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IMMERSE. INTERACT. INVESTIGATE

INFINITY

D3.1 Research report on immersive reality, collaborative, and analysis methods

PUBLIC

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EXECUTIVE SUMMARY

This deliverable details five key areas: the current systems used for CSCW, data analysis and its uses in CSCW, the effectiveness of CSCW, XR applications and hardware, and visualisation techniques for data analysis. Each of these areas examines existing research and from that research guidelines and opportunities are provided. These guidelines are intended to help inform future developers of data analysis systems that want to utilise XR to improve immersion and collaboration. The guidelines cover the hardware considerations that need to be made, the opportunities available for CSCW specific for data analysis in XR, and considerations for building the XR environment. The INFINITY project is expected to also follow these guidelines.

ABBREVIATIONS

2D	Two-dimensional
3D	Three-dimensional
3DOF	3 Degrees of Freedom
6DOF	6 Degrees of Freedom
AR	Augmented Reality
AWF	Analysis Work File
CAVE	Cave Automatic Virtual Environment
CSA	Cyber Situational Awareness
CSCW	Computer Supported Cooperative Work
EEG	Electroencephalography
FIESTA	Free-roaming Immersive Environment to Support Team-based Analysis
FLINTS	Force Linked Intelligence System
FOV	Field of View
HD	High-Definition
HMD	Head-Mounted Display
ICE	Interactive Collaborative Environments
IPD	Interpupillary Distance
IR	Infrared
LEA	Law Enforcement Agencies
LCD	Liquid Crystal Display
MAUVE	Multi-criteria Assessment of Usability for Virtual Environments
MR	Mixed Reality
MS	Member States
NLP	Natural Language Processing
OLED	Organic Light-Emitting Diode
PC	Personal Computer
RGB	Red, Green, Blue
SA	Situational Awareness
SLAM	Simultaneous Location and Mapping
SOC	Security Operations Center
sRGB	Standard Red, Green, Blue
TP	Third Parties
UHD	Ultra-High Definition
VE	Virtual Environments
VIA	Virtual Investigative Assistant
VR	Virtual Reality
WMR	Windows Mixed Reality
XR	Extended Reality or Cross Reality

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1 INTRODUCTION

1.1 OVERVIEW

This deliverable is known as D3.1 and is titled "Research report on immersive reality, collaborative, and analysis methods". It will review existing research on XR applications, CSCW, and data analysis with specific focus on how it can be applied to the security domain. Finally, guidelines will be provided for any future applications that are seeking to develop data analysis systems in immersive reality as well as considerations for CSCW in these applications.

1.2 DELIVERABLE POSITIONING

This deliverable aims to produce guidelines to be considered when developing the INFINITY project. Future development within INFINITY should refer to the research here to get an indication of the best way to develop the environments and use the lessons learned by other researchers to ensure innovation is being developed.

This deliverable aims to provide input on the considerations needed for:

- Which XR hardware to choose
- Developing virtual environments
- Creating immersive data analytics
- Inter-organisational collaboration

These guidelines can also be applied to any other applications that wish to develop collaborative or data analytical systems within XR.

1.3 DELIVERABLE STRUCTURE

This deliverable is structured with six main sections:

- Existing intelligence data analysis systems in collaborative environments. This section discusses the meaning of intelligence data analysis, current collaborative data analysis systems used by LEAs that have been discussed in the public domain, and currently data analysis systems that exist within XR.
- Data analysis in collaborative working spaces for CSCW. This section looks at current CSCW systems and what needs to be considered with regards to the team, remote collaboration, handling data, and specifically how this applies to LEAs.
- Effectiveness of collaborative environments. This section discusses the different types of collaboration and the effects those may have.
- XR technologies. This section looks at the current state of the art for XR. As technology is continually evolving, the different technologies that need to be considered is discussed.

- Visualisation for advanced data analysis. This section looks at data analysis and how the different visualisation techniques can be used and applied. The considerations are on 2D graphs, 3D graphs and how those can be considered in immersive technology.
- Guidelines and opportunities. The final section of this deliverable brings together guidelines from all the other sections to provide an easy reference point. It also highlights any opportunities that may be interesting to develop.

2 EXISTING INTELLIGENCE DATA ANALYSIS SYSTEMS IN COLLABORATIVE ENVIRONMENTS

To develop a flagship collaborative analysis environment, current practices and procedures need to be thoroughly understood so they can be sufficiently implemented and improved upon. This section introduces Computer Supported Cooperative Work (CSCW) and its role within intelligence data analysis and how it can be used collaboratively.

2.1 INTELLIGENCE DATA ANALYSIS

Intelligence data analysis is referred by Famili (1999) as techniques that include: all areas of data visualisation, data pre-processing (fusion, editing, transformation, filtering, sampling), data engineering, database mining techniques, tools and applications, use of domain knowledge in data analysis, big data applications, evolutionary algorithms, machine learning, neural nets, statistical pattern recognition, filtering, and post-processing.

Intelligence data analysis is heavily supported by Computer Supported Cooperative Work (CSCW). "CSCW is a generic term which combines the understanding of the way people work in groups with the enabling technologies of computer networking and associated hardware, software, services and techniques" (Wilson, 1991, p. 1).

The main task of intelligence data analysis is to sort through vast amounts of data and combine seemingly unrelated events to construct an accurate interpretation of a situation. These datasets are typically represented with a collection of sources such as written and oral reports, photographs, satellite images, maps, and numeric data tables (Hutchins, Pirolli, & Card, 2006).

The goal is to help users understand these datasets and make difficult judgments to access the relevance, reliability, and significance of these intricate pieces of information and combine them with their empirical knowledge in a collaborative environment to identify solutions and patterns to a problem (Hutchins, Pirolli, & Card, 2006).

2.1.1 THE ROLE OF COLLABORATION

Collaboration is an important aspect of intelligent data analysis. The process sees a collective focus of two or more researchers regarding a shared body of data and the correct interpretation of these data sets. Collaborative data analysis has many benefits such as confirming another analysists work, constructing new ideas, and bringing a diversity of perspectives to the analysis by comparing and producing less opinionated and more accurate results.

Choi & Tausczik (2017) performed a research study using a model developed by Lee and Paine (2015) called the Model of Coordinated Action framework to describe collaboration in open data analysis projects. They looked at the characteristics of collaboration in the emerging practice of open data analysis found that collaboration was an essential part of 89% of open data analysis projects.

The model developed by Lee and Paine (2015) said that collaboration can be expressed and measured across seven dimensions in data analysis. These dimensions are scale, turnover, planned permanence, number of communities of practice, synchronicity, physical distribution, and nascence. Each dimension will be looked at to fully understand the effects of it on CSCW.

The scale dimension refers to the team's size and structure, for example, how many people were working on the team full time or part-time and the nature of the contribution to the project, such as providing guidance, feedback or conducting analysis. Another factor that influences scale during a project is the degree that the team's conclusions and findings were made public for anyone to access during the project.

Turnover measures how often people join or leave the team during a project. This is often related to the resources and the budget of a project.

Planned permanence refers to the duration of the project and the end goal the researchers want to achieve. Most of the projects have a specific goal they want to achieve, which has an immediate impact on the duration of the project.

Communities of practice describe the background of the participants and their collaborators. This can often range from software development to data science, journalism, and city government, depending on the research project, and the number of different groups highlights the cultural diversity.

Choi & Tausczik (2017, p. 840) said "A community of practice is a collection of people who share norms, practices, expertise, and tools.". They found most of their interviewees reported to have at least one person who acts as a domain expert and one person who is a technical expert. The first is responsible for providing information about the large picture of the data, and the second is responsible for analysing and displaying the results.

Synchronicity and physical distribution refer to the communication between the group members and the physical or remote sharing of information. Choi & Tausczik (2017) found that synchronous communication was critical for some projects because of the interdisciplinary nature of the groups in which domain and technical experts took on different roles. According to them, most of the groups relied on synchronous information channels such as face-to-face meetings, audio calls, and video calls for communication.

Nascence is the degree to which a coordinated action is new and developing versus old and established (Lee & Paine, 2015).

The results of the study performed by Choi & Tausczik (2017) (which used the Model of Coordinated Action framework) revealed that many participants experience some degree of uncertainty in their work. It is not clear whether this uncertainty is an inherent part of data analysis or whether the uncertainty will be reduced as open data analysis practices become more established. This uncertainty is something that CSCW may want to examine in future experiments. There is also the possibility for XR to affect this uncertainty as well.

2.2 CURRENT COLLABORATIVE DATA ANALYSIS SYSTEMS IN LEAS

Data analysis systems play a significant role in law enforcement agencies. Mobile communications, social media and the rise of the web have increased the environment that law enforcement agencies need to police to investigate and utilize illicit activities and organized crime (Keyvanpour, Javideh, & Ebrahimi, 2011).

2.2.1 COLLABORATIVE INVESTIGATION SYSTEMS

Crime recording and investigation systems can be categorised into three main areas, major crime, volume crime and data combination systems. Adderley (2007) found that many of the crime and volume systems currently in place have been developed by the police internally and revolve around investigating crimes that have already been committed and are classified as reactive.

They reported that these data combination systems use several disparate police sources with advanced data analysis techniques such as data mining, artificial intelligence, and data mapping technics to act proactively and reactively in crime analysis. These programs are used by law enforcement agents to process large crime datasets and conduct crime analysis, including exploring and detecting crime patterns and their relationships with suspects and criminals.

An example of a data analysis system used in LEAs is FLINTS – the Force Linked Intelligence System (West Midlands Police, 2014). FLINTS provides information on forensic intelligence, geographical profiling, prolific offenders, and other data points such as names, addresses, vehicles, and telephone numbers. It then combines these data sets to identify the current problems to a specific area of interest by predicting and analysing the criminal network of a suspect. FLINTS can link offenders who have been arrested and charged for the same offence or there is forensic evidence like fingerprints and DNA that connects two offenders on a previous crime (Adderley, 2007).

2.2.2 DATA MINING TECHNIQUES & APPLICATIONS

The primary data mining techniques that have been used for crime analysis are entity extraction, cluster analysis, association rule mining, classification techniques and social network analysis (Hassani, Huang, Silvia, & Ghodsi, 2016). These advanced data mining techniques are used in data mining applications to focus on structured and unstructured data collection to detect crime patterns. Hassani, Huang, Silvia, & Ghodsi (2016) reviewed the different techniques and applications used in data mining.

"Entity Extraction is the process that automatically identify particular patterns or significant information that is essential for corresponding analysis" (Hassani, Huang, Silvia, & Ghodsi, 2016). Entity Extraction tools can extract specific data from unstructured text such as crime data from witness narratives by combining natural language processing (NLP) and text mining.

