect**). Conditions can be added to the interactions. For instance, we could add as a condition that the button should be pressed with the left hand and not the right one.

To author an interaction, Alice would have to define an action that would act as a trigger, define an action that would be the effect of the interaction, and link both to show that one provokes the other. There are multiple ways to define these actions to the system, it could be programmed in a script or visually in the VR scene, but in this work, we choose to use *Demonstration*. As explained before, programming by demonstration can be easier to understand for non-programmers and can be done directly in context (i.e. inside the virtual scene). In our scene, if Alice wants to author the interaction "When a user touches the cube, it falls on the ground", she has to demonstrate the first action: *touching the cube* that is the trigger, and then demonstrate the second action: *the cube falls on the ground*

(that can be done by having Alice moving the cube to the ground) that is the effect.

In our framework, we define 4 steps to author an interaction:

1. Recording the interaction: In this step, the user records one or several actions that will be used as trigger and one or several actions that will be used as effect. Table 5.1 shows all the actions that can be recorded by our prototype as trigger, effect, or both.
2. Inspecting the interaction: In the previous step, all actions performed either by the user or objects were recorded, however, not all of them are relevant to the interaction the user wants to create. In our example, when Alice records the action *touch the cube*, an action corresponding to the movement of her hand is recorded, then the action of her hand colliding with the cube. She needs to remove the action of the movement, else the interaction will be triggered only when the hand follows the same movement as the one demonstrated and then collides with the cube.
3. Linking the trigger and the effect: The user needs then to tell the system which set of actions is the trigger of the interaction and which set is the effect.
4. Testing the interaction: The user can then test the interaction to make sure it has the appropriate behavior.

5.2.2 Prototype

Based on our framework we implemented a prototype of a system that allows for the authoring of interactive immersive scenes.

Basic functionalities

To allow users to author an interactive experience, it needs to provide first a set of basic functionalities. The prototype allows users to create a static scene with basic 3D geometries, 3D objects, and images. Using an inspector, a panel that is displayed near a selected entity, users can change their size, color, and visibility. The system also allows users to draw trigger areas on the floor or in the air. Wireframe visual representations allow the users to position them in the environment (see Figure 5.2). Then, during the actual experience, these trigger areas become invisible but have a collider meaning that they can trigger a collision event. They can be used to create interactions in which the trigger is *When the*

Table 5.1: List of the actions that can be recorded by the tool either as a trigger or as an effect.

Action (Dim.)	Description	Trigger	Effect
Collision (C)	Collision between two entities (e.g. objects, users' hands, users' head)	✓	✗
Move (M)	Specific movement of an entity (e.g. objects, users' hands, users' head)	✓	✓
Grab (G)	Grabbing of an object by users using the hand or a controller (pressing the trigger or grip button)	✓	✗
Release (R)	Dropping of an object by users (after it was grabbed)	✓	✗
Drag (D)	Movement of an object that has been grabbed by users	✓	✗
Look (L)	Gaze of users is focused on an object	✓	✗
Enter (En)	Users enter a trigger area	✓	✗
Exit (Ex)	Users exit a trigger area	✓	✗
Property Change (Co: Color, S/H: Visibility)	Property (e.g. colors, visibility) of an object is changed	✓	✓

user or the object moves to this specific area or When the user or the object leaves this specific area. Finally, users can navigate inside the scene either by physically moving or by using teleportation.

Recording interactions

A recording mode in the system can be activated by users at any moment and starts the saving of the performed actions. To limit the number of actions recorded, users can choose to only record either their own actions (hands/head movement, collision, grab, etc.) or the actions of objects. The user recording mode allows users to create 5 types of actions: movement, collision, grab, drag and drop. In the object recording mode, users can either record object movements or collisions with other objects or property changes such as color or visibility changes.

A puppet is also available to users that can be used to demonstrate, from a third-person perspective, actions also done by the user as it can be moved in space and each hand can be independently manipulated (see Figure 5.1). It can demonstrate movement and collision with hands and body. The puppet is also used to record the specific action of *Looking at a specific object/area*. As the users' gaze stares at many different objects and moves a lot, recording such an action directly

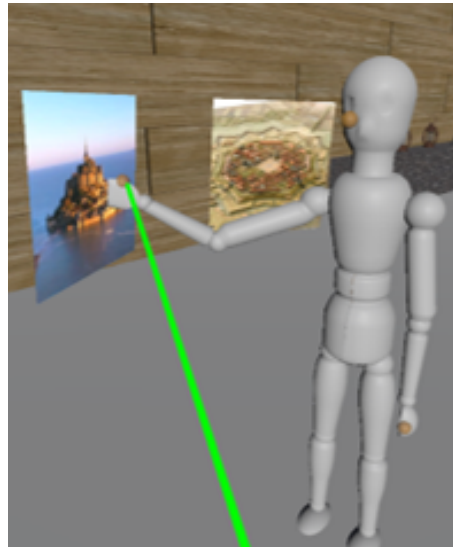


Figure 5.1: Users can record interactions using a puppet that represents the user. In this picture the user manipulates the puppet to make it touch the picture and create a collision event between the picture and the user’s hand.

with the tracking of the user’s head would lead to too many events or would require to create an interaction, such as pushing a controller’s button, to instantiate the creation of the event. Yet, the possibilities for such an interaction are limited since it needs to be triggered without the user looking elsewhere, which would be especially difficult for novices. Therefore we believe that using an intermediary such as a puppet could solve this issue. A yellow sphere, shown in Figure 5.1, in front of the puppet head represents its gaze, it can be moved by users and when it collides with an object or area it creates a Look action. This way, users have full control over the creation of look actions which limits the creation of unwanted actions.

Inspecting the interaction

After the recording, the saved actions are displayed in the scene using semi-transparent bubbles with a letter indicating the type of the recorded action (see Figure 5.3 and Table 5.1 for the meaning of each letter). Actions that were recorded but not wanted by users can be removed. In order to provide more information about the action, when users point at a bubble, a ghost simulation of the action is played. The bubble is positioned near the object it concerns, except when it only concerns the user’s movements actions.

By clicking on the bubble of a movement or drag action, users can show the

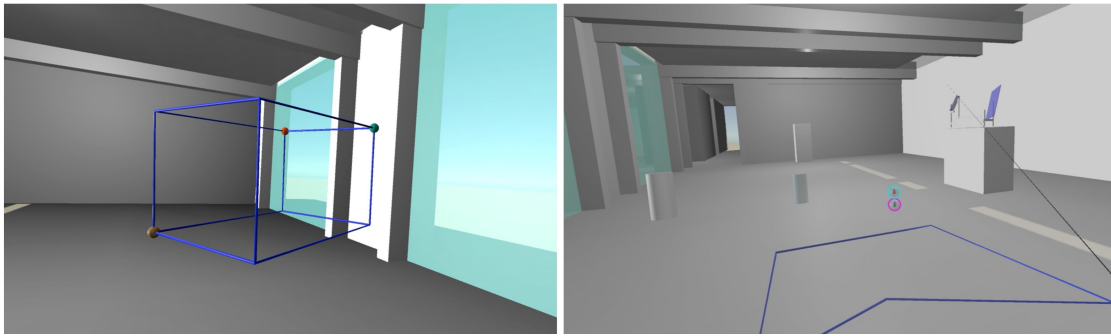


Figure 5.2: Users can create trigger areas. They can shape 3D cubes (on the left) or draw an area on the floor (on the right)

trajectory with all the recorded points⁵, and move or delete them (it is not possible to add points). It is also possible to turn the trajectory into an infinite move following the vector \vec{AB} with A the center of the object and B the position of the last point.

Inspecting the action bubbles can be done at any time in the authoring process. It is not a mandatory action from users but it is rather meant to provide information on the action to users and allow them to modify trajectories.

Actions saved during the same recording are linked through a thin purple thread and the first and the last created events are highlighted with different colors. The order of their creation is used to specify in which order they have to be done. For instance, if users want to define a trigger in which a cube, a sphere, and a cylinder should be touched sequentially, they would record their hand touching these three objects in a row. This functionality allows users to integrate some sequences of actions into their interactions.

Linking the trigger and the effect

Up to this step, there are only actions, users now need to define which ones are the trigger and which ones are the effect of the interaction. This relationship is defined by drawing an arrow that goes from the last action of a set of actions (this set will be the trigger) to the first action of another set of actions (the effect). An effect can have several triggers meaning that it can be triggered by any one of them. A trigger can be linked to several effects. Using a thread to represent a link is quite common in visual programming and is used in several immersive

⁵In order to keep a limited number of points, the trajectory is filtered using the Ramer–Douglas–Peucker algorithm. It allows to only keep the points that define the main shape of the trajectory.

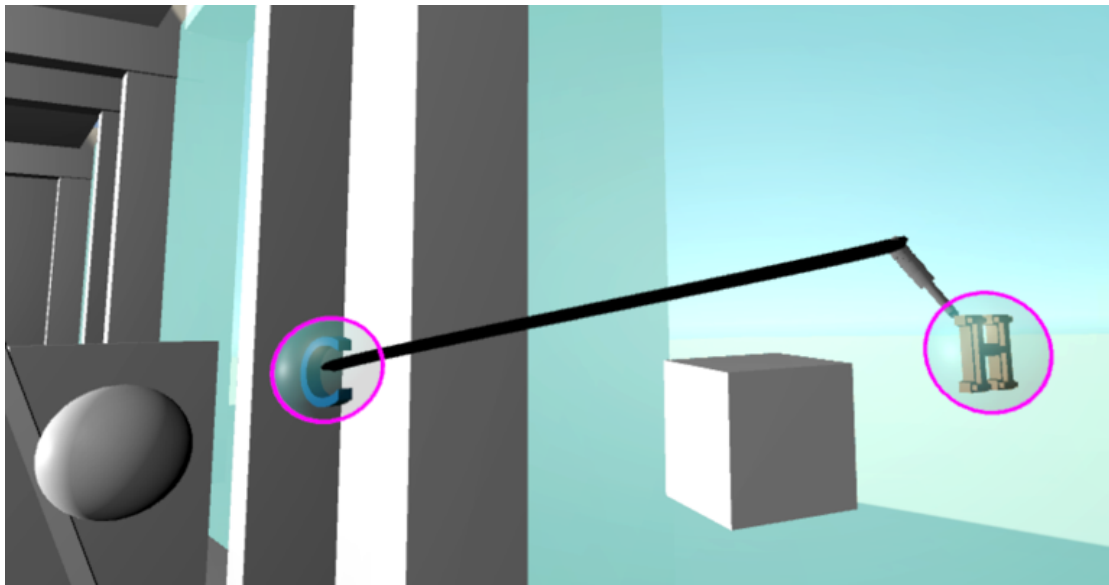


Figure 5.3: Events are visualized with a floating bubble. In this simple example the Collision of the sphere with the user’s hand, makes the cube become invisible (Hide)

authoring tools [205, 148, 68]. The system does not contain manipulable logical operators, however, linking two different actions to the same effect is equivalent to the OR operator.

Testing the interaction

It is important to allow users to quickly and easily test while creating the interactions. Thus, they can verify if the interactions behave as expected and make sure that they are adapted to the final users. For instance, users can make sure that after moving, an object will still be accessible for the next interaction (neither behind a wall, invisible, nor too high). In test mode, users can choose to show or not the graph (bubbles + links) of the recorded interactions.

5.2.3 Implementation

The prototype was implemented with Unity 2019.4.18f1 using C# and SteamVR. The prototype runs on a HTC Vive and a laptop computer MSI GT63 Titan 10SF with an Intel Processor Core i7-10750H CPU 2.59 GHz, 16Go RAM and a Nvidia

GTX 2070 graphic card. The code is publicly available and open source⁶.

5.3 Use cases

In this section, we present and discuss two interactive experiences, a Beat Saber inspired scene and an escape game, authored with our prototype. The figures 5.4 and 5.5 are provided in this chapter as a graphical representation of the authored interactions to help readers better understand the interactions, however, participants to the study described in section 5.4 did not see such visualization.

5.3.1 Beat saber

For this interactive scene, we drew inspiration from the VR game Beat Saber ⁷.

Scenario

The user starts facing a picture with "Press to start" written on it. When they touch the picture, it disappears and two green cubes and one red cube move toward them. The user needs to touch the green cubes to make them disappear. However, if they touch the red cube with their hand, all cubes disappear and a "game over" picture falls in front of them.

Authored interactions

We describe here the logic behind the Beat Saber scene and provide a diagram (see Figure 5.4) as a support to the description. To create this interactive scene we first created a collision event (C1) between the user's hand and the "Press to start" picture.

Each cube has three events attached to it, an infinite linear movement event (M1, M2, M3), a collision with the user's hand event (C2, C3, C4), and a hide event (H1, H2, H3). C2, C3 and C4 trigger respectively H1, H2, and H3, which makes the cubes disappear when they collide the user's hand. C1 is linked to M1, M2 and M3 so when the user touches the picture, the cubes start moving toward them. It is also linked to a hide event (H4) to make the picture disappear once the game starts.

The "Game Over" picture has two events attached to it, a show event (S1) to make it appear and a move event (M4) to make the picture fall in front of the user. Finally, C4, which is attached to the red cube, is linked to S1 and M4.

⁶https://gitlab.inria.fr/egros/authoring_by_demonstration

⁷https://store.steampowered.com/app/620980/Beat_Saber/

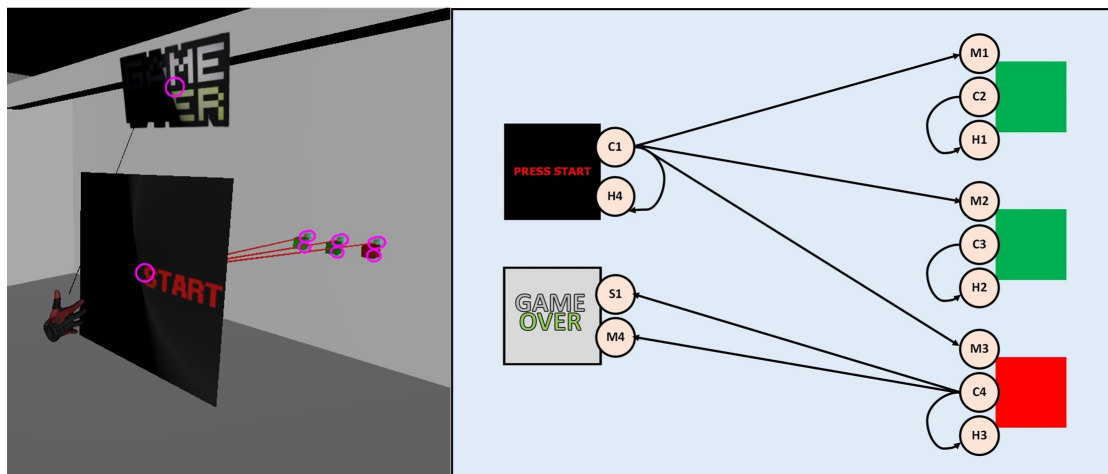


Figure 5.4: On the left, a screen capture of the authoring of the Beat Saber scene. The diagram on the right describes the logic behind the Beat Saber interactive scene we authored.

Discussion

In order to make the game interesting, we would need lots of cubes coming at the player. If we used the copy and paste tool to create them all, the authoring environment would soon be overcrowded. Thus, users need a way to specify that they want multiple identical objects with the same behavior created over time. In order to do so, we would need a *"virtual printer"* that would take a template as input and can be activated or deactivated during the experience.

Since we don't want all cubes to come at once, we would also need the possibility to control when they are produced by the virtual printer. Thus, the trigger sent to activate the printer needs to be conditioned with a time delay. To improve enjoyability of the game, we need to add randomness to this time delay.

Finally, since the interactive experience is a game, we want to count points. For instance, each time the player touches a green cube, a score displayed on the wall in front of them would get incremented. This requires to have a variable that the user can modify and apply arithmetical operations on, such as additions or subtractions.

5.3.2 Escape game

Scenario

The user is in a virtual room with no accessible exit since there are three huge blocks blocking the corridor. In order to escape, the user needs to solve three enigmas. All three enigmas are scattered inside the room. The first enigma is a bomb on a block in the middle of the room. The bomb has three colored wires, blue, green, and red. Next to the bomb, there are a wire cutter and a sphere half sunk inside the block. When the user grabs the wire cutter and touches the blue wire with it, nothing happens. The user drops the wire cutter and touches the sphere with their right hand. The sphere turns red, then green, then blue. The user grabs the wire cutter again and touches in order the red, the green, and the blue wires. Each time the wire cutter collides with a wire, the wire disappears. Once all wires disappeared, the bomb disappears as well as one of the blocks inside the corridor. The first enigma is solved.

For the second enigma, the user has to open a chest. When the user touches or tries to grab the chest, nothing happens. The user starts looking for a key and finds one hidden in the room. When they drag the key to the keyhole of the chest, the top of the chest disappears. At the bottom of the chest, there is a hammer. The user grabs it and starts walking to the corridor. In the corridor, one of the two blocks is cracked. The user uses the hammer to hit it and the block disappears.

For the last enigma, there is a maze on the wall with a red sphere in the middle of it. In front of the maze are displayed four buttons, up, down, right, and left. As the maze is a spiral, the user needs to press alternately the down, right, up, and left buttons until the sphere is outside the maze. When the sphere gets outside the maze, the last block in the corridor disappears.

The user then walks through the corridor and reaches the exit. When the user crosses the exit, a trophy and a picture with 'Congratulation' written on it appear.

Authored interactions

We now describe the logic behind the Escape Game interactive scene. We also provide a visual support to this description in Figure 5.5. Each of the three blocks that seal off the exit has a hide event (H1, H2, H3) attached to it. The first enigma is composed of six objects, a bomb, a wire cutter, three wires (red, green and blue) and a sphere. The wire cutter has four events attached to it, a grab event (G1) to specify this object can be grabbed by the final user, and three collision events (C1, C2 and C3) that are connected with an order link so they have to be triggered in the right order. Each collision event is linked to a hide event attached to a wire (H4, H5, H6). The sphere has four events attached to it, a collision event (C4) with the user's hand that is linked to a red color event (Co1) which is linked to a

green color event (Co2), which is finally linked to a blue color event (Co3). Finally, the bomb has a hide event attached to it (H7) which is linked to H1.

The second enigma is composed of four objects, a key, a closed chest, an open chest and a hammer. A grab event (G2) and a drag event (D1) are attached to the key. The drag event's trajectory depicts the key going through the chest key hole. The closed chest has a hide event (H8) and the open chest a show event (S1) attached to it. These two events are triggered by D1. A grab event (G3) is attached to the hammer as well as a collision event (C5) that is triggered when the hammer collides with the cracked block at the exit. Finally, C5 is linked to H2.

The third enigma has six objects, a spiral maze, a ball and four direction buttons, and it only has two types of events, four collision events (C6, C7, C8, C9) between the direction buttons and the user's hand, and 11 movement events (M1 to M11). The movement events describe the 11 movements the ball needs to do to get out of the maze and are connected with an order link. C6 is linked to all the left movements (M4, M8), C7 to all the up movements (M3, M7, M11), C8 to all the right movements (M2, M6, M10), and C9 to all the down movements (M1, M5, M9). Finally, the last movement M11 triggers H3.

The exit has two objects, a congratulation picture and a cup, as well as an interactive object, a 2D trigger area. The trigger area covers the exit of the room and has an entry event (En1) attached to it that is triggered when the user enters the area. En1 is linked to two show events (S2, S3) attached to the picture and the cup.

Discussion

In order for an event to work with either the right or the left hand, the creator needs to record it twice, one time for each hand. For instance, for the bomb enigma in the escape game, when the user touches the sphere, if we want the sphere to change color no matter which hand touches it, we need to record two collisions, one for each hand. As the system relies on a single demonstration of the interaction, it needs additional information to deduce if the interaction targets one specific hand or both.

In this scene, if the user touches the wires with the wire cutter in the wrong order, for instance by touching first the blue wire instead of the red wire, nothing happens. To create a "Game Over" message that appears when the user cuts the blue wire, we would need to add a condition "The event collision between wire cutter and red wire hasn't been triggered" which requires using the NOT and AND logical operators. Yet, our system does not allow its users to create logical operators.