Cluster Analysis is the technique of grouping similar objects together that are more similar than objects in another group. Murray & Grubesic (2001) outline using cluster analysis alongside a Geographic Information System to identify crime hot spots within a local area, they state that "combining cartographic visualization of crime events with statistical tools provides valuable insight for detecting areas of concern."

Hassani, Huang, Silvia, & Ghodsi's (2016) research suggested one of the most successful implementations of the clustering technique is CopLink (Coplink, 2021). CopLink uses "a statistics-based, algorithmic technique that identifies relationships" (Hauck, Atabakhsb, Ongvasith, Gupta, & Chen, 2002, p. 30), this can used to find links between suspects, victims, and other data quickly and efficiently, enhancing law enforcement efforts.

Association rule mining is a technique that tracks the relationships between observations, uncovering information in large datasets, used commonly "for applications where observations consist of transactions, and a subset of the available items appears in each transaction" (Hassani, Huang, Silvia, & Ghodsi, 2016, p. 143). Association rule mining was first proposed by Agrawal, Imielinski, & Swami (1993) and was used in the context of supermarket data, finding which sets of items were frequently purchased together and then being able to determine a confidence score for the probability. Since the introduction of association rule mining, researchers such as Buczak & Gifford (2010) have used the same approach to find crime patterns at a community and national level across America.

Classification techniques are one of the more fundamental approaches for identifying and clarifying observations based on rules and attributes mined from a database. Decision trees, neural networks and Bayesian Belief Networks are classification techniques that have been used collectively in crime data mining for identifying suspicious emails with a 95% success rate (Hassani, Huang, Silvia, & Ghodsi, 2016).

Social Network Analysis (SNA) is a method of analysing and investigating social structures among observations for locating important information. An application that implements social network analysis is the SocialNet that assists law enforcement agencies in discovering suspects' identities and establishing connections and correlations in a crime group with geographical information (Shadow Dragon, 2021).

Each of the data evaluation techniques; entity extraction, cluster analysis, association rule mining, classification techniques and social network analysis, all demonstrate merit and importance for crime detection, analysis, and prevention. The correct application of these techniques provides an efficient method for revealing relationships across Big Data and have become a common practice for crime analysis (Hassani, Huang, Silvia, & Ghodsi, 2016). The understanding of these techniques, and their implementation may be critical to the success of projects that wish to provide data analysis.

3 DATA ANALYSIS IN COLLABORATIVE WORKING SPACES FOR CSCW

CSCW has seen various iterations and is used in a vast range of industries. Interactive Collaborative Environments (ICE) use the traditional CSCW concept and focus further on the dedicated spaces that support group work on more complex tasks. These spaces normally involve a number of constraints including considerations for physical space and the budget required.

Benyon & Mival (2015) utilise an ICE environment, consisting of an interactive boardroom table, and wall mounted multi-touch screens. They describe a blended space where “analogue media should co-exist happily alongside the digital space” (Benyon & Mival, 2015, p. 10). Combining the two mediums creates a place for the user to be able to take on new activities or even perform their traditional activities in a new way that may provide insights that would otherwise be unavailable.

The performance of data analysis activities is essential for the LEAs and depends on data managment, collaboration and decision making. Data analysis can be performed alone but often culminates into a collaborative activity. It is the sum of joint and interdependent activities to achieve a common goal (Hauber, 2008), such as abstraction, inference, and synthesis. During the collaboration, team members make a joint effort to align and integrate their activities in a “transparent” manner and without interruption (Schmidt K. , 2002). In this regard, Gea, Gutiérrez, Garrido, & Cañas (2002) define four components impacting the collaborative system:

1. the **group** (groups, roles and actors)

2. the **cognitive processes** (self-regulation, motivation),
3. the **interactions** (protocols, devices, media) and
4. the **information** (resources, documents, messages).

Driskell (1987) also explain that a team's performance is influenced by three factors,

1. the **individual-level factors**, the skills and knowledge of each team member;
2. the **group-level factors**, the organisation (co-located or remote, internal, external);
3. and the **environment-level factors**, the nature of the task, here data analysis, and the nature of the environment for collaboration, as virtual or real environment.

3.1 EXISTING CSCW PROTOCOLS AND GAP ANALYSIS

As the INFINITY project aims at implementing a collaborative environment assisted by computer, based on Computer Supported Cooperative Work (CSCW), it is important to understand what the existing CSCW protocols are and understand the gaps that are present.

CSCW has been the focus of many studies in the last ten years, responding to the new needs of working with remote and/or external collaborators. CSCW can be designed for a cooperative work arrangement (Bannon & Schmidt, 1989) utilising different skills, goals, and interactions of team members, in addition to upgrading the environment to upgrade to improve team performance (Schmidt & Bannon, 1992) .

3.1.1 TEAM CONFIGURATION IN CSCW

Even before CSCW configuration research, researchers focused on the factors that influence collaboration among members of a team, such as group size, task structure, and group composition, which influence the quality and quantity of contributions during a task of data analysis and problem solving (Nunamaker Jr, Briggs, & Mittleman, 1996). Today, CSCW researchers build their own studies based on this paper, as understanding collaboration tasks is an important issue in the development of team configuration in CSCW. CSCW are mediating tools for collaboration between users, using different information and data. Therefore, immersive virtual environments can be considered as CSCW tools (Casarin, Pacqueriaud, & Bechmann, 2018). On this topic, the authors have listed characteristics that a CSCW system must consider to effectively support collaborative tasks (see Section 4.1).

Zhang (2008) developed a theory, listing ten principles to take into consideration when designing technology supporting collaboration activities. This theory is called the Motivational affordance and demonstrates the importance of motivation on user behaviour and performance. This theory was used to extract recommendations of use for CSCW system.

Table 1: Design principle for achieving motivation information and communication technology. Adapted from Zhang (2008)

Motivational needs	Design principle	Primary Theoretical Base	Recommendation for CSCW
Psychological: Autonomy of the Self	*Principle 1.* Support autonomy *Principle 2.* Promote creation and representation of the identity of the self	Self-determination theory. (Deci & Ryan, 1985)	The collaborative environment must grant the user autonomy in completing tasks and possibility to exercise choice, e.g: no time limit for completing a task in the informative environment. The ability to modulate the avatar can support the self-definition.
Cognitive: Competence and achievement	*Principle 3.* Design for optimal challenge *Principle 4.* Provide timely and positive feedback	Flow theory. (Csikszentmihalyi, 1975) (Csikszentmihalyi, 1990); Goal theories (Elliot & Church, 1997)	Users of communication technology and CSCW need to feel competent and motivated to exert effort to overcome optimal challenges, but the complexity must match their current capabilities. E.g. Expert and non-expert mode should be proposed for some specific tasks of data analysis. The system provides feedback.
Social, psychological: Relatedness	*Principle 5.* Facilitate human-human interaction *Principle 6.* Represent human social bond	Social interaction studies (Baumeister & Leavy, 1995)	Principles five and six are concerned with the human need to form close emotional bonds and attachments. It is important that the system allows interaction with others involving representation of human social bonds (audio, message, game Visio, avatar)
Social, psychological: Power leadership, followership	*Principle 7.* Facilitate one's desire to influence others. *Principle 8.* Facilitate one's desire to be influenced by others	Affect control theory (Heise, 1985)	The seventh and eighth principles refer to the need for organisation and alignment between the social world and the personal plan (personal and team goal, organisation, role). The system must support the process of negotiation to promote the building of a common ground and a shared representation of the situation. (See also D2.1)

Emotional: Emotion and affect	*Principle 9.* Induce positive emotions via information and communication technology surface features *Principle 10.* Induce intended emotions via information and communication technology interaction features	Affect and emotion studies (Russell, 2003); (Sun & Zhang, 2006)	Principles nine and ten developed the importance to consider the impact of CSCW system, and avoid negative affect. Helping negotiation and communication can help job satisfaction, problem solving and decision making, and eventually the collaboration.

The different theories mentioned in Table 1 provide awareness that numerous of studies already exist in this field and provide information on CSCW and how collaboration in data analysis can work. Today CSCW is often tied to virtual environments (VE) and tools in AR or VR are mediating collaboration between users and information. Seeing the impact of the human needs behind collaboration and motivation, the different types of collaboration are discussed in Section 4.

3.1.2 LOCATION AND TEMPORALITY OF COLLABORATIVE WORK

CSCW offer the possibility of new kinds of interaction and collaboration, particularly around geo-location. Until recently, team members had to go on the same space to collaborate, to have discussion and share documents. Today, CSCW and many tools allow team members to do remote collaboration, being physically in different places, co-location is no longer required to collaborate thanks to the new digital tools allowing communication (Zoom, Teams), virtual whiteboards (Visio), and document sharing (SharePoint; screen sharing).

Another point to take into consideration when we work on collaboration is the temporality of the work of team members: whether they are working synchronous (on the same time) or asynchronous (on different moments). Collaboration is often synchronous but may also be asynchronous, for various reasons. For instance, because the different members have their own tasks, and it can be difficult to find time to work together on the same tasks. Alternatively, some different tasks can be interdependent and team members must provide different inputs before the meeting.

Because different configurations of location and temporality lead to different types of interactions, researchers have developed principles of interaction design. Digital ecosystems, such as VE for CSCW, bring remote collaboration. This framework is then centred on remote collaboration with different temporalities: simultaneous, i.e. synchronous and sequential, i.e. asynchronous. The proposed framework identifies four dimensions: Communality, Continuity, Collaboration and Complementarity. This 4C framework, shown in Figure 1, can help to design the interaction according to the characteristic of the collaboration (Sørensen, Raptis, Kjeldskov, & Skov, 2014).

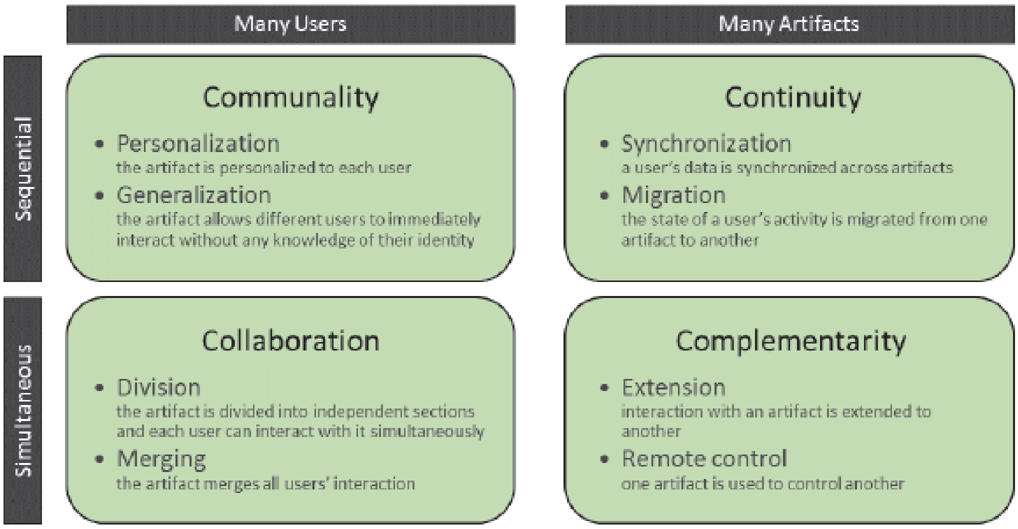

Figure 1: The 4C Framework of principles for interaction design in digital ecosystems (Sørensen, Raptis, Kjeldskov, & Skov, 2014)

As the CSCW projects could involve many LEAs using large datasets for data analysis, we can use the principle of the two column "many users" and "many artefacts", to design the interaction according to the temporality of the LEAs actions tasks.