Finally, to make the sphere move into the spiral maze, we recorded all expected

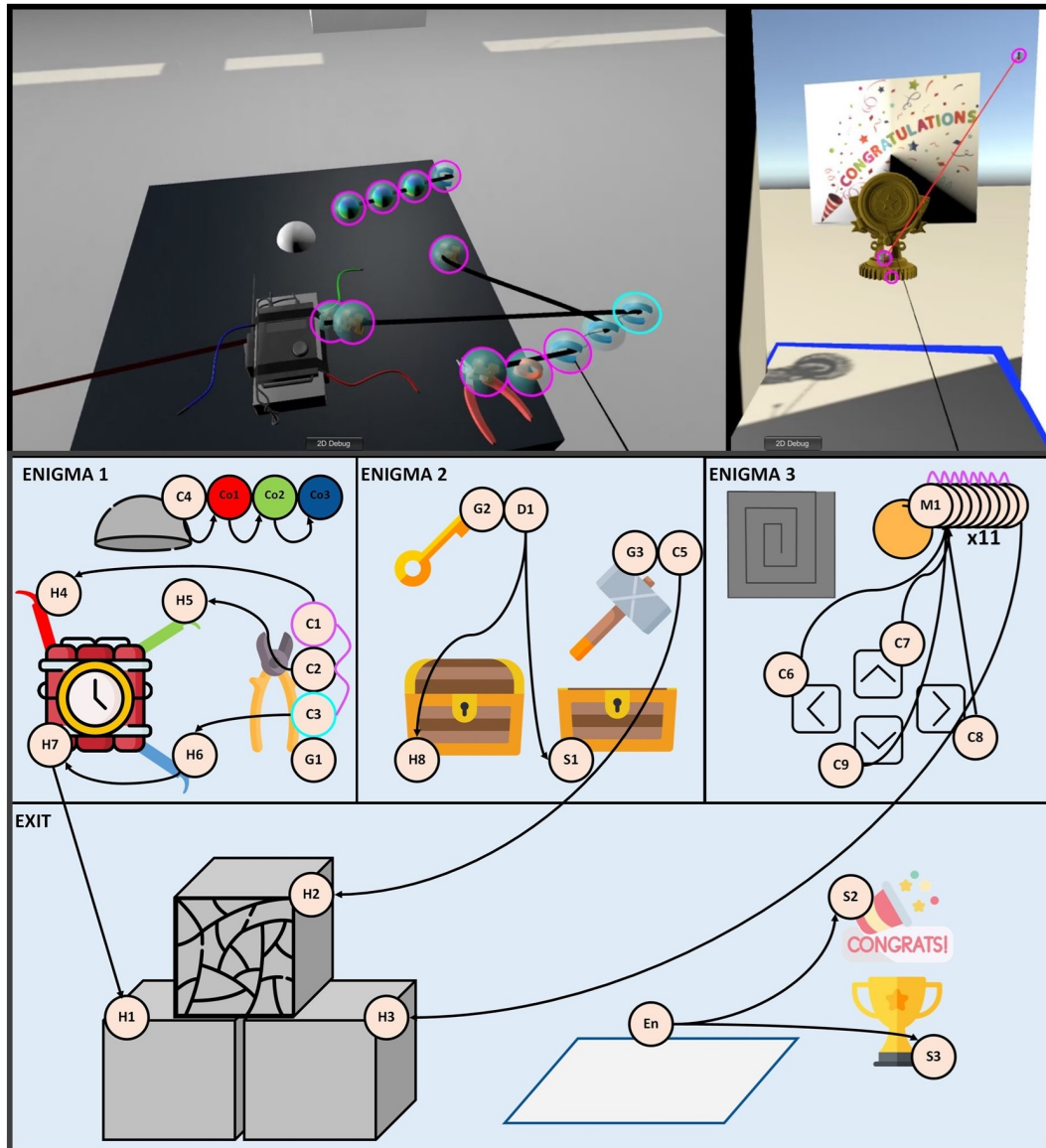


Figure 5.5: A screen capture of the first enigma's logic (top left), a screen capture of the logic of the exit animation (top right), and a diagram that describes the logic behind the Escape Game interactive scene we authored (bottom).

movements in one recording. Thus, as explained in the section 5.2.2, all actions were linked by a time constraint forcing the action n to be triggered before being able to trigger the action $n+1$. In this case, in order to trigger the third expected movement, the first two movements needed to be executed. However, it is not possible to go backward, nor choose between two different directions. This example would require to have the object itself as a reference frame for the movement as well as being able to control the length of the translation as distances vary in the maze. In our system, movements have the world as a reference frame, which means that the coordinates (0,0,0) refer to the origin of the world coordinates and not the object's position in the world.

5.4 Feedback session

We performed a feedback session to better understand the challenges that participants could face while authoring interactions. In this section we discuss not only the challenges inherent in interaction authoring, but also those related to design flaws so it could benefit to future designers.

5.4.1 Study design

Participants

We had 6 participants (4 female and 2 male) aged 24 to 29, (average:26), all participants had experience with either virtual or augmented reality. All participants had experience in programming in general, however, two of them had no programming experience in neither virtual reality nor augmented reality. Among the participants, two of them were left-handed.

Procedure

The participants were first asked to fill out a demographic questionnaire. To show the participants an example of what can be authored with the tool, we started trials by showing the participants a reduced version of the escape game. We showed the participants the test mode without the logic appearing so they could not see it first. We then let them try the experience by themselves. Then, we explained all functionalities to the participants through demonstration and answered any questions they could have.

For the next step, the participants were instructed to author two interactive experiences given by the experimenter. The first instruction, "When the user touches an object, the color of the object changes" described a low-complexity scene and was meant to help the participants get familiar with interaction authoring. The

second instruction, "When the user gets out of the room, an object appears behind him. When the user turns over and looks at it, the object starts falling.", depicted a more complex scene and forced the participants to use the puppet recording mode as well as the trigger area functionality.

Once the participants performed both tasks, they did a free authoring session with no time constraint. The only condition was to create at least one interaction. During the constrained and free creation steps, automatic backups were made every 30 seconds. The creation tasks were followed by a semi-structured interview during which participants were asked to share their feelings about their experience. At the end of the study, participants were asked to fill out a raw NASA-TLX questionnaire [83] followed by a semi-structured interview.

5.4.2 Results

5 of the 6 participants showed a significant improvement during training and one participant had difficulties understanding how the authoring tools for interaction worked and couldn't create successful interactions during the free creation step. In total, the participants spent less than two hours using the system. At the end, the participants mentioned feeling more confident with the system and experimenters noticed that participants progressively made less mistakes and needed less help during the session.

NASA-TLX

Results to the raw NASA-TLX questionnaire are depicted in Figure 5.6. The participants had a tendency to find the system mentally demanding as only two participants rated the mental demand below 50 and half of them rated the effort they put into their work above 50. Yet, most participants seemed satisfied with the work they achieved, all participants rated their performance equal or below 50, meaning they judge their work as successful. Moreover, the frustration scores were very low as 5 of the 6 participants rated their frustration equal to or below 20.

Interactions log

We analyzed the final results of the free creation task and seek which interactions were the most created and whether they were correctly used. On Figure 5.7, we can observe that the events move, collision, show, color, and zone collider are the most used. On the other side, the events drag, drop and look were never correctly used. The most popular events actually are the events that were necessary to complete the two constrained tasks. We can notice that the look event was not used during

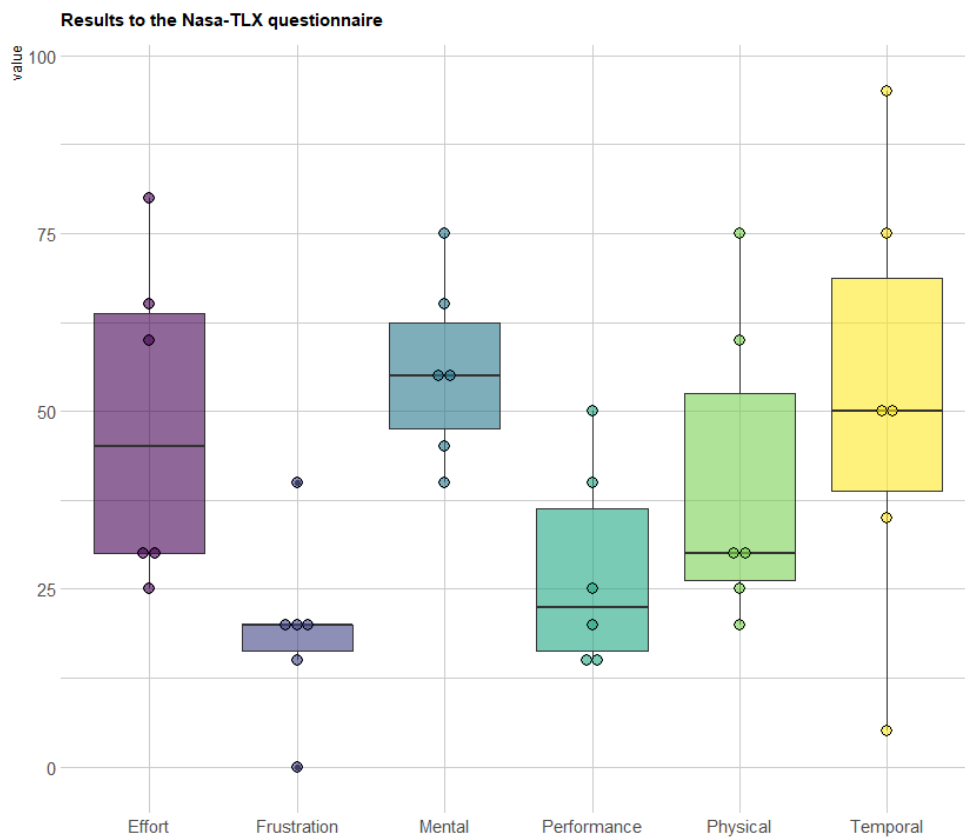


Figure 5.6: Results to the NASA-TLX questionnaire

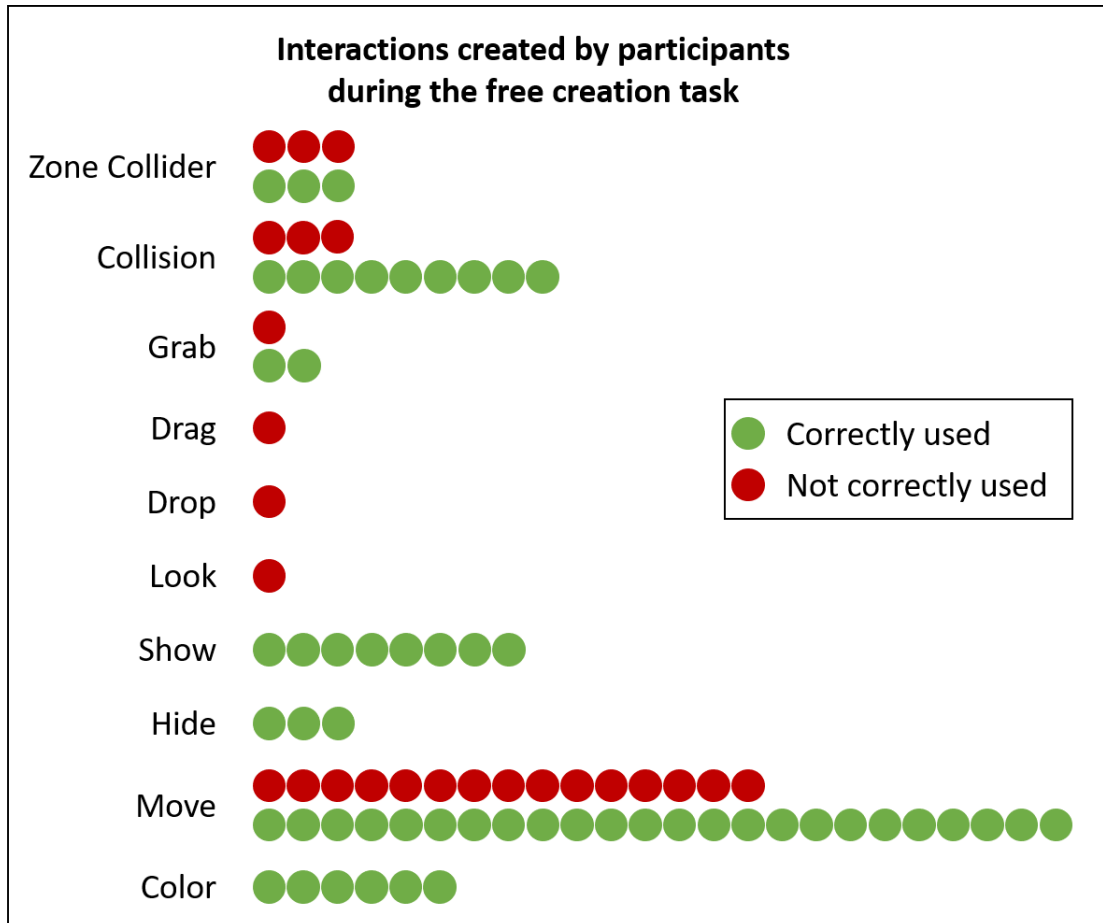


Figure 5.7: Interactions created by the participants during the free creation task: the participants mostly used interactions that they had to use during the first two constrained tasks

the free creation task even though it was required in the second constrained task, however, many participants did not instinctively realize the need for the look event and either realized it by themselves during creation or had to be reminded.

Feedback from interviews

One of the main difficulties reported by the participants was the difficulty to assimilate all functionalities. The participants not only had to learn how to use the interaction authoring tools but also the modeling tools, as well as how to navigate and how to manipulate objects. Therefore, the participants had a lot to remember, which hindered their experience and could explain the high mental demand found in the NASA-TLX scores. Moreover, all participants thought that they would get better if they had more time to learn how to use the tool.

P1 suggested adding a history to the palette in order to easily visualize what had already been created and what is left to make. The possibility to add a history or a 2D representation of the authored interactions on the palette was also mentioned by P5. Indeed having a mixed interface, both 2D and 3D would allow the user to have a global view of the program. Once the program is authored, the user could easily rearrange or select blocks of codes.

The participants could easily read and understand the events they created. The letters inside bubbles were a first clue to remember the nature of the event and the participants could easily get more information by pointing at the bubble in order to launch the ghost simulation. They particularly enjoyed the ghost visualization for events, however, they believed it could be improved. For instance, when the collision simulation is launched, a ghost of the object appears next to the collided object and hits it. Yet the user doesn't know where the ghost will appear. P5 suggested adding a textual label that could be hidden attached to the event.

Experimenters' observations

Several participants had difficulties understanding how to link triggers to the effect. Two of them linked the effect before the trigger and therefore inverted the relationship between the two events. In a more general manner, most participants reminded themselves out loud the order "trigger then effect" to avoid any mistake. During the first constrained task P4 forgot to link the trigger to its action before testing and P2 launched the test mode before creating the trigger and expected the action to be triggered by default. All these observations happened during the two constrained tasks and did not happen again after our clarification.

During the first constrained task, 3 participants misidentified the events they were expected to create. For the first task "The color of the object changes when the user touches it", P2 and P4 created a grab event instead of a hand collision

and P3 kept a hand movement event in addition to the collision.

The participants also had a tendency to get confused about the way attributes work. Some of them started changing the object's color without recording, thinking it would create a color event. Several participants also forgot to set the default visibility before recording and ended up creating the opposite event (show instead of hide or hide instead of show).

During the free creation step, two participants launched the wrong recording modes. P1 recorded the left hand actions instead of the right hand and P3 launched the right hand recording instead of the objects recording mode.

5.5 Discussion

In this section we discuss the challenges of authoring by demonstration as well as the limitations to our study.

5.5.1 Impossible manipulation

Authoring by demonstration allows users to specify an event by grabbing an object and directly manipulating it. Yet, some wanted behaviors could be conflicting with the users' physical constraints. For instance, if the user wants an object to spin and turn on 360° or more, their arm won't be able to turn that much, therefore the recorded move will not be smooth nor complete. A similar problem could occur if the user wants to move the object over a long distance or manipulate very large objects. One solution to this problem is to use a World-In-Miniature (WIM) [182], yet visualizing and manipulating small objects in it would be laborious.

5.5.2 Demonstration of abstract concepts

Looking back at the Beat Saber use case (see Section 5.3), let's imagine we want to create the following interactive experience, "Every 0.2 to 2 seconds, a red or green cube appears and moves towards the player. If the player touches the green cube, they win a point, but if they touch a red cube, the game stops and a game over message is displayed". These two sentences involve the demonstration of many abstract concepts such as time to specify the delay between two appearances, randomness to make this time vary, multiple instantiations of objects with similar behaviors, generalization of an interaction to all green or red cubes and not just the one the user interacts with during the demonstration, and variables for score management.

Some of these concepts are intangible and therefore are not directly manipulable for the demonstration. In our example, it is the case for time, randomness,

multiple instantiations, and digital values. To make these concepts manipulable and allow demonstration, one solution would be to materialize them by creating manipulable metaphors. For instance, in the Beat Saber use case (see Section 5.3), we mentioned a virtual printer to instantiate multiple times interactive objects. One of the main challenges for this kind of virtual metaphor is to create a visualization that speaks for itself and is easily manipulable. We believe that the manipulation and demonstration of time is an interesting research topic. We encourage future research to explore how users may include time concepts such as delays or order restrictions during the authoring process.

In the same example, we would also need to be able to generalize the collision between the player's hand and the green cubes, to both of the player's hands on one side, and to all green cubes on the other side. To do so the user starts the recording and touches a green cube with their dominant hand. This demonstration has several possible interpretations. The collision can involve either both hands or the dominant hand only. Similarly, the system does not know if the interaction targets only this specific cube, all green cubes, all cubes, or all green objects.

This constitutes a second challenge involved by abstract concepts, generalizing a demonstration to a set of entities sharing one or several similar properties. Such a deduction isn't possible based on a single demonstration as there are too many possible interpretations. Thus, future research should focus on either context specification or the use of multiple demonstrations, a method already explored for authoring by demonstration [171]. Such a method would also enable logic deduction, and differentiate conjunction from disjunction.

5.5.3 Process ambiguities

One demonstration can lead to several outcomes. As the user performs the demonstration, the recording is polluted by all the actions the user has to do to simulate the event but that are not the target of the demonstration. We illustrate this challenge with a simple demonstration. *"The user **walks** to the sphere, they **reach** for it, as the hand **touches** the sphere they **grab** it, **drag** it on their right and **drop** it, and finally stop the recording."* This single demonstration has many possible interpretations. Does the user want the sphere to move when they walk toward it, or when the hand touches it? The point of the collision or the hand's trajectory could also matter. Another possible interpretation is the demonstration of a dragging movement.

As we can see, it is unsure which actions are of interest nor which object is the focus of the demonstration (user body, hands, or sphere). To partially resolve this issue we split the recording according to the referent of the action, yet it disables the possibility to demonstrate an interaction at once as well as automatic logic creation.

The issue of ambiguous demonstrations has previously been studied in human-robot interaction. Naive human teachers are likely to perform ambiguous and incomplete demonstrations to robots which need to interpret the teachers' intent. Future VR authoring tools by demonstration could for instance build upon Breazeal et al.'s work [30], they designed a robot which is a socially engaged and cognitive learner.

5.5.4 Creating and visualizing logic

To improve the Escape Game use case (see Section 5.3), we may want the bomb to explode if the player does not cut the wires in the right order. To do so, the user needs to specify "If the player cuts the blue wire (Event A) or the green wire (Event B) but the red wire is not cut (! Event C), then the bomb explodes (Event D)." which corresponds to the following logic "If (A || B) && !C, do D". Yet, the link connectors commonly used in immersive systems such as our prototype or the systems mentioned in the related work [148, 18, 205] can only specify the logical operator OR by connecting two trigger events to the same action event.

Enabling all logical connectors would require to complicate this logic creation process whereas participants are already struggling to handle the current logic (see Section 5.4). Thus we believe the logic should be created by the system and deduced from the recorded demonstration. Yet, it raises the question of how the system can differentiate conjunction from disjunction in a demonstration. Such logic elements will also need to be visualized and understood by non-programmers and avoid crowding too much space. Visual occlusion is one of the challenges mentioned in FlowMatic [219]. There is also a risk of creating an interaction graph that would become complex to read as interaction can be scattered in the virtual space. Some participants of the user study already mentioned getting confused with the current graph and suggested using a 2D visualization or a history.

Moreover, the logic is not limited to the OR, AND and NOT operators. In this chapter, we limited our framework to triggers being the result of a binary change of state (done or not done), yet, it could also be continuous based on the state of an object. For instance, the color of a virtual thermometer could vary depending on the size of a virtual mercury bar. Other elements could also be added to this trigger-action relation, such as delays, order constraints and iterations. We could also consider other logic concepts such as Vernier and Nigay's framework [203] or applying the set theory to movements. Thus, creating logic using programming by demonstration is a complex subject which requires to be explored.

5.5.5 Visual programming and programming by demonstration

The goal of the chapter is not to claim the superiority of programming by demonstration over visual programming. We believe that it is first necessary to identify and study the challenges raised by immersive authoring of interactive experiences by demonstration.

During the feedback session, we did not provide the participants with visual representations similar to figures 5.4 and 5.5 because we wanted participants to create the interactions by demonstration from spoken language without going through a graphical programming representation first. In future studies, it would be interesting to compare the participants' capacities to create an interactive experience from spoken language using either visual programming or programming by demonstration.

It is most likely that, when compared, visual programming and programming by demonstration happen to have both drawbacks and benefits. Thus, both methods could be complementary. Programming by demonstration is likely to show strengths whenever spatiality is involved (movements, collisions...) and when figuring out the relations between objects. However, visual programming seems more promising to easily get an overview of the created interactions and to handle abstract concepts. Thus it would be interesting to explore, in the future, the use of an authoring system combining both methods.

5.5.6 Provide assistance to users

All our participants had at least basis in programming, yet they still struggled to decompose the interactive experiences they had to author into primary events. Creating the logic, despite being reduced to its minimum, also required the users to go through a learning phase. Learning Authoring by demonstration can induce an important cognitive load for users. They need to learn how to navigate and interact with the virtual environment, model objects, author and debug interactions. As the authoring tool gains in power and expressivity, functionalities are likely to multiply and the complexity to rise.

Thus, we believe authoring systems should provide as much assistance as possible to their users. In VRFromX [94] users can benefit from IA assistance during the modeling phase and an affordance recommender during the authoring phase.

5.5.7 Limitations

Our analysis of the challenges faces the limitations of our prototype and feedback session. All of our participants had at least basic knowledge in coding, thus, we

might have missed challenges that non-developers users would have. Yet, we believe that the challenges we identified with our participants can be generalized to non-developer users and that our work provides a foundation for future research in interaction authoring. In order to create interactions, users needed to get familiar with prerequisite functionalities such as navigation, grabbing, and modeling. These functionalities were not the focus of our study yet were necessary to be mastered by users. This resulted in an increased learning curve of the prototype. In addition to that, the learning phase was hindered by the communication and awareness issues inherent in the isolation of VR HMDs. Finally, the participants experience was hindered by the technical limitations of our prototype. We implemented a basic modeling tool for this study, yet we noticed that the limitations of the modeling system has repercussions on the expressivity of the authoring, as well as its usability.