Designing the interaction on the Virtual Environment is important as good communication is essential and determinant for the performance of remote team. The principal issue of remote collaboration is to communicate and to be able to share a common ground and understanding. Collaboration aims to do a task and resolve a problem. But to do that team members have to negotiate, work on data analysis, find information and share it with other team members, to construct together a good situational awareness.

A Cyber Situational Awareness model was specifically developed for LEAs and Cybersecurity (Tadda & Salerno, 2010). This topic is further developed in D2.1. Developing a situational awareness (SA), and more precisely Cyber Situational Awareness (CSA), requires sharing a common representation, which may be complicated in remote collaboration. To that regard, VE can provide a shared and common area to work, an area of meeting and help to have a first common ground. Also, if well designed, the interactions can be facilitated that can reduce the friction on the development of common understanding. The CSCW can contribute to a good CSA and the decision making and problem solving can gain in efficiency and time.

Finally, it is important to have a look on the number of participants that can be involved on the CSCW system. The optimal number of participants depends on the purpose of the meeting. When the purpose is to present information, as in a conference, there is no maximum number of participants and the issue is much more about awareness than collaboration. When the purpose is collaboration, it is interesting to have a look at the theory of group dynamic, proposed by Anzieu & Martin (1971), psychological and social researchers. They found out that for collaboration, to exchange and find a solution on one subject, the group must be between two and six participants maximum. Beyond six participants, collaboration can be deteriorated, with less participation due to a certain fear of the other judgments (Newman, 1990) (Newman, 1990; Newman, 1990)or also dissemination of responsibility (Darley & Latané, 1968).

Anzieu and Martin (1971) also explain that if roles and goals are perfectly defined and tasks planed, groups can go between six to twelve participants maximum. They determined that the ideal size of participants is between two to five to solve a specific problem, two to six to solve several problems, and twelve to fifteen to obtain new idea or exchange opinions. Care must be taken with this number because the research made to find them was in co-located and synchronous situation. For remote collaboration, synchronous, a maximum of six participants is proposed, to be able to communicate with everybody without having issue to hear, understand, and share opinions and documents. To finish, it must be noted that effective communications depend on the consistency of members: "Homogeneity of the level of culture and of mental frames of reference" (Anzieu & Martin, 1971, p. 9). To collaborate more efficiently, a homogenization of the frame of references can be made before the collaborative task, and a shared space, as it is possible with VE on CSCW can help to increase the consistency between team members.

3.1.3 DATA HANDLING IN CSCW

Dealing with complex and multiple data is a main concern for LEA activities, and CSCW can be a good tool to manage this. But some problems can emerge with data handling in CSCW.

First, the communication can impact data handling. As we have seen before, communication can be synchronous, that can help to work on the same time on the same data, but also asynchronous. Distributed collaboration (in space and time) can require more concentration, to understand other and give feedback (Wang & Dunston, 206).

A lack of feedback can bring to a feeling of discomfort and lead the partner to be more polite and take more time and concentration to communicate. This phenomenon can also be due to a misunderstanding of the role of each LEA, the tasks related to each user on the CSCW system but also the grade and the authority. The system must provide indication of the grade, to facilitate identification of users and feedback request. Also, role and tasks should be accessible and quickly identifiable to help self-regulation of activity (Pintrich, 2000).

The number of people should be restrained to avoid group effect (six maximum, see Section 3.1.2) as motivation decrease. Motivation is identified as an important factor of effective collaboration (Jung, Schneider, & Valacich, 2010), and feedback on task making is considered to improve motivation, especially when goals and tasks are well defined.

Narayan, Waugh, Zhang, Bafna, & Bowman (2005) in their study warn on the impact of asymmetric levels of immersion for communication and collaboration. They find that different levels of immersion (computer vs virtual reality) can create different representations and different cognitive models of the complex data representation. Such discrepancies on mental representation and situational awareness can lead to more effort to communicate on the same data (Endsley, 2000). Slater, Sadagic, Usoh, & Schroeder (2000), have shown that people with the highest level of immersion tend to take the leadership, high level of immersion is also associated to better performance for collaborative task.

Finally, Olson & Olson (2000) also supported the idea of the importance of distance (remote work), and they focus on four sociotechnical conditions, required for effective remote work: common ground, coupling of work, collaboration readiness, and collaboration technology readiness.

Accordingly, CSCW can be useful for data handling:

First, CSCW provide a common spatiality reference. People and objects, as data, can have a common space, they are located on a shared space. Information and data can be referred to a spatiality and coreference is easy to do with gaze and gesture.

Also, CSCW offers multiple communication channels (text chat, comment, voice, avatar), which can provide information on the participants workflow and help to communicate on complex information and quickly provide feedback on multiple way. Annotation techniques are besides identified to be a good channel for data handling: it generates less cognitive load to shared understanding (de Belen, Nguyen, Filonik, Del Favero, & Bednarz, 2019).

About data handling, this author also highlighted the importance of dividing task between users on (synchronous or asynchronous) cooperative object manipulation techniques, as scaling, translation, rotation, to avoid conflicts in the data manipulation. AR/VR interfaces are pointed to naturally support collaboration and support nonlinear analysis workflows, e.g. users can save different states of analysis for sharing it with different people, on different times and spaces.

CSCW had received a great attention from academia and industry over the last decades, bringing innovative data analysis environments, that we will approach on the next chapter. But what came out of the literature analysis is that CSCW should support parallel interactions during data handling and articulation and organization of activities, to help coordination, schedule, and alignment (Casarin, Pacqueriaud, & Bechmann, 2018; Gross, 2013; Raposo, da Cruz, Adriano, & Magalhães, 2001).

3.2 INNOVATIVE DATA ANALYSIS IN LEA COLLABORATIVE ENVIRONMENTS

LEA activities rely on information that are complex to obtain and even more complex to share for security reasons. Studies on this field is quite reduce but some interesting research provide important new way to think the collaborative environment for the data analysis.

A recent research has studied a novel solution of data visualization for large scale 2D and 3D information, called dataspace (Cavallo, Dholakia, Havlena, Ocheltree, & Podlaseck, 2019). This environment is not a full immersive environment, but instead uses mixed reality. The authors have imagined a new conference room, allowing both remote and co-located collaboration to take place either synchronously or asynchronously. They defined it as a "dynamic physical environment for experiencing complex data and jointly making better-informed decisions". This space provides 15 high-resolution displays, each of which being dynamically reconfigurable, a central table to projected information, and integration of AR and virtual reality VR headsets and other mobile devices, see Figure 2.

Figure 2: Dataspace illustration, extract from (Cavallo, Dholakia, Havlena, Ocheltree, & Podlaseck, 2019)

Butscher, Hubenschmid, Müller, Fuchs, & Reiterer(2018) developed a new immersive technology for collaborative analysis of data. This environment is used on HTC Vive and allows users to see on the same time data representation of scatter plots. The users can have two modes: visualization, to have an overview; and configuration to manipulate the data (add plots, move; select; colorize; flip; cluster). Immersive technologies here facilitate the visual perception of the data and their understanding, helping them to quickly identify areas of interest, meaningful patterns, anomalies, and structures between artifacts(Nguyen, Marendy, & Engelke, 2016), shown in Figure 3.

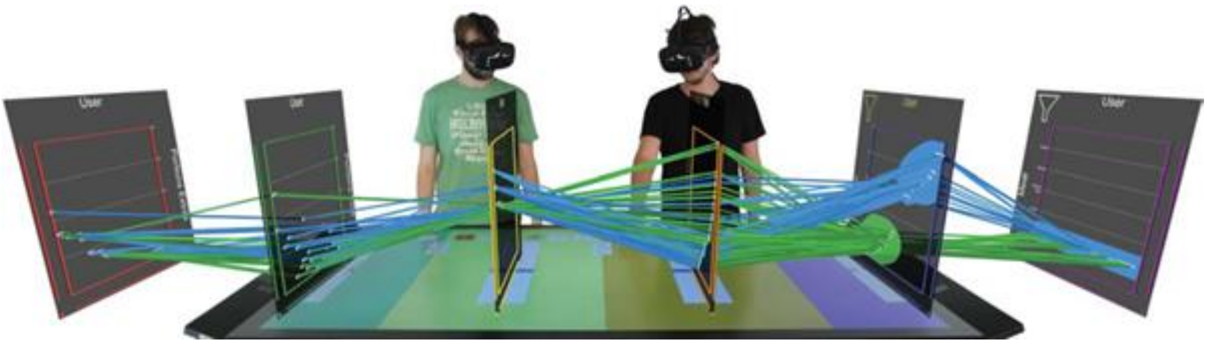

Figure 3: Immersive technology for collaborative data analysis (Butscher, Hubenschmid, Müller, Fuchs, & Reiterer, 2018)

They extracted from the experience some recommendations:

- the system should support fluid workflows, by allowing the configuration of visualization;
- Support nonlinear analysis with snapshots allowing for new analysis branches;
- Provide sorting and colorization functionalities;
- Highlight relative differences;
- Integrate additional non abstract information (pictures);
- Allow the navigation through gestures;
- Combine navigation styles (non-egocentric or egocentric);
- Provide individual visualization that allows reconfiguration and navigation.

In the field of data 2D/3D visualization, other studies have demonstrated that tools had to provide certain key functionalities, mentioned before for some of them, such as filtering and clustering the data (Elmqvist, Dragicevic, & DanieL, 2008), or adding, removing, and rearranging the dimensions (Collins & Carpendale, 2007; Fanea, Carpendale, & Isenberg, 2005). Researchers have also suggested that VR's wider field of view, instead of 2D visualization, increased sense of presence on the activities of data analyses, VR can lead more natural exploration of large data sets (Millais, Jones, & Kelly, 2018).

These authors developed an 3D immersive environment in VR to see data and compare it to 2D visualization on a computer. Two modalities of data visualisation were proposed:

1. be the data: users are immersed in Scatter plot and can have an overview of the data set, see Figure 4 and Figure 6;
2. parallel planes: presentation of the different dimensional dataset and their interaction, see Figure 5 and Figure 6.