5.6 Conclusion and perspectives

In this chapter, we investigate the challenges of immersive authoring by demonstration of interactive VR experiences through the design, implementation and evaluation of a prototype. We expect this work to pave the way of future research on immersive authoring by demonstration, by highlighting design issues that need to be studied.

Beyond authoring prototypes, immersed authoring by demonstration is useful to edit trainings and tutorials directly in the immersive environment. Lécuyer et al. [118] actually enable medical training using authoring by demonstration which could be generalized to other domains of application. Implementing a tutorial for complex VR application is laborious and an authoring tool by demonstration would greatly facilitate the process.

Chapter 6

Conclusion and Perspectives

In this PhD thesis, I investigate some of the main opportunities and challenges of immersive virtual reality for creating immersive visualization experiences. This work focuses on applications for non-expert users, by this term, I refer to users without expertise in either virtual reality or development. Enabling immersive visualization experiences to non-experts involves several challenges that need to be addressed. In this thesis, we investigate three of those challenges through 1) the study of current practices in virtual reality onboarding, 2) the exploration of how immersion can be used to favor the users' engagement in data visualization, and 3) the investigation of authoring of interactive immersive experiences through demonstration and direct manipulation for non-expert users. This thesis is a first step to support the design and adoption of immersive visualizations to educate and raise awareness of complex data and phenomena. Before discussing the opportunities and perspectives for future work, I will briefly summarize this thesis' main contributions.

6.1 Summary

6.1.1 Study of virtual reality onboarding

First, in Chapter 3, we investigated the primary difficulty to the use of VR for non-expert users, which is the onboarding process. We investigated the main practices and challenges in both computer and instructor-assisted immersive onboarding.

To do so, we first conducted a heuristic evaluation of 21 tutorials that were directly integrated into the VR application. This tutorial review allowed us to identify some practices or designs that could hinder the efficiency of computer-assisted tutorials. 1) We identified some practices that can hinder the intelligibility of tutorials such as hardly perceivable instructions due to clustering or exclusive audio

instructions. 2) We highlighted the importance of feedback and feedforward in the onboarding process. Relevant and informative feedback is necessary for users to better understand how well they perform, and how they can improve. Feedforward provides insights regarding what's to come for users in both the short and long term. As users know what to expect, it helps them get a global understanding of the onboarding process. 3) Finally, we observed that tutorials are usually not designed to adapt themselves to the users which can affect their accessibility. Most applications do not provide different tutorials based on the users' level and they do not adapt to the users' pace.

Then, we studied instructor-based onboarding through the interviews of 15 experts in VR onboarding. Based on a thematic analysis of the interviews, we defined and elaborated on three main challenges that instructors faced during onboarding sessions, 1) the impact of the novelty of VR, 2) the lack of awareness for both the instructor and the novices, and 3) the communication barrier in VR.

Based on our review of the literature, our tutorial evaluation, and interviews, we propose a conceptual framework for general assisted VR onboarding. This framework aims to give an overview of the forms onboarding can take and to facilitate the exploration of new onboarding processes.

Finally, we provide guidelines for general and instructor-assisted onboarding. These guidelines are lessons learned from our tutorial review and expert interviews and their goal is to assist future onboarding designers.

6.1.2 Engaging users through immersive zoomable empathetic visualizations

In Chapter 4, we explored how to make use of immersion to design empathetic visualizations. In this chapter, we aimed to bridge the gap between abstract data visualizations and the concrete experience personal stories can bring. To do so, we introduced a new type of visualization, zoomable empathetic visualizations. We implemented a prototype in VR that transitions from an abstract bar chart to an immersive scene that materializes individuals through avatars and where users can explore the individual and personal data associated with each avatar.

In order to illustrate the potential of such a visualization, we created three use cases. Two use cases illustrate how our visualization can be used to raise awareness about human welfare through the examples of femicides and bike accidents. Our last use case explores how such a visualization could be used to raise awareness on other topics such as animal welfare.

To investigate the potential and limitations of our prototype, we also conducted a user study. Participants explored the visualization of the femicide dataset and then answered a semi-structured interview. We then did a thematic analysis of the

interviews. Our user study suggests that the visualization managed to promote engagement. Immersion contributed to this phenomenon by humanizing the individuals behind the data and adding a sense of realism. Our results also support the visualization's ability to provide both objective and subjective experience of the data as the participants not only manifested emotional engagement but also showed interest in the data.

6.1.3 Empower non-developers by enabling the authoring of immersive interactive experiences

The fact that the creation of immersive interactive visualization is currently limited to developers constitutes the last challenge we aimed to tackle in this thesis. In Chapter 5, we investigated how to enable the authoring of immersive interactive experiences for non-expert users.

We studied the concept of immersive programming by demonstration through the prototyping of a VR authoring tool. The prototype enables the authoring of interactive immersive experiences directly in the virtual environment through the recording of the user's direct interactions with the virtual objects.

To investigate the strengths and limitations of our prototype, we introduced two use cases and conducted a user study. Based on our results, we were able to identify five challenges to the concept of immersive authoring by demonstration. 1) Some interactions and behaviors might be impossible to demonstrate as they involve impossible manipulations, 2) the issue of demonstrating abstract and intangible concepts needs to be addressed, 3) demonstrations can be ambiguous as they might lead to several outcomes, 4) complex interactions and behaviors involve the use of logic for which creation and visualization require to be adapted to non-expert users, and finally 5) despite more accessible methods, non-experts users are likely to require assistance for the authoring of complex interactions.

This work represents a first step to empowering non-experts in the domain of visualization and helping them appropriate the edition process in order to create visualizations that best suit their own expertise domain.

6.2 Perspectives

6.2.1 Authoring training and onboarding tutorials

In Section 5.6, we started mentioning how accessible authoring tools could benefit the creation of onboarding tutorials. Currently, creating a tutorial for an application is not only time-consuming but also requires development skills. Some immersive applications try to mimic natural interactions from the physical world.

However, some applications might be more complex and provide both basic and expert functionalities. All users need to be trained to use those basic functionalities, however, when it comes to expert functionalities, they might be necessary for only very specific purposes. Thus, users should only be trained on how to use them if needed. With a generic tutorial, novices would have to go through the entire tutorial and learn how to master useless functionalities. Not only this situation would be a loss of time for them but it could also overwhelm them with useless information and hinder their learning of the few necessary functionalities. It is thus necessary to adapt the tutorials to the users' needs. These needs are usually defined by instructors who are expert users of the application but might not be part of the developers. Thus, there is a need to enable the creation of integrated tutorials by instructors.

We identified three levels of integration of the tutorial into the application. These levels of integration have a direct impact on 1) how the tutorial authoring tools would work, 2) the complexity of implementing and integrating them into applications, and 3) the complexity of the authoring process for instructors. We believe future research should explore how the level of integration of tutorials can impact these three dimensions when creating tutorial authoring tools. In the following paragraphs, we elaborate on these three levels of integration as we hope it will encourage future study.

The lowest level of integration would be to incorporate visual and audio clues over the virtual environment. There would be a full separation between the two parts which means that the tutorial system and the application system would be unaware of each other. This solution is technically similar to *TranceiVR* [192] and benefits from not needing access to the application code. Yet, in order for the user to follow the tutorial, they would have to manually pass the instructions as they fulfill them. Moreover, the tutorial would not provide any feedback regarding the user's accomplishments. Enabling the authoring of such tutorials to instructors would provide a universal solution allowing instructors to design tutorials for any VR application.

The second level of integration would be to enable the authoring of tutorials with unilateral awareness. The onboarding system would be aware of the state of the application but not the other way around. The clues added in the virtual environment could evolve depending on both the user's interaction and the state of the application, however, the application would run independently from the tutorial system. Implementing this tool would require access to the application's code, however as the system only needs to be aware of the state of the application, there would be less overlap in the code which could prove to be easier to implement. Moreover, if the tutorial is aware of the state of the application, it means that the authoring tool has to be aware of it too which enables authoring by demonstration.

The instructor could demonstrate how to use the application and explore several scenarios (e.g.: correct and incorrect use of the application). One limitation of this solution is the fact that it might not leave the novices the liberty to make mistakes. As the application is unaware of the tutorial process, if the novice performs an incorrect action, they might not be able to go back and try again.

The highest level of integration would be for an application to be tightly linked to the tutorial system. The application state would be influenced by the tutorial. Such a level of integration would enable the design of onboarding scenes inside the application, environments specifically designed for the learning process. Moreover, it also enables a high level of feedback and novices get the right to make mistakes. It would even be possible to disable incorrect actions. Yet, this solution also has limitations. First, implementing the tutorial authoring tool would have a big impact on the implementation of the application. More importantly, the authoring process for the instructors might turn out to be quite challenging as the instructors would have to edit not only the clues but also the application's behavior depending on the tutorial's stage and the novice's actions.

To conclude, tutorial authoring systems could be more or less integrated to the applications. We believe that future research should investigate and compare the three levels of integration of authoring tools for tutorials. A better understanding of the benefits and limitations of each solution would be a first step in providing authoring systems adapted to the instructors' needs.

6.2.2 Authoring of data-driven storytelling

In the previous chapter, we introduced an immersive authoring tool for non-expert users. That tool enables the edition of interactive experiences, however it does not handle the integration of data. The content and events in the interactive experience cannot vary depending on the data. Enabling the integration of data would allow non-expert users to create visualizations similar to the one introduced in Chapter 4.

Such a tool would allow communication workers and educators to create visualizations that support their activities. Authoring tools for immersive data visualization have been explored before [161, 47, 177, 187]. Yet, there is still a lot to explore, and, except for MARVisT [47], these tools are not meant for storytelling experiences but rather for data analysis. Thus, various challenges still need to be addressed in order to enable the authoring of immersive data storytelling to non-experts.

First, data can be represented in many ways which are more or less abstract. In order to offer as much expressivity as possible, we need a clear understanding of the existing possibilities. We believe that in order to implement a relevant data storytelling authoring tool, researchers should rely on a design space of immersive

data representation. Some research studies focus on the conception of a design space for data representation, yet, they often target a specific subcategory of data visualization as data can be represented in various ways, and building an exhaustive design space can prove to be challenging. For instance Brath and Banissi [28] introduce a data visualization design space focusing on the role of text. Although they do not focus on immersive data representation but on immersive analytics in general, including the technology used and the input modality, the design space introduced by Saffo et al [170] could provide a strong basis for a design space on immersive data representation that could then be used as a support to design an data visualization authoring tool.

A second challenge we identified is the fact that linking the data to the content and its behaviors implies handling abstract and intangible concepts which is a challenge mentioned in Chapter 5. If we wanted to reproduce the visceral visualization of Olympic sprint speeds from Lee et al [119], we would need to create as many avatars as data rows and link each avatar's speed to the speed value indicated in the data row. To do so, we need to specify that the quantity of avatars is linked to the number of rows (not a specific value) and then associate each avatar and their behavior to the data row it is related to. Authoring such a scene exclusively through programming by demonstration and direct manipulation appears to be challenging. Hence, a first research direction would be to explore how to enable intuitive authoring that handles abstract and intangible concepts based on a hybrid solution of visual programming and programming by demonstration.