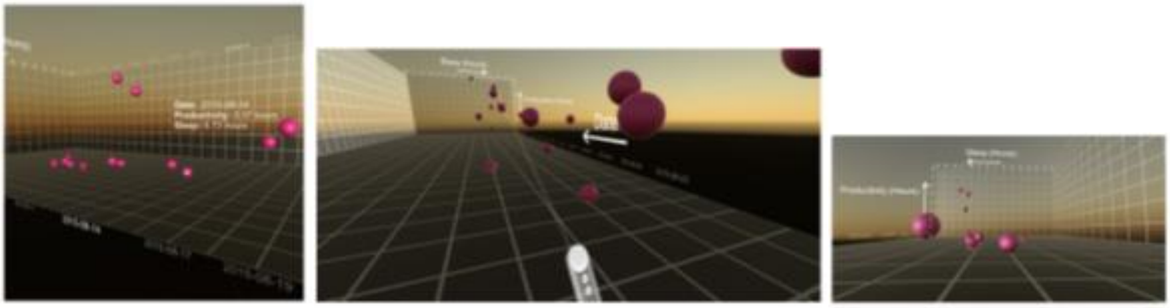

Figure 4: Be the data (VR) (Millais, Jones, & Kelly, 2018)

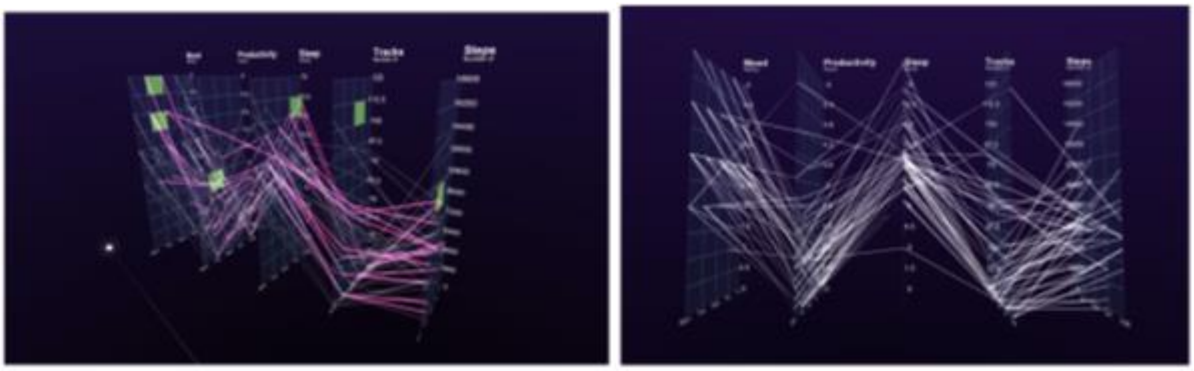

Figure 5: Parallel planes (VR) (Millais, Jones, & Kelly, 2018)

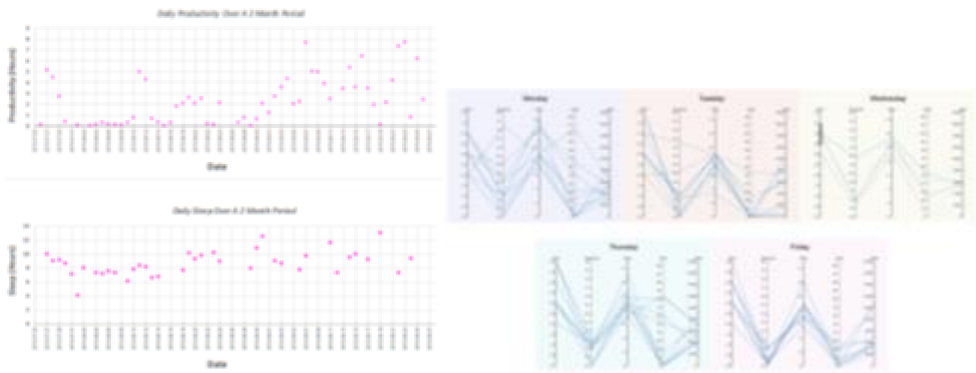

Figure 6: (1) & (2) in 2D computer (Millais, Jones, & Kelly, 2018)

The author found, with the use of the Nasa TLX questionnaire, that users feel more performant in VR environment than with computer, but no difference was found between VR and 2D regarding the workload. This result suggests that VR may help people to engage more and deeper in effective data analysis. However, care has to be taken with this result, because actual performance hadn't been evaluated: people may prefer a device, it doesn't mean they are more performant on their tasks with this device. It is called also the paradox of preference vs performance (Amadieu & Tricot, 2006; Amadieu & Tricot, 2014). To develop virtual environment that will be efficient for performance on data analysis, collaboration and work a user centric approach should be adopted, thinking to how they collaborate and how CSCW can support their activities.

Finally, Lukosh, Lukosch, Datcu, & Cidota (2015) have reviewed numerous studies using an AR system for collaboration. They presented Nilsson, Johansson, & Jonsson (2009), who developed an AR collaboration system supporting placing and modifying symbols and events on a shared digital map associated to a crisis management scenario. Here it demonstrated that team cognition is supported by providing information for joint work and joint manipulation of symbols. Alem, Tecchia, & Huang (2011), developed ReMoTe, a guiding system of hand gesture communication for industry. The system provides the hand gesture from a remote expert to a local user's workspace, to help collaboration. (Streefkerk, Houben, van Amerongen, Haar, & Dijk (2013) found that remote annotation on virtual tags can speed up the time for documentation and collection process during collaborative work sessions. And finally, Domova, Vartiainen, & Englund (2014) are listed to have shown that instantly synchronized snapshots and annotation lead a general acceptance of the system and support efficient communication between located and remote teams' members.

4 EFFECTIVENESS OF COLLABORATIVE ENVIRONMENTS

In Section 3, different innovative environments to collaborate have been described, this section will describe how to model collaborative behavior in CSCW as well as the considerations that may want to be made for CSCW in different environments and situations.

4.1 MODELLING COLLABORATION IN CSCW

Cavallo, Dholakia, Havlena, Ocheltree, & Podlaseck (2019) listed characteristics that a CSCW system must have to efficiently support collaborative tasks:

- **Shared Data Exploration**: the space should encourage both co-located and remote users to collaborate.
- **Egalitarian Access to the Data**: support individual involvement in the shared experience, by providing tools and interactions for individuals to take various roles throughout data exploration (e.g. orienting or focusing content and lighting in a particular direction, responding to the current speaker).
- **Flexible Data Immersion:** Combining results from several applications in different types of visual content, each associated with unique interactions, focus, and levels of data immersion.
- **Multimodal Interaction:** The system should support a variety of naturalistic interactions, such as keyboard/mouse, touch, spatial controllers (6 DOF joysticks), and voice-activated interfaces.
- **Seamless:** The system should integrate heterogeneous devices. Heterogenous device should however be considered with caution as they lead to different levels of

immersion and different mental representations (Narayan, Waugh, Zhang, Bafna, & Bowman, 2005). Considering data handling activities by LEAs, we should avoid increasing the complexity and limit the number of device and representations. This should avoid the need for creation of new mental model for every data, which can lead to cognitive overload (Sweller, 2003).

Researchers have found that the number and quality of participation is increased when the environment provides feedback during the collaboration about the performance and their progress in the tasks (Jung, Schneider, & Valacich, 2010). Feedback contributes to overcome asymmetric knowledge to provide mutual awareness. The question of how to generate the feedback is important. Generating the feedback may require a definition of the action plan, including identification of main tasks, possibly broken down in sub-tasks. However, teams within the security domain often had to deal with a multiple variables simultaneously, unpredictable for some of them (Smith, Kaminstein, & Makadok, 1995), making it difficuly to preempt when to give feedback.

CSCW should provide a shared space, to facilitate and support conversational grounding and feedback providing, with the expectation that there will be an improvement in collaborative task performance (Fussell S. R., Setlock, Yang, Ou, & Mauer, 2004; Fussell, Setlock, & Kraut, 2003; Gergle, Kraut, & Fussell, 2013). A place dedicated for sharing on CSCW may also answer the need of overview of availability and location of other team members identified by (Streefkerk, Houben, van Amerongen, Haar, & Dijk, 2013). In line with this, Casarin, Pacqueriaud, & Bechmann (2018) have identified additional requirements for the design of CSCW, see Section 3.1.3.

Regarding the shared context, Fussell, Setlock, & Kraut (2003), Fussell, Setlock, Yang, Ou, & Mauer (2004) and Kim, Lee, & Sakata (2013) agree that independent views of video mediated remote collaboration is more efficient than a dependant view from one user. Also, because a shared context involved a shared space, pointer cues are found to increase the feeling of being connected in a synchronous mutual collaboration. In the context of asynchronous collaboration, annotation cues in the spatial environment are more effective.

Finally, the shared environement can be designed to provide large screen displays (Cavallo, Dholakia, Havlena, Ocheltree, & Podlaseck, 2019), to help the exploration of multiple datasets at the same time and help the spatial contiguity that increases the inferences and overview of situation. It can respond to the human need of cognitive load, to reduce the sources of mental effort (Sweller, 2003) by presenting information in a close pace area, to reduce intrisic load and help better understanding and shared understanding of the situation (Mayer, 2005). Presenting information within the same space can limit the split attention effect and facilitate the visualisation of heterogenous information during the pace of time users search for potential related information (Chandler & Sweller, 1996; Rose & Wolfe, 2000). This is confirmed by the meta analyse (Ginns, 2006) of 31 studies supporting prior theorizing concerning the negative consequences of splitting complexe information over time and display due to a high cognitive ressources consumption to integrate and understand the materials.

4.2 LOCAL COLLABORATION ENVIRONMENTS

Some researchers have studied collaborative activity on a cross domain activities such as cybersecurity, requiring skills including data analysis, scripting, compilation, risk assessment and many others. (Kabil, Cuppens, Le Compte, Halgand, & Ponchel, 2018) observed that the operators of cybersecurity teams were able to exchange information directly during meetings with co-located team members, but they expressed the need of a tool that would allow them to share information with another remote team and interact simultaneously. This remote collaboration tool should ease the access, allowing support and expertise from colleagues, in addition to allowing them to share situational awareness, which is one of the most important challenges on collaboration emergencies. LEAs may also need to involve a third party, such as an external expert, or other collaborators to work on a case, such collaboration will be addressed in following Section 4.4.

Kabil, Cuppens, Le Compte, Halgand, & Ponchel (2018) developed 3D CyberCOP, a system for local collaboration on 3D data visualizations and analytics that fits with the need of investigation and reporting. The authors were able to influence the collaboration behaviour while modifying some dimensions. Several benefits were identified for each type of users:

- Analyst: the possibility to switch between the cyber and physical representation of the situation positively influenced the understanding of the situation.
- Coordinator: the immersive 3D visualization of data helped the analyst to easily explain the situation to the coordinator who gained an improved overview of the situation.
- Decision maker: the immersive 3D visualisation positively contributed to the decision making.

It is interesting to indicate that a mixed environment (not only within VR but with interaction within a physical environment) was considered as more usable and preferred by operators of cybersecurity (Kabil A. , 2019; Kabil, Cuppens, Le Compte, Halgand, & Ponchel, 2018). This system also brought new collaborative interactions, see Figure 7.

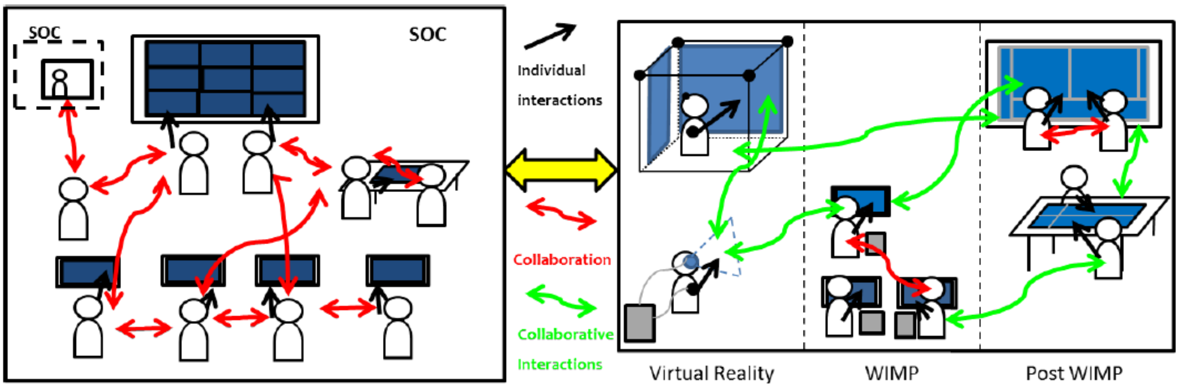

Figure 7: Classical activities for Security Operations Centers (SOC), cybersecurity employees (Left) and the new interaction bring with 3D CyberCOP (Right) In (Kabil A. , 2019)

They considered three relevant dimensions to modify collaborative behaviour:

1. Reflect the different roles and associated access rights to different kinds of data (only for local collaboration):
    a. Analysts: Can dive into data and can report incidents.
    b. Coordinator: Maintains a high-level view of situation. They will take the report made by analysts and give them instructions
    c. Decision Maker: The client who can authorize remediation action from analyst or status report from coordinator.
2. Offer a flexible view of data, 2D/3D users can visualize classical 2D dashboard or immersive 3D environment and have the possibility to switch between egocentric or exocentric view to have different point of view on data and to filter it.
3. Respect access rights in horizontal collaboration (between users with same level of access (e.g. analysts)) and vertical collaboration (between users without the same level of access (e.g. analyst and coordinator)) and support asymmetric interaction and let the different actors to provide mutual awareness using annotation or orders.

These findings are taken into consideration in Section 7.2.

4.3 INTER-ORGANIZATIONAL COLLABORATION

The Law Enforcement Agencies represent several teams spread across the EU Member States (MS). The INFINITY project aims at developing the capabilities of LEAs across the EU countries, supporting remote cross boarder collaboration of LEAs from different MS.

Immersive virtual collaborative environments are expected to facilitate remote collaboration, as it is a technology bringing a shared sense of space, a shared sense of presence, a shared sense of time, a way to communicate and a way to share information (Kabil A. , 2019). Using XR is relevant to help to the construction of situational awareness, to agree on the situation between users (Endsley, 2000). The importance of role, mentioned in the context of local collaboration (Section 4.2), is also relevant in the context of remote collaboration. The roles can be defined by an ID number related to the access, data level authorization related to the handling code, or to Analysis Work File (AWF), a database on a specific crime area. This identification may be used for automatic access management to data, rooms, areas, and functionalities of the system.

It was mentioned above (Section 4.1) the requirement for a tool to define an action plan (tasks and subtasks) and monitor the progression. In the context of cross border collaboration, this dashboard should consider the statement of Council framework decision from the European Union, which defined rules for the management of information request between MS. It defines that a request is sent with a status, urgent or non-urgent, which is associated to time limits for reply. The system should implement a tool to monitor these delays to support the inter-organizational collaboration for interrelated tasks, scheduling, and self-regulation of the activities.

The developed platform is thus expected to facilitate inter-organizational remote collaboration, in terms of data access, remote interactions and collaborations. The use of XR technologies should be considered depending on the nature of tasks but also the role of the users. For instance, immersion with AR/VR should be preferred for information display, while a mixed reality system may be preferred for management tasks such as to enter code or to involve a new external collaborator.

4.4 EXTENDED NETWORK COLLABORATION

The core analysis group benefit from specific prerogatives such as direct data retrieval from AWF; AWF development steering (amending and inviting other parties) and Secondment of Third Parties' (TP) analysts to participate in the activities of an AWF[1].

Invited TPs do not benefit from the same prerogatives as analysis group members: TPs can be associated to the activities of an analysis group but not to the analysis work itself, they have the right to attend analysis group's meeting, to be informed by Europol of the development of the AWF, and to receive analysis results.

These rights should come along with an access to the system for extended network collaboration for some specific collaboration tasks and to share information and data. A virtual environment can provide to this extended network as for remote LEAs, a shared place, a common ground to work and make it easier to reach the common situation awareness. While the developed system should provide space accessible to AWF participant to analyse data, it should also provide a dedicated space to offer an overview on data, without the possibility to work, that can be shared quickly with external expert.

[1] See Europol Convention, Article 10

5 XR TECHNOLOGIES

Extended reality (XR), sometimes referred to as cross reality, is an umbrella term, including virtual reality (VR), augmented reality (AR) and mixed reality (MR). VR is a completely computer-generated environment with no real-world aspects included while AR and MR are a mix of real world and virtual aspects. The difference between AR and MR is the immersivity. In AR, the virtual aspects do not need to necessarily blend with the real world, while in MR the goal is to completely blend the virtual aspects into the real world (Pomerantz, 2020; Unity, 2021) . This is illustrated in Figure 8: XR, VR, AR, and MR below.

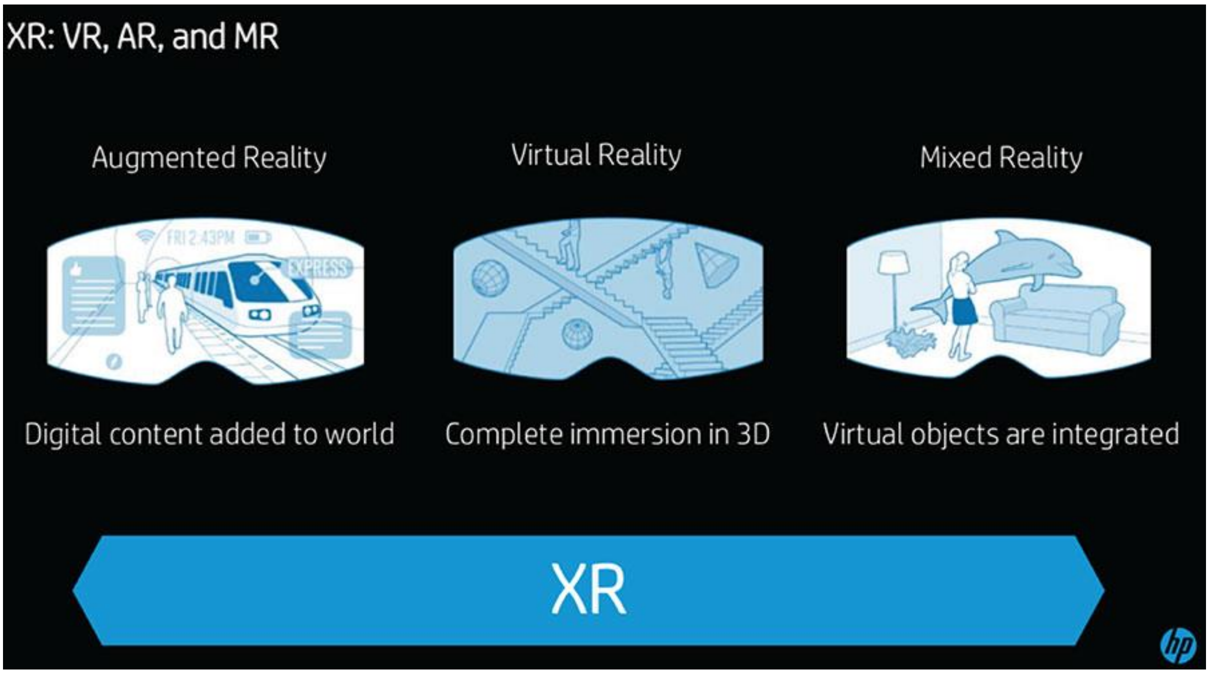

Figure 8: XR, VR, AR, and MR (Pomerantz, 2020)

These are still rather ambiguous concepts on a scale from the perceived real-world reality to completely immersive virtual reality as seen in the Figure 9: The Reality-Virtuality continuum **Error! Reference source not found.** below.

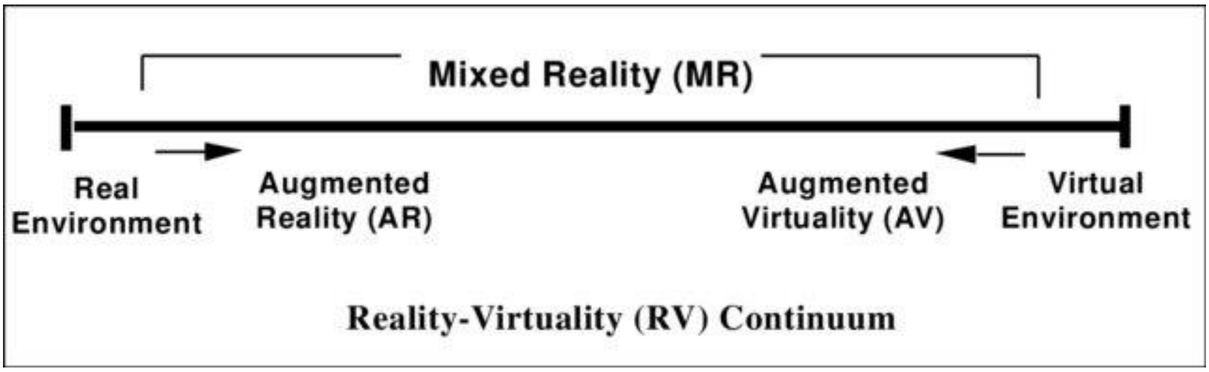

Figure 9: The Reality-Virtuality continuum (Paul Milgram, 1994)

Note that in Figure 9: The Reality-Virtuality continuum the name Mixed Reality was suggested as the umbrella term for AR and VR in 1994, but as of 2021 the name Extended Reality has been adopted instead (Paul Milgram, 1994; Unity, 2021). As opposed to AR, Figure 9: The Reality-Virtuality continuum **Error! Reference source not found.** also introduces the term Augmented Virtuality, meaning a virtual environment augmented with real world aspects. It has not become a common term however in the general discussion of XR. While the XR technology can be made with any kind of sensory input that immerses the user, most product innovations in 2021 are done on visual or audio-visual virtuality. In 2021 the head mounted display (HMD) seems to be the most common type of interface in XR, allowing audio-visual immersion. Other interface types are often composed of traditional computer displays in various forms as seen in subsection **Error! Reference source not found.**.