Another challenge comes from the fact that data can take many forms that need to be supported. Data is usually quantitative numbers (discrete or continuous) or qualitative text. Yet, it can take many other forms such as images, videos, and virtual objects. For instance, the visualization introduced in Chapter 4 handles data such as 360° images and personalized avatars. We believe that supporting unconventional forms of data is especially important for immersive data storytelling in order to fully benefit from the advantages of immersion.

More generally, the authoring tool needs to allow taking advantage of the benefits VR has to offer in both data visualization and education and awareness raising. It would be irrelevant to propose an authoring tool that only enables the creation of two-dimensional bar charts in a VR environment. An immersive data storytelling tool could for instance facilitate data visceralization. For instance, pregnancy applications help future parents visualize the size and weight of the fetus in utero as well as what the baby looks like. Such applications also contain storytelling components as they explain the baby's development and the symptoms the mother will most likely experience. Size and weight are often compared to fruits or animals, yet understanding the size of a puffin at 20 weeks can be challenging. Similarly, real-size 3D visualizations of what the baby looks like are quite limited on a 2D

smartphone screen. A similar application in virtual reality could offer a much more concrete experience by displaying real-scale models of the fetus and the elements of comparison. Thus, authoring tools should for instance facilitate the association of scale and weight values with 3D models.

6.2.3 Support expert control over data storytelling

In Chapter 3, we investigated the current practices for onboarding and based on interviews, we studied how instructors teach novices how to use VR applications. In this thesis, we have a vested interest in data-driven storytelling and how it can be used to educate and raise awareness for the general public.

If the onboarding process is necessary to guarantee engaging and efficient VR experiences, the role of the instructor could extend beyond the onboarding phase. Museums often enhance the visitors' experience with either audio guides or even human guide tours. One could compare the classical data-storytelling experience to audio guides. Users/visitors are on their own but free to explore the visualization/museum at their own pace. Despite the growth of audio guides, museums still provide human guide tours. These guide tours are a unique and living experience as the guides answer the visitors' questions and are capable of adapting their speech depending on the audience. This audio vs human guide comparison can relate to the data storytelling. After the onboarding phase, the instructor could become a guide and rely on asymmetrical collaborative visualizations to educate the audience. The visualization would be asymmetrical in the sense that the guide and the audience wouldn't have access to the same functionalities. The guide's functionalities would enable the authoring of the visualization as well as guiding tools to point at elements and orient the audience, whereas the audience would interact with the final visualization and their functionalities would support the exploration of the visualization. In their paper, Isenberg et al. [95] describe three levels of engagement in collaborative visualization, in this case, the audience's role would correspond to either the *viewing* or the *interacting/exploring* levels, whereas the role of the instructor would be *sharing/creating*.

Adaptative storytelling can be a key to providing more engaging visualization experiences. Yet, it might be challenging to implement systems that adapt the storytelling to its user in a way that is relevant and efficient regarding both engagement and comprehension of the data. We can find many research regarding adaptive systems. De Lima et al [58] introduce adaptive narrative storytelling based on the audience's personality and preferences. Yet, adapting a story differs from data storytelling as the data storytelling not only depends on the user's personality but also their interactions with the system as well as their interrogations.

During the user study introduced in Section 4.4, participants raised many questions regarding the data as they explored the visualization. Some expected addi-

tional information or data, yet we had to limit the amount of available data to the users so they would not be overwhelmed by information. For instance, the report from the government on violent death among couples presents a lot of data which can be heavy and overwhelming for its readers. Indeed, as the report shares a lot of text and data, not only the readers might not be able to choose which information they should read and which one to start with, but they might also be repelled by the idea of having to read that much information. Thus, we believe that introducing new data and information depending on the users' interests would be more engaging.

In this section, we wish to encourage the exploration of asymmetrical collaborative and interactive data-driven storytelling. On one side, the user would still be able to explore the data similarly to the experience proposed in Chapter 4. Indeed, in order to favor the user's engagement and interest in the data, it is important for the user to actively interact with the data and keep a certain degree of control over it. On the other side, the instructor would not only have tools to help the user navigate the data but could also dynamically edit the visualization.

6.2.4 Study the benefits of immersion to explore individual data

In Chapter 4, we explored the benefits of immersion to promote user engagement through empathetic visualizations that allow the exploration of individual data. In this visualization, individual data was used as a support to humanize the data. Yet, exploring individual data can be beneficial beyond the empathy it might induce.

We mentioned in Chapter 4 the fact that the individual representation of data as well as the immersive scene could also be used to represent non-codable data and to provide context. Contextualizing the data can prove to be very useful. For instance, in the bike accident use case (see Section 4.3.2), various data are shared regarding the accidents. One might want to analyze the data to better understand the main risk factors for such accidents. Two accidents could be associated with very similar data (luminosity, type of road, victim's profile...), yet in one case the victim was unharmed and in the second the victim died. The immersive scene provides additional context by showing the locations of the bike accidents. As the user is immersed in the 360° pictures of the locations of the accidents, they can analyze the environment and try to understand what could make the locations more or less prone to accidents.

Research papers in immersive analytics highlight the benefits of immersion for data analysis [69] and in Chapter 4 we investigate the benefits of immersion to promote engagement. We believe it would be interesting to explore the benefits of

immersion in the exploration of individual data and study the scenarios in which immersion is relevant to provide context. Moreover, there is a need to better understand how the exploration of individual data can be supported and designed in order to foster insights.

6.2.5 Augmented and virtual reality for empathetic visualizations

In Chapter 4, we introduce a virtual reality empathetic visualization. This visualization allows us to raise awareness about topics the users are often more or less ignorant about. This lack of awareness is often due to the fact that the phenomenon is distant from the user in the sense that it happens far away or they are not directly involved in the matter. Using virtual reality, we can make the users feel closer to the subject by diving them into a virtual environment in which we represent the victims and their environment. This immersion is meant to support the users in taking the victims' perspectives and understanding their experiences.

Augmented reality has the ability to incorporate virtual elements directly into our physical environment. In their work, Assor et al [9] use AR to incorporate the users' waste directly into their environment. Their work was motivated by the fact that we usually don't see the total amount of waste that we produce as it is progressively taken away. Similarly, we are rarely direct witnesses of human misery, either because it happens behind closed doors in the victims' houses (e.g.: femicides, child abuse...), in remote areas (e.g.: migration crisis, famine...), or punctually at a given time so we are most likely not to be around (e.g.: accidents, assault...).

Augmented reality offers the opportunity to incorporate empathetic visualizations directly into our personal environment which could promote perspective-taking. *"If London were Syria"* [1] is a video featuring a young Londonian girl going through a civil war in Great Britain. This charity commercial transposes the Syrian civil war in Great Britain. In this way, the British (or even Western) audience is more likely to identify with the characters in the video. This video tries to incorporate a remote human crisis directly into the audience's environment. Similarly, we believe that AR visualizations could be used for a similar purpose. We could for instance imagine an AR application similar to the one introduced in Chapter 4. While exploring data about war victims and refugees, the user could select one individual and see the victim and their family sitting in the user's living room with only candlelights, and mattresses in front of the window to protect themselves from the blast of bombs and flashes and the sound of detonations could come from behind the windows. Such a striking view could help the audience understand the experience of civil war victims.

Hence, we believe there is an opportunity to explore and compare AR and VR empathetic visualizations but also investigate hybrid AR/VR visualizations. Indeed both technologies have benefits and limitations for empathetic data visualizations and a hybrid system would allow us to take advantage of the best of each technology.

Appendix A

Supplementary Material Chapter 3

A.1 Tutorial review: heuristic evaluation

Tutorial Ergonomic Questionnaire

Reminder: Report all occurring problems even if they look like being due to a "mistake" from the user. One of the main goals of this questionnaire is actually to know whether the system is capable to assist a novice user who might make unintended actions.

A question "Additional comments" appears at the end of each section. It is meant for you to add clarification regarding some questions that would seem relevant to you or to comment a point that wasn't in the question but is related to the theme. A question "Additional comments" is also at the end of the questionnaire for any comment you couldn't categorize or you forgot.

1. Name of the application

2. Link to the web site

3. Succinctly describe the concept of the application (game, tool, what type...)

General questions

Figure A.1: Questions for the heuristic evaluation of immersive tutorials in VR. Part 1

4. What form do the instructions take?

Une seule réponse possible.

- Text
- Images
- Sound
- Video
- Animation
- 3D static elements
- Autre : _____

5. Details on the form of the instructions

6. Does the tutorial teach the user how to use the controllers?

Une seule réponse possible.

- Yes
- No
- I don't know

7. Are controllers meant to reproduce hand gestures? (Joystick for the thumb, trigger for the index and grip for other fingers)

Une seule réponse possible.

- Yes
- No
- I don't know

Figure A.2: Questions for the heuristic evaluation of immersive tutorials in VR.
Part 2

8. Additional comments

Guiding the user

The goal of this section is to know how the system guides the user through the tutorial.

9. *Une seule réponse possible par ligne.*

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The elements related to the tutorial are easily identifiable in the virtual environment.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Instructions are always in the field of view of the user.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The instructions do not occlude the virtual environment to any great extent.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The user knows easily when and what action is expected.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
There is a feedback when the user performs a task.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The user can easily identify the steps done and to be done.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
There is consistency between the different instructions.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Figure A.3: Questions for the heuristic evaluation of immersive tutorials in VR. Part 3

10. Additional comments

Compatibility

The goal of this section is to know if the application is accessible to all.

11. *Une seule réponse possible par ligne.*

Strongly disagree Disagree Neutral Agree Strongly agree

The instructions in the tutorial are feasible and understandable.

12. Additional comments

Explicit control

The goal of this section is to know the level of control the user has on the system. We don't talk here of the capacity to adapt to the user's specificities (level, preferences...). We try to know whether the system works "with" the user.

Figure A.4: Questions for the heuristic evaluation of immersive tutorials in VR. Part 4

13. *Une seule réponse possible par ligne.*

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The tutorial reacts logically to the user's actions.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Instructions do not have a timer.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

14. Additional comments

Signification of codes, denomination and behaviors

15. *Une seule réponse possible par ligne.*

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
When approaching an element, the user knows what actions he can perform.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

16. Additional comments

Figure A.5: Questions for the heuristic evaluation of immersive tutorials in VR. Part 5

A. Supplementary Material Chapter 3

Workload The goal of this section is to know the effort required from the user to perform the tutorial

17. *Une seule réponse possible par ligne.*

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The instructions are not ambiguous.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
All instructions are relevant.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Information is easy to remember for the user.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The tutorial is not physically demanding.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

18. Additional comments

Adaptability The goal of this section is to evaluate si the tutorial can adapt itself to the user's profile

Figure A.6: Questions for the heuristic evaluation of immersive tutorials in VR. Part 6

19.