XR systems aim to serve multiple different customer segments, including simulation, surveillance, planning, design, gaming, entertainment in general, training and maintenance (Business Finland, 2021). The reasons to why XR is so lucrative are many. With just the human need of experiencing different scenes and worlds with high immersion, lies a huge market for entertainment and games. However, in 2019 the industry had already overtaken the game industry on XR spending according to the International Data Corporation (IDC, as cited by Accenture, 2019).

The possibilities of XR in the industry are vast. In many different fields, training can be done much more effectively, safely, and sometimes even cheaper with XR than traditional methods. Simulation of events and design objects as interactable virtual 3D objects is much more descriptive than a traditional 2D model on a display. Also, material consumption in many areas, such as scenery/interior architecture or any other design heavy area, are diminished, as design iteration can be made virtually without needing physical prototyping. Less material consumption might also lead to increased sustainability. Safety is also improved with XR, as many safety critical procedures can be rehearsed with XR before the real thing (NEC, 2020; Daniel Le Jehan, 2018).

As of now, XR as a technology is still in an evolving state with displays, sensors and networking technologies being refined year-by-year. Especially 5G technology is expected to heavily improve XR prospects in coming years (Accenture, 2019; Qualcomm, 2018). The trend of XR is however on the rise as the global market value of XR is expected to multiply in the coming years (Statista, 2019; Mordor Intelligence, 2020; Marr, 2020). This can also be seen in the news as many powerful companies like Qualcomm, are investing on the evolution of XR (Qualcomm, 2020).

5.1 XR HARDWARE CAPABILITIES AND SPECIFICATIONS

Several kinds of XR devices have been developed, including CAVE and HMDs. While CAVE have been widely used in the past, especially by the industry, the use of HMDs has significantly grown over the past ten years. This section mainly focuses on HMDs and other specific devices are briefly described in section **Error! Reference source not found.**.

On one hand, HMDs may be either see-through or closed systems and on the other hand they may be either tethered or standalone. In see-through systems the users can see the real-world through glass-like goggles, as opposed to closed systems which do not use see-through material for visualization. Tethered displays are connected to a separate PC or other computer device with a cable, whereas untethered systems are standalone without cables or outside computing. Tethered systems also have rather high computing capacities. The interaction methods with HMDs is also varied, with some systems allowing hand or eye tracking, while other systems operate with specific, often hand-held, controllers. The capabilities of the wide range of devices are usually very specific for the use case that they are designed for, although some high-end devices aim to be rather general in their use case and cater to a wide array of use cases. There are also multiple ways for the hardware to interact with the user. This is called feedback and it includes visual cues, sound feedback and various kinds of haptic feedback. Last, but not least, some high-end devices even allow spatial mapping, which allows 3D digitization and registration of the real-world to a virtual 3D model, opening a variety of exciting new ways for augmented and mixed reality.

5.1.1 HEAD MOUNTED DISPLAY TYPES

HMD displays can be see-through, like safety goggles and visors or closed boxes with displays for the eyes. See-through systems are often designed for AR/MR solutions, while some modern closed displays can also work as AR/MR solutions as they often have external cameras allowing the user to “see through” the display. Closed displays allow also full VR solutions.

The benefit of see-through HMDs is that the user can commonly see the real world through the glasses in higher resolution than is achievable with cameras and displays, while still including virtual elements. Because of the nature of see-through HMDs as of now, the rendered objects are all transparent, like holograms, while with closed headsets, one can see also solid looking objects.

The closed HMD in AR have a rather high computational need, as they need to have extensive camera stream from the outside of the headset, while adding virtual objects on top of that. The advantage is that compared to see-through solutions, the virtual objects can look solid, which adds to the immersion. The closed HMDs with cameras allows free spectrum from reality through the camera to complete virtual reality.

The displays in headsets have a few important metrics to consider. A common refresh rate of VR displays is around 90 Hz, while it does range from 70 to even 180 Hz. The refresh rate is perceived by users as how smooth motion is in the display and it is more important in XR than in regular displays, as lower refresh rates of 75 Hz or below are reported to induce simulator sickness (Panagiotis Kourtesis, 2019). This is assumed to be caused by the difference of what your body's balance organ senses compared to what your eyes are seeing. This includes rotating scenes where your body is trying to reach balance and with lower refresh rates, stuttering scenes, where the motion of the head does not correspond well with what the eyes perceive (Kidwell, 2018).

The resolution of the screen is another major factor in displays, as it is also associated with simulation sickness. Studies show that low resolution of 960 x 1080 subpixels per eye are likely to induce simulator sickness (Panagiotis Kourtesis, 2019). The effects between high and very high resolutions are not mentioned in this study as very high-resolution HMDs are a rather recent phenomenon. The modern HMD resolutions vary from around Full HD resolutions (1920 x 1080) to Ultra HD resolutions (3840 x 2160) per eye. The aspect ratios vary too from traditional display ratio of 16:9 to 1:1 ratio. A high resolution creates a clearer picture, which increases immersion. However, there are other metrics that also account to the picture quality, such as subpixel layout, colour reproduction and lens optics (Valve, n.d. a).

The resolution is closely tied to the field of view (FOV), which is the angle of view in the display around your eye. This is measured separately in horizontal and vertical axis or, as more often the case, diagonally. An accurate value of FOV is hard to measure in a headset, as the fit and facial features are varied in every individual and they affect the actual perceived FOV. Still the FOV values that manufacturers give gives some indication of the matter, as there are HMDs with claimed FOV values ranging from 90° to 200°. Studies show that a FOV of less than 110° might induce simulator sickness in VR (Panagiotis Kourtesis, 2019). A larger FOV is not all good however, as you have a set resolution for the screen and a larger FOV spreads that around, which makes the picture look more granular. Therefore, some use the metric of angular pixel resolution to accommodate the connection between resolution and FOV. This measures the number of pixels per degree, so it is a more accurate measurement unit for the quality of the picture (Valve, n.d. a).

Besides the forms, resolution, and smoothness of the displays, and the colour quality also play a pivotal role in immersion. The displays used in the HMDs are in this sense the same as traditional monitors. The metrics to watch for with colour are colour gamut, colour resolution and display panel type. Colour gamut tells how large area of the human discernible colours can be produced by the display. There are a few colour gamut standards to compare the displays, like sRGB and Adobe RGB as shown in Figure 10: Common colour gamut standards These are usually used as reference with display specifications, such as "covers 98% sRGB", means the display covers most of the sRGB standard area of colours. The colour resolution describes in essence how many different shades of colours are available. Common colour resolutions are 6-, 8- and 10-bit. Higher resolution equals more unique colour shades.

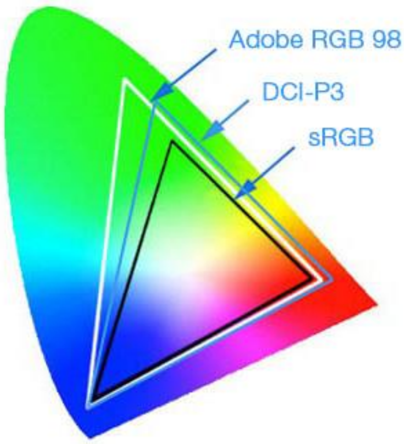

Figure 10: Common colour gamut standards (Frich, 2015)

The display panel types commonly used for HMD's are commonly divided into LCD and OLED panels. Furthermore, LCD panels are divided into TN-, IPS- and VA-panels. Roughly generalizing, TN-panels are very fast in response and cheaper, but have poor colours, VA-panels have slow response times, good contrast ratio and mid-range colour quality, IPS-panels have mid-range response times, mid-range contrast ratios and good colour, while OLED panels have great contrast and great colour but increased cost, shorter lifespan, and risk of screen burn-in.

With VR headsets OLED displays are commonly made with PenTile matrix design[2], which has less sharp picture quality compared to same resolution LCD screens, but lower production cost. There are a few headsets with OLED RGB design that is not PenTile too. The headset producers do not seem to advertise their panel type outside being LCD or OLED, and it is hard to find accurate information about it. Speculations say that TN would be a valid choice for HMD's the cheap production and fast response times (high refresh rate), but also IPS for the good colour reproduction (Rakver, 2021; OLED-info, 2019; Kore, 2018; Intel, n.d.).

[2] https://www.oled-info.com/pentile

5.1.2 TETHERED AND UNTETHERED HEADSETS

Whether a device is tethered or untethered is a major design choice with XR headsets. A untethered HMD implies more freedom for the end-user, as no cables are attached to the headset that could hinder user's movement. The trade-off here is that they also include a battery, which makes them heavier and more cumbersome, while also sacrificing some computing power. As you are limited by the energy consumption and cooling capabilities of the headset, standalone headsets often have less computational power compared to tethered headsets. This can be seen in the software offered for tethered versus untethered models from the same provider, as some software is only for tethered headsets, while most of the untethered software is available also to tethered headsets. The battery in untethered headsets also obviously includes a time limit until the battery needs to be recharged.

The cooling and energy availability are a key aspect when the rendered software goes from mobile processor chips towards PC powered tethering. The power that the computer consumes, mostly comes off as excess heat, and desktop computers consume much more power than mobile platforms. As a power comparison, a modern mobile processor spends only around a few to several watts of power in gaming (PC Mag, 2018), while a high-end PC running a high-graphics game can spend close to 500 W (Mills, et al., 2018). This gives a good idea why heat dissipation and power availability are the bottlenecks with standalone headsets. While PC hardware can utilize large heatsinks and fans, mobile solutions, including standalone XR headsets, are limited by the weight and usability factors. A heavy headset would be more cumbersome and unwieldy for long sessions and fanning solutions for cooling have a noise factor, which limits the usability and immersion. Also, higher power consumption in mobile device would require a bigger battery for the same use time.

Manufacturers tend to provide accessories to increase the flexibility of tethered and standalone HMDs, for instance:

- Wireless connector for tethered HMDs
- PC connexion cable for standalone HMDs
- External battery

5.1.3 INTERACTION METHODS

There are many ways to interact with XR systems. The most common way is to use separate controllers that often come with the various HMDs, although some headsets include integrated controls in the headset itself. The integrated controls are normal buttons, of which one could find in any electronic device. As separate controllers are all wireless, they need a tracking method for position and orientation known as 6 degrees of freedom (6DOF). Also, the headset in itself needs tracking. Some older headsets only had tracking for orientation, known as 3DOF, but according to the specifications of modern HMDs 6DOF seems to be the common standard currently in headset and control tracking. Some controllers are still only tracked in 3DOF however (Barnard, 2019).

There are effectively two different types of tracking used with XR. The inside-out method uses the cameras and sensors placed in the headset to track the surroundings, controllers and/or hands, while outside-in method uses sensors, often cameras, outside the headset to track the controllers, the user, and the headset. The inside-out method is further divided into Lighthouse method and the Simultaneous Location and Mapping (SLAM) method. In the lighthouse method, special base stations (the lighthouses) are used. They sweep the room repeatedly horizontally and vertically with infrared lasers. The headsets and controllers have arrays of IR sensors and measure the time it takes between sweeps to get the position and orientation of the headset. SLAM utilizes cameras on the headset to see the surroundings and using computer vision algorithms, gyroscope, and accelerometer the position of the headset can be determined. Commonly the SLAM headsets sense the controllers with separate IR cameras, as the controllers have a specific "constellation" of IR LEDs. The constellation's orientation and position determine the position and orientation relative to the headset (Heaney, 2019).

The outside-in and lighthouse methods require external devices, wiring and setup, which make them more cumbersome and expensive. The lighthouse method however is considered to be the most accurate and reliable tracking method available at the moment. SLAM method is cheaper, less restrained and requires almost no setup, but loses track of the user's controllers/hands if they are not in the vision of the cameras, like behind their back (Heaney, 2019).

The most common modern controllers are the HTC Vive[3] controller, Valve Index[4] controller, Oculus Touch[5] controller and Windows Mixed Reality (WMR) controllers. The HTC Vive controller is also called wand, for its distinctive elongated shape compared to other controllers. It is inside-out lighthouse tracked, has a USB-charged battery, grip button, trigger button, menu button, system button and a trackpad. There have been a few evolutions of these controllers with different headsets and only the VIVE Pro controller supports the latest base station 2.0 tracking[6]. All of the evolutions have had the same form and functionality, however.

Oculus Touch controller is AA-battery powered, inside-out SLAM tracked controller for the Oculus[7] Quest 2 headset. Separate editions of the controller are for different headsets and are not interchangeable, even though the form and functionality are the same in them all.

[3] https://www.vive.com/uk/accessory/controller/
[4] https://www.valvesoftware.com/en/index/controllers
[5] https://www.oculus.com/quest/accessories/
[6] https://store.steampowered.com/app/1059570/Valve_Index_Base_Station/
[7] https://www.oculus.com/

Touch controllers have trigger button, grip button, menu button, thumb-stick, and two buttons. All the buttons and the thumb-stick are also capacitive, so it senses if you have you have your finger on them (Oculus, n.d.). This allows the user to point at things in VR with your index finger or give a thumbs-up naturally for instance, although the buttons do not accurately sense your finger position, just if it is on the button or not.

Microsoft has made a reference controller design for its WMR system (Feltham, 2017). Samsung and HP among others have made their own controller models from that base design. Samsung Odyssey+ controllers are closer to the reference design with menu, windows, trigger buttons, grip buttons, a trackpad, and a thumb-stick. They have a refined ergonomics compared to the original, however. HP Reverb G2 controllers on the other hand are for WMR but are very similar to Oculus Touch controller in form and ergonomics. G2 controllers also have the same buttons as Touch controllers plus a windows button.

Valve Index controllers are inside-out, lighthouse tracked and have a thumb-stick, trackpad with force sensor, system button, trigger button, grip force sensor, two buttons and accurate finger tracking. The finger tracking allows the user to do even complex hand gestures or actions and to pick up objects in a natural motion. The pressure sensors on the grip also allow the user to “squeeze” objects. The controllers are powered by USB-charged battery (Robertson, 2019; Dingman, 2019).

Hand tracking and gestures are under much research for the use of interaction in XR. As stated by Karam (2006), hands are the most suitable part of the body for human-computer interaction, even though gestures can be implemented with other limbs as well. Recently, using deep-learning, Oculus advanced the state-of-the-art in hand tracking (Han, et al., 2020) and has integrated the technology in all Quest 2 headsets. Their method relies on four monochromatic camera streams attached to the outer surface of the headset. For successful tracking, the user’s hands need to be in the field of view of the outer cameras. The method provides accurate 3D hand pose estimation and runs at 60Hz on modern PC or 30Hz on a modern mobile processor. Similar hand pose estimation methods have also been implemented by HTC in VIVE headset series. However, based on the headsets’ computing power, different headset models offer different hand tracking capabilities, with the less powerful models offering simple hand position estimation (no finger tracking) and simplified gesture recognition, instead of a full hand pose estimation capability. The accuracy of hand tracking, especially when fingers/hands are occluding each other and standardization of certain gestures to specific functions are a few ongoing hot research topics (Smith, et al., 2020; Li, Huang, Tian, Wang, & Dai, 2019).

Gestures can also be categorized by the implementation method used for the gesture, including wearable sensor devices, touch devices and computer vision. Touch device gestures are familiar from smartphones, while wearable and computer vision gestures are not that common in modern applications. Wearable smart watches have some gesture controls and step counters, which are often implemented by sensing swishing hands. Also, the Valve Index controllers are technically wearable hand gesture sensors, while also serving as controllers. Computer vision has been around for a while, but its use in hand gestures is still under research.

Microsoft Hololens 2 has support and documentation for several hand gestures, including touch, hand ray and air tap. The gestures are implemented with computer vision. In addition to hand gestures Hololens 2 supports gaze controls with its eye tracking sensors.

Leap Motion by Ultraleap is another device for accurate hand controls and is popular especially among researchers. Leap Motion is a binocular IR camera that can be used for more accurate hand tracking than a normal monocular camera. While a separate from HMD sensor, there have been applications using Leap Motion on a table or attached to an HMD for hand gesture recognition (Li, Huang, Tian, Wang, & Dai, 2019).

In addition to hand tracking, many applications utilize gaze tracking. This can be divided into head tracking and eye tracking. With head tracking there is a pointer in the middle of the displays and the user's turns their head to move it. With eye tracking there is no need for a pointer. The user can just look at an object and if the used headset supports eye tracking, it can sense where you are looking at. Although eye tracking is faster, lower effort (for the user) and does not require a cursor, it is also not a smooth in movement (not good for drawing lines etc.) and also has difficulties with small objects. Head tracking on the other hand can provide smooth, controlled movement, is more reliable with precision and does not require eye tracking hardware, which is often expensive. Gaze tracking is often used like mouse movement in traditional systems, while the mouse clicks are implemented with hand gestures, voice commands or controller buttons (Microsoft, 2019b).

Regarding eye tracking, most recent headsets that ship with this capability, usually utilize IR technologies, either integrated on the headset or as a separate extra module (such as 7invensun's eye tracking module utilized by Pimax's headsets[8]). The technology used in Varjo's devices (U.S. Patent No. US 10,452,911 B2, 2019) is worth mentioning as it utilizes two IR cameras for each eye that operate at 100 fps with a 1280 x 800 resolution, which projects a complex IR illumination pattern, resulting in a highly robust eye tracking system.

Kat-VR[9] has made wearable set of sensors, which are designed for moving in VR. The idea is to walk in place to move forward. The direction of movement is tied to the user's lower body, not the direction the headset is pointing. This is done with calibration of three disk shaped sensors, one for the waist and two for the ankles. Another wearable solution are the Cybershoes, a kickstarter project that is expected to see launch in April 2021 (Nield, 2020). This solution involves two accessories (Cybershoes) that you strap onto your feet, either

[8] https://pimax.com/

[9] https://www.kat-vr.com/

without shoes or on top of shoes, a carpet (Cybercarpet) and a swivelling stool. The user sits on the stool, which is on the center of the round carpet. The cybershoes have a roller on the bottom, that senses when the user “walks in place” while sitting on the stool. The carpet ensures optimal operation with the rollers. The experience is reported not to be like walking, but rather “a step in the right direction for more immersive VR” (Switzer, 2021).

The treadmill platforms come in two variations, either a mechanical omnidirectional treadmill, like Infinadeck[10] platform, or a low-friction platform to be used with low-friction shoes like Kat Walk (by Kat-VR), Virtuix Omni[11] and Cyberith Virtualizer[12] platforms. Treadmill platforms are advertised to feel more natural when moving in a VR environment and also reduce simulator sickness, which is usually involved with movement in VR environments. The Virtuix Omni treadmill is shown in Figure 11: Virtuix Omni treadmill .

Figure 11: Virtuix Omni treadmill (Lang, Virtuix Exploring Crowdfunded Equity Investment Under US ‘JOBS Act’, 2016)

[10] https://www.infinadeck.com/
[11] https://www.virtuix.com/
[12] https://www.cyberith.com/

Voice is another interface that is fast popularizing with computers and XR. As virtual assistants like Siri, Google and Cortana are becoming more able and ubiquitous, speech recognition is fast evolving. Hololens 2 and WMR platforms in general support specific voice commands by default. There is also an option to make custom commands in WMR, speech dictation or use Microsoft virtual assistant Cortana with speech commands. Voice commands are singular preconfigured commands for specific functions, while speech dictation is meant for using speech to type text without keyboard. Magic Leap One, AR glasses, and Oculus headsets also support voice commands and Oculus also supports speech dictation. There are also platform independent software such as Voice Bot[13] and Voice Attack[14] available for voice commands and speech dictation in PC environment, including XR environments. These allow the user to save macros for specific custom voice commands (Microsoft, 2019a; Strange, 2019; Oculus, n.d.).

There are a few accessories for XR headsets out there that claim to "sense your brain [activity]". This is done via electroencephalography (EEG), which includes a non-invasive sensor(s) on the scalp of the user. These allow already rudimentary controls in VR environment, such as pressing a button by concentrating on the button on the screen as Nextmind[15] has done. These buttons have a tag that is optimized for visual cortex and can then be sensed by EEG and decoded by computer software. Another way of interacting with EEG device is to measure general attentiveness or relaxation as Looxid[16] has done. They have a few apps ready for their device that allow you to try and lift objects by concentrating hard or see your raw EEG data on screen. What you need to concentrate on and how is not specified.