Une seule réponse possible par ligne.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
It is possible to choose the form that the tutorial will take.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
It is possible to remove unnecessary instructions.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
It is possible to choose the level of the tutorial.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
It is possible to skip the tutorial.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
It is possible to redo the tutorial.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

20. Additional comments

Homogeneity and coherence

21.

Une seule réponse possible par ligne.

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
The system does not change the format of instructions without user intervention.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Figure A.7: Questions for the heuristic evaluation of immersive tutorials in VR. Part 7

22. Additional comments

Error management

The goal of this section is to know the system's capacity to react to the user's incorrect actions

23. *Une seule réponse possible par ligne.*

	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
It is not possible to accidentally quit the tutorial.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
The user knows if the action he has just performed is correct or not.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
In case of incorrect action by the user, the system gives feedback on what to correct.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
As long as the user did not do the expected action, the tutorial does not move on	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Conclusion

Figure A.8: Questions for the heuristic evaluation of immersive tutorials in VR. Part 8

24. Did you identify missing elements from the tutorial?

25. Additional comments

Figure A.9: Questions for the heuristic evaluation of immersive tutorials in VR.
Part 9

A.2 Tutorial review: equivalence table Figure 3.1

Equivalence table for Figure 1 : Results of the tutorial reviews

Intelligibility

Bar denomination	Corresponding question
Relevance	All instructions are relevant.
Format	The system does not change the format of instructions without user intervention.
Identification	The elements related to the tutorial are easily identifiable in the virtual environment.
Feasibility & Understandability	The instructions in the tutorial are feasible and understandable.
Occlusion	The instructions do not occlude the virtual environment to any great extent.
Ambiguity	The instructions are not ambiguous.
Memorization	Information is easy to remember for the user.
Field of view	Instructions are always in the field of view of the user.

Feedback and feedforward

Bar denomination	Corresponding question
Expected actions	The user knows easily when and what action is expected.
Immediate feedback	There is a feedback when the user performs a task.
Logical reaction	The tutorial reacts logically to the user's actions.
Accidental closing	It is not possible to accidentally quit the tutorial.
Consistency	There is consistency between the different instructions.
Binary feedback	The user knows if the action he has just performed is correct or not.
Steps information	The user can easily identify the steps done and to be done.
Possible actions	When approaching an element, the user knows what actions he can perform.
Corrective feedback	In case of incorrect action by the user, the system gives feedback on what to correct.

Adaptability and accessibility

Bar denomination	Corresponding question
Physical demand	The tutorial is not physically demanding.
Unnecessary instructions	It is possible to remove unnecessary instructions.
Timer	Instructions do not have a timer.
Redo tutorial	It is possible to redo the tutorial.
Waiting	As long as the user did not do the expected action, the tutorial does not move on
Skipping	It is possible to skip the tutorial.
Form choice	It is possible to choose the form that the tutorial will take.
Level choice	It is possible to choose the level of the tutorial.

Figure A.10: Equivalence table for Figure 3.1

A.3 Expert interviews

Main topics		
Expert's profile	Years of VR experience	
	Years of experience in VR onboarding	
	VR application's type	Domain
		Complexity
Onboarding conditions	Symmetrical/Assymetrical	
	Used devices	
	Environment	
	Learners' profiles	
Encountered issues	Communicating	Point
		Controllers
		Explain
	Understand the learner's experience	What they're watching
		What's around them
	Feelings	Frustration / Discouragement
		Good or bad experience
Impact on the learner's feeling		
Solutions	Already existing	Personnal solutions
		Known solutions (used or not)
	Future	Wished
		Gesture

Figure A.11: Main themes tackled during the interviews

	Is ok with you if I record the interview ?
	How long have you been working with VR?
	How long have you been doing demos in VR/teaching how to use VR applications?
	What kind of VR applications are you making demos of?
	How complex would you say these applications are?
	What kind of setup do you have when teaching VR? (symmetry, devices, environment...)
	How would you describe the VR users' profile? (knowledge in VR/computer science, purpose...)
	Could you tell me the last time you had to do a demo? How did it go?
	What would you say are the main difficulties when teaching VR?
	How difficult would you say it is to communicate with the VR user? (Pointing, controller instructions, explain)
	Do you have difficulties understanding the VR user's experience and visualizing the virtual environment?
	What consequences would you say the difficulties have on the VR user's VR experience and yours?
	Do you think that your demo sessions significantly improved since you began?
	Did you find or developed some solutions to overcome these difficulties ?
	Have you heard or tried other techniques ?
	Can you think of other techniques or methods you wish existed?
	Can you remember a time where you were doing gestures while communicating and realized the VR user couldn't see you? Do you think that enabling gestural communication would help ?

Figure A.12: Leading questions during the interviews

Appendix B

Supplementary Material Chapter 4

B.1 Guidance support during the user study

Phase d'entraînement

Avant de mettre le casque - Présentation du matériel :

Montrer les contrôleurs : Nous allons commencer par voir les contrôleurs. Il s'agit de deux manettes à tenir dans la main (*montrer comment les tenir*). Ces manettes sont détectées dans l'espace donc elle définiront la position de vos mains en réalité virtuelle.

Pour cette expérience, nous utiliserons principalement ce bouton du contrôleur (*montrer la gachette*). Je l'appellerai la **gachette** lorsque que nous échangerons oralement. Vous pouvez appuyer dessus avec votre index.

Une fois le casque mis, je vous passerai les contrôleurs, je vous demanderai en revanche de mettre et serrer les dragonne.

Montrer le casque : Ceci est un casque de réalité virtuelle Oculus Quest 2. Pour le mettre, il suffit tout d'abord de le desserrer avec la molette, de poser le casque sur la tête puis ajuster le casque avec la molette et la sangle au dessus. Si vous y voyez flou, il est possible que le casque soit mal ajusté (pas assez serré ou pas aligné avec vos yeux).

Une fois en VR :

Il est possible que vous ayez un message en face de vous qui vous demande de valider la session en cours. Si c'est le cas, vous devriez avoir en face de vous un cadre gris avec écrit en haut "Edwige Gros", une photo d'avatar et en dessous, deux boutons "Switch User" et "Continue". Vous pouvez cliquer sur le bouton bleu "Continue" en le visant avec un contrôleur et en appuyant sur la gachette.

Vous êtes à présent dans une scène d'entraînement. Les techniques d'interaction dans cette scène sont les mêmes que pour la scène de visualisation de données. L'objectif est donc de vous entraîner ici afin d'être plus à l'aise au moment d'explorer la visualisation de données.

Premièrement, je vous conseille pour toute la durée de l'expérience de faire des mouvements doux et pas trop rapides pour interagir avec la scène, ça permet d'éviter des transitions trop violentes.

Vous avez devant vous un monde vertical. Vous pouvez le faire **glisser** horizontalement ou verticalement en le visant avec un contrôleur et en maintenant la gachette appuyée. Un peu comme pour faire bouger une image sur un écran tactile.

A gauche de la visualisation, vous avez un **bouton**, vous pouvez cliquer dessus en le visant et en appuyant sur la gachette. Une fois cliqué, le message sur le bouton devrait changer. En revanche il ne se passera rien, c'est juste pour apprendre à cliquer.

On peut ensuite passer à l'étape suivante en **zoomant**. Pour cela, c'est encore une fois comme sur un téléphone, vous pouvez, avec vos deux contrôleurs, viser la scène, appuyer sur les gachettes et écarter les points pour zoomer. Je vous conseille de bien espacer les deux pointeurs pour plus de précision. Attention, au delà d'un certain niveau de zoom la scène va basculer pour se retrouver en position horizontale en dessous de vous.

Teleport

Figure B.1: Guidance support during the user study. Part 1

Nous sommes avec la scène en position horizontale. Vous pouvez vous déplacer un peu en marchant, cependant vous allez vite être limité en distance. Vous avez donc deux autres possibilités, une première possibilité est de faire bouger la scène horizontalement (comme quand elle était verticale) en visant le sol et en appuyant sur la gachette. Vous pouvez aussi vous **téléporter** en visant un point au sol et en cliquant brièvement. Si vous avez l'impression que ça ne fonctionne pas, essayez de cliquer plus près, nous avons limité la distance de téléportation afin d'éviter de se téléporter trop loin par erreur.

Dernière étape de l'entraînement ! Il y a des **sphères** dans la scène, vous pouvez les attraper en appuyant sur la gachette. Soit directement avec votre main, soit avec la petite boule du laser, en revanche assurez vous que le laser soit court car il faut ensuite plonger votre tête dans une sphère pour être projetée dans une scène 360.

Scène 360

Vous pouvez regarder autour de vous. Pour quitter la scène, vous pouvez rattraper la sphère au niveau de votre tête et l'éloigner.

Pause (Retrait du casque)

Phase d'exploration de la visualisation

Avant d'être en VR:

Avertissement:

“Les données visualisées aujourd'hui sont les données sur les féminicides conjugaux présumés en France pour l'année 2022, recensés par le collectif Féminicides par compagnons ou ex. Nous tenons à préciser que certaines enquêtes sont toujours en cours.”

Pour rappel, à la suite de cette expérience, nous aurons un entretien dont l'objectif sera de collecter vos impression concernant, non seulement les données, mais également ce type de visualisation. Ce serait donc bien d'essayer de garder en tête les réflexions que vous allez vous faire et votre ressenti pendant la phase d'exploration. Vous pouvez bien évidemment partager ces dernières à voix haute pendant l'exploration si vous pensez que ça ne vous gênera pas.

En VR:

Vous avez face à vous un graphique en barre qui représente les proportions de victimes en fonction de leur âge. Il est normal que le graphe n'ait **pas d'axe des ordonnées** car à ce stade, seules les proportions et la répartition nous intéressent. Vous pouvez réutiliser les commandes testées pendant la phase d'entraînement. Vous pouvez faire bouger la visualisation en maintenant la gachette appuyée.

Prenez un instant pour analyser ces données. Que remarquez vous ?

Vous pouvez tester d'autres variables en visant et cliquant sur les boutons à gauche. Vous pouvez les trier également par cause de décès ou en fonction du mois de décès. **Si vous regardez les causes de décès pour commencer, quelles sont les trois causes les plus communes ?**

Figure B.2: Guidance support during the user study. Part 2

Regardons à présent par mois de décès. **Quels sont les mois avec le plus et le moins de féminicides ?**

Avant de continuer, je vous laisse choisir la variable qui vous intéresse le plus.

Si vous zoomez doucement vous pourrez découvrir le nombre de victimes pour chaque catégorie.

Zoom

Ici, chaque cube représente une femme victime de féminicide. **A votre avis, combien y a-t-il de victimes au total ? (Réponse: 113)**

Je vous laisse observer un moment la visualisation puis vous pourrez continuer à zoomer.

Zoom -> Avatars

A présent, vous pouvez soit cliquer, soit zoomer à un endroit de la visualisation pour vous retrouver à cet endroit. Cela fonctionne de la même manière que dans la scène d'entraînement.

Zoom -> Bascule

Vous vous retrouvez à présent au milieu d'avatars représentant les victimes. Vous pouvez vous déplacer soit en faisant glisser la visualisation en visant le sol, soit en cliquant à un endroit.

En vous approchant des avatar, vous verrez un panneau apparaitre avec des informations sur cette personne. **Pouvez vous me lire les informations de l'avatar le plus proche de vous ?**

N'hésitez pas à vous balader pour en découvrir plus sur les victimes.

Il y aura également une sphère qui apparaîtra devant chaque avatar. Comme pendant l'entraînement, vous pouvez l'attraper et vous projeter dans une vue à 360° en l'approchant de votre tête. Ces vues à 360° représente la vue google maps de l'endroit où les victimes ont été tuées. N'hésitez pas à explorer plusieurs vues à 360° pour comparer ces endroits.

Si vous explorez les données, pouvez vous trouver des noms de villes que vous connaissez ?

Attrape une sphère -> Vue 360°

Quand vous souhaitez quitter la vue, il vous suffira de cliquer sur le bouton X indiqué sur votre contrôleur gauche, ou de rattraper la sphere, comme pendant l'entraînement.

Quitte la vue 360°

Je vous laisse continuer à explorer la visualisation. N'hésitez pas à faire des aller-retour entre les différents niveaux, comme par exemple retourner à l'étape du graphique en barres pour changer la variable de tri.

Pouvez vous trouver Emilie Leclercq ? Elle a été abattue le 21 avril 2022 et avait 89 ans. (Donner uniquement l'info pertinente en fonction de la variable choisie)

Figure B.3: Guidance support during the user study. Part 3

B.2 Main questions during the semi-structured interviews

Catégorie	Question
<p>Au cours de cet entretien, je vais vous poser des questions. Il faut savoir qu'il n'y a jamais de bonne ou mauvaise réponse. Je n'attends pas de réponse spécifique de votre part, mon objectif est de comprendre votre expérience d'exploration de la visualisation. Vous avez le droit de ne pas savoir, ne pas vous souvenir ou ne pas vouloir répondre.</p>	
Rappel	<p>Pour commencer, je vous propose qu'on refasse la chronologie des étapes que vous avez suivie lors de l'exploration. Vous rappelez vous de la première chose de vous avez faite ?</p>
Pensées spontanées non orientées	<p>A présent je vais vous mentionner les différentes étapes que nous venons d'évoquer et je souhaiterais que vous me fassiez part de vos réflexions, ce que vous avez pensé ou ressenti à chaque fois.</p>
Comprendre les apriori, est ce que la personne a découvert/appris des choses.	<p>Avant d'explorer la visualisation, aviez vous des aprioris sur ce que vous alliez découvrir ? Aviez vous une idée de ce que vous alliez voir ?</p>
	<p>Cela correspondait il à ce que vous avez effectivement expérimenté ?</p>
Emotions et empathie	<p>Y a-t-il une ou plusieurs personnes représentées qui vous ont marqué ? (Demander de développer si besoin) Qu'avez vous ressenti ?</p>
	<p>Vous êtes vous imaginé à la place d'une de ces personnes ? Qu'avez vous ressenti ?</p>
	<p>Avez vous comparé certaines informations visualisées avec votre cas personnel ? (Demander de développer si besoin)</p>
<p>Revenons à présent sur la visualisation en elle même.</p>	

Figure B.4: Main questions during the semi-structured interviews. Part 1

B.2. Main questions during the semi-structured interviews

Feedback sur la visualisation	La visualisation peut se découper en plusieurs étapes. On a d'abord un graphique en barre, puis la barre est divisées en cubes qui se transforment en avatars, puis vous pouvez marcher au milieu des avatar et enfin vous pouvez explorer une vue à 360°. On va appeler transition le passage d'une étape à une autre. Comment décriveriez vous ces transitions ?
	Pendant l'expérience, y a-t-il un ou plusieurs moments où vous avez ressenti de la confusion ou de la frustration ? Ou alors comme impression générale ? (Demander de développer si besoin)
	Avez vous le sentiment que quelque chose était manquant ou inadéquat ?
Il faut savoir que chaque année, le gouvernement publie un rapport avec des données agrégées sur les morts violentes au sein du couple. Par agrégées, je veux dire que nous n'avons pas d'informations sur les victimes individuellement. Nous avons ici un extrait de ce rapport. Je vous laisse regarder un peu ces informations et nous pourrons en discuter ensuite. N'hésitez pas à commenter à voix haute pendant que vous lisez. Prévenez moi quand vous aurez terminé.	
Comparaison avec données agrégées	Quelle est votre première impression après lecture de ces informations ?
	Que pensez vous que ce rapport vous apporte de plus ou de moins par rapport à la visualisation en réalité virtuelle ?
Je n'ai plus de questions. Merci beaucoup d'avoir répondu à mes questions. Nous tenons à rappeler que parmi les cas de féminicides visualisés aujourd'hui, certains pourraient ne pas être avérés. Pour information, notre visualisation recense 113 victimes, le gouvernement quant à lui rapporte 118 cas de femmes mortes suite à des violences au sein du couple. Nous ne pouvons cependant pas assurer que les 113 cas sont tous compris dans les 118 cas comptabilisés par le gouvernement. J'ai ici, la version complète du rapport du gouvernement que je peux vous laisser si vous êtes intéressé. Si vous le souhaitez, je vous propose un moment d'échange plus ouvert. Ce moment est prévu pour répondre à toutes votre interrogations ou décharger vos émotions.	

Figure B.5: Main questions during the semi-structured interviews. Part 2

B.3 Extract of the government report presented to the participants

Extrait de l'Etude Nationale sur les Morts Violentes au Sein du Couple 2022

MINISTÈRE
DE L'INTÉRIEUR
ET DES OUTRE-MER
*Liberté
Égalité
Fraternité*

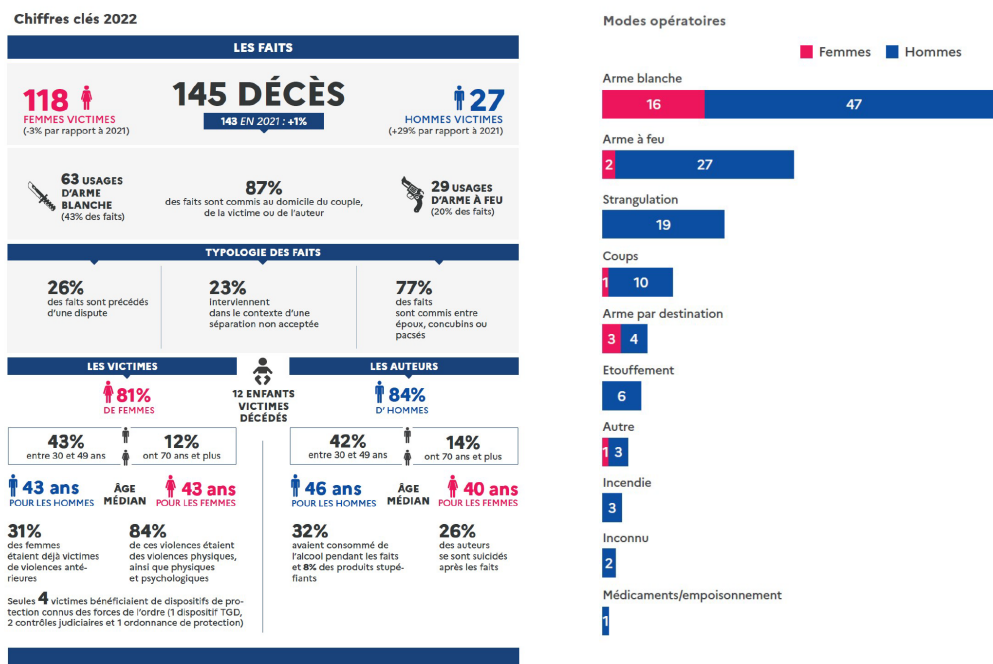


Figure B.6: Extract of the government report presented to the participants. Part 1

B.3. Extract of the government report presented to the participants

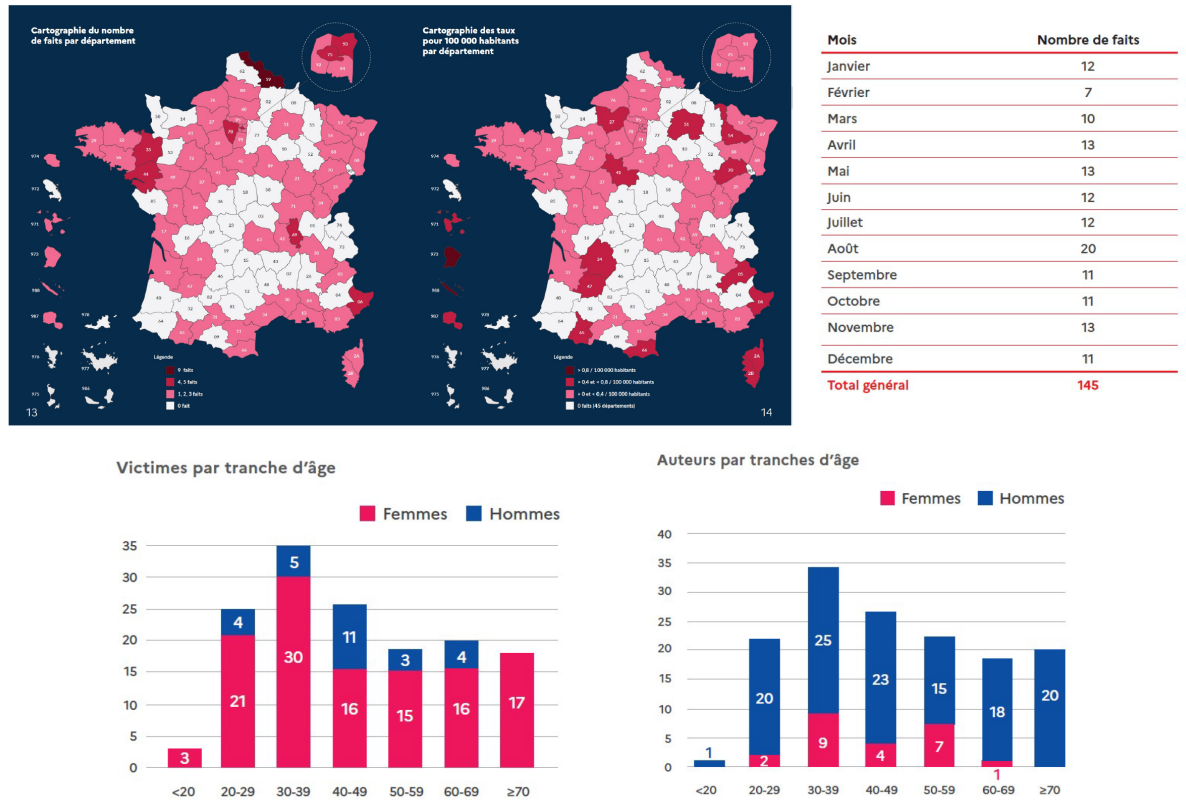


Figure B.7: Extract of the government report presented to the participants. Part 2

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