5.1.4 FEEDBACK METHODS

Usually, the feedback for actions with computers is auditive or visual. So, when a button is pressed, either a sound can be heard or it is possible to see the button change colour, blink, or visually go down. But there are other ways to get feedback on XR. For instance, Dexta Robotics[17], VRGluv[18], HaptX[19] and Manus[20] have made glove controllers, with full hand motion capture and force feedback for each individual finger. This allows for the mapping of individual fingers and gives a feeling of actually touching or holding objects in XR. A step further from gloves are the haptic suits provided by Teslasuit[21] and bHaptics[22] for instance.

[13] https://www.voicebot.net/
[14] https://voiceattack.com/
[15] https://www.next-mind.com/
[16] https://looxidlabs.com/
[17] https://www.dextarobotics.com/
[18] https://www.vrgluv.com/enterprise
[19] https://haptx.com/
[20] https://www.manus-vr.com/
[21] https://teslasuit.io/
[22] https://www.bhaptics.com/

Both offer suits that have dozens of haptic actuators for different body areas. However, Teslasuit is designed for industrial and military sector with the haptics being implemented with electro-stimulation and also including biometrics and motion capture embedded in the suit, while bHaptics is marketed for gaming sector with vibrating motors for haptics and a much lower price point.

Another way to give haptic feedback is with ultrasound, as provided by Ultraleap[23] (previously known as Ultrahaptics). Assembling an array of ultrasound speakers, a light feedback can be induced in mid-air. This is hard to impossible to do in millimetre precision however as for instance 40 Hz ultrasound has a wavelength of around 0.9 mm. Ultraleap promises various patterns of sensations to the palm of the hand to differentiate between various actions. There have been many studies about using ultrasound to induce mid-air haptic feedback during the years, but as of now it has not seen much widespread commercial application (Carter, Seah, Long, Drinkwater, & Subramanian, 2013; Rakkolainen, Sand, & Raisamo, 2019).

In addition to visual, auditive and haptic feedback, there are some start-up companies like OVR and Feelreal, exploring controllable scent inducing devices (Kalish, 2019). The devices use an array of different scents to mimic real-life scents. The companies seem to have varying amounts of scents available and most of them are attachable below commercial HMDs. The Feelreal also has a feature for spraying air or mist into the users face when activated, for instance when you would cross a river in VR.

5.1.5 3D SOUND

Sounds are also an important aspect of perceived space and objects. Traditional 3D surround sound systems like 5.1 or 7.1 do not work well with XR however. The traditional model assumes fixed positions of speakers, such as front centre and rear left, but with XR the user able is to yaw, pitch and roll their head freely which needs to be taken into account if an accurate immersion is to be accomplished. The research on this subject is ongoing and evolving, but there are already some providers of 3D audio plugins and solutions. However, the major breakthrough and consensus on how to do 3D audio is still to come. (Wesemann, 2017; Johansson, 2019)

5.1.6 OTHER XR HARDWARE SOLUTIONS

Other immersive XR solutions include stereoscopic 3D screens, Cave Automatic Virtual Environments (CAVE), mobile (phone) AR and different physical platforms.

Stereoscopic screens have varying techniques, but they all aim at giving each eye a picture from its own perspective. Thus, the human brain can combine those pictures into a

[23] https://www.ultraleap.com/

perception of a 3D object or world. An example of this is Nintendo DS[24] game console. The Nintendo DS screen projects a different image for each of your eyes by projecting them to onto different directions. This only works when your face is at a certain distance from the display and directly in front of it (Oxford, 2020).

CAVEs consist of 3 to 6 screens that are often in cubic form around the user, an example of which can be seen in Figure 12: A CAVE solution by IGI **Error! Reference source not found.**. The screens can be rear projection screens for projectors, large displays, or arrays of bezel-less displays. The screens are also usually stereoscopic screens, allowing 3D scenery in every screen. To get a large cave to work with stereoscopy, the viewer's eyes or head need to be tracked in the cave environment to ensure the screen picture is according to the perspective of the user. Even with the popularity of HMD's, there are multiple companies offering CAVE and similar XR solutions. The benefit that the providers market is the complete freedom of movement and the natural interaction with the system (Viscon, n.d.; Tarbi, 2020).

Figure 12: A CAVE solution by IGI (IGI, n.d.)

Mobile AR might refer to any mobile AR system, but more often it refers to AR made for mobile phones. One good example of this is the IKEA Place app, which allows you to create a scan of your room and then try out different IKEA products to see how they would look in the room as shown in Figure 12: A CAVE solution by IGI . The app also scales the IKEA products according to the scan. Another famous AR app for smartphones is the Pokémon GO game, but there are also numerous other applications available (Kataja, 2019; Ayoubi, 2017).

[24] https://www.nintendo.co.uk/Nintendo-DS/Nintendo-DS-Family-Nintendo-UK-s-official-site-Nintendo-DS-Nintendo-DSi-Nintendo-DSi-XL-116380.html

Figure 13: IKEA's Place app displaying a sofa in AR (Inter IKEA Systems as cited in Ayoubi, 2017)

Physical platforms for XR include treadmills (covered in 5.1.3), cockpits and some specialized solutions. An example of a specialized XR platform is the Birdly[25]. Birdly is a physical VR platform for flying, including a fan for wind simulation, wing control with arms and hands and a moving platform for tilt and yaw. The platform is used in conjunction with a HMD, which is responsible for the 3D audio and visuals. This can be seen in Figure 14: Birdly platform in use

[25] https://birdlyvr.com/

Figure 14: Birdly platform in use (Lilly, 2020)

The VR cockpit platforms are usually very use-case specific. They range from racing seats, for racing simulator games to aeroplane cockpits (for example, Figure 15: A Full cockpit for VR **Error! Reference source not found.**) for training and simulation purposes. There are also multiple do-it-yourself projects on VR seats and platforms. Many of them aim to be more general, so they can be used with car or flying simulation when needed (Cockpit-VR, n.d.; Next Level Racing, 2021; Hall, 2020).

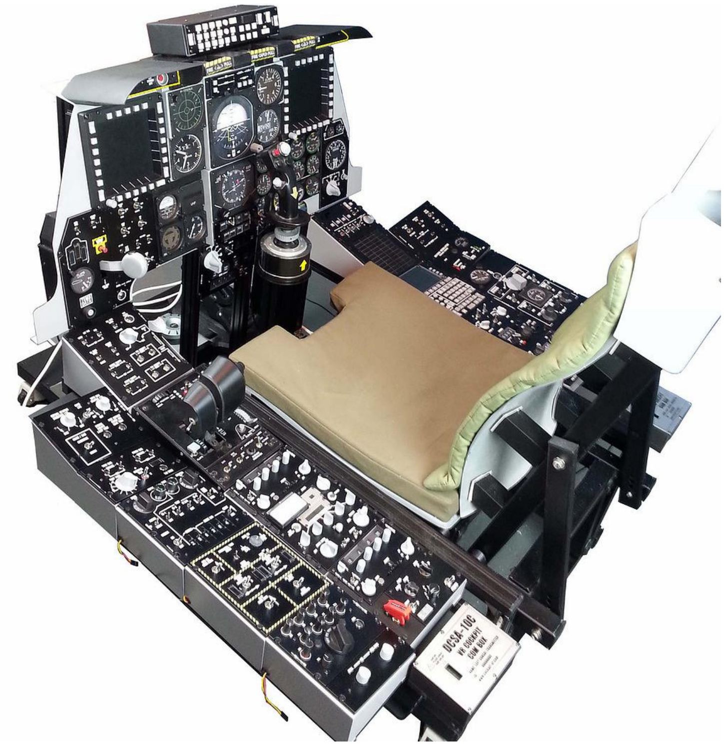

Figure 15: A Full cockpit for VR (Cockpit-VR, n.d.)

5.1.7 LIST OF XR DEVICES

A list of the most recent or otherwise notable XR headsets can be found in Appendix A. The information gathered here is general specification easily available online and the list is non-exclusive in both headsets and their features.

The following information is given:

- **Released**: The release date
- **Price**: Price from the manufacturer or typical price from a popular shop like Amazon
- **Display type**: see-through / closed, LCD/OLED/CLPL and subpixel layout (pentile/RGB)
- **Resolution**: Resolution per eye. Dual display if not stated otherwise
- **Processor**: The model of any embedded processor
- **Platforms**: Advertised software or operating system platforms (very much non-exclusive list)
- **Battery**: Use time with battery or not applicable (N/A) for tethered systems
- **Interaction**: Default interaction methods advertised
- **Sound**: Speakers, mics and audio jack connections
- Other miscellaneous features or notes

All the headsets and their controllers in the list are tracked with 6DoF unless stated otherwise.

5.2 XR ENVIRONMENTS IN DIVERSE DATA ANALYSIS TASKS

There are a few key benefits to using XR instead of traditional computer interaction methods. Most notably, the immersion can be on a whole new level with XR. There are multiple benefits to higher immersion. When human brain perceives the surroundings as more real and immersive, it creates a more persistent memory of the event. Also, human-to-human interaction through more immersive methods give rise to social skills, as it creates more accurate presence and emotional response to situations and other human beings. (Eric Krokos, 2018; Chan, 2020; Gillies, 2018)

In the light of the COVID-19 pandemic, remote communication methods have become paramount. The shortcoming of video calls is that the presence of other people is not there, and it is not possible to present things in three dimensions as you would in real life meeting. Also, team-building and orientation activities are hard to accomplice with video calls. With XR, you could have group conferences with better presence of others by using avatars and you can present and brainstorm 3D objects, provided the objects have been made or replicated into the digital environment. Also, with the team presence and the possibility of virtual breakrooms, orientation and team building are possible in a higher efficiency than with traditional methods. There are also ways to highlight and draw in many of the conference or artistic apps in XR, which makes brainstorming and sketching much more viable in XR than traditional video conferences. (Griffin, 2020; Stern, 2020; Long, 2020)

As gaming and movie industry have required numerous 3D objects for a long time, there are many professional software and hardware solutions available for creating digital 3D objects. For hardware, there are 3D scanners of various sizes for replicating objects. It is also possible to scan 3D environments and objects using LIDAR or depth camera solutions, which are rather common in HMD's designed for professional use, such as Microsoft Hololens 2 and Varjo XR-3. The new iPhone also has LIDAR, which technically makes it a portable 3D scanner, albeit one without professional precision (All3DP, 2021).

For software side, there are many professional 3D creation studio software available, such as Maya and Blender. Creating and modifying 3D objects in VR is also becoming more common. Traditional programs for 3D object creation like Blender and SketchUp are adding VR interfaces into their programs, while other companies, not associated before with 3D modelling, like Google, Facebook and Mozilla, are also making their entry into the field with new applications. There's also the company Gravity Sketch, which has recently made their own VR artist tool by the same name, which is considered to be a professional level VR artist application (Immersive Learning, 2020; Geis, 2018; Harris, 2018; Bennett, 2018).

There are also many companies and 3D artists that offer 3D modelling or libraries as a service. The content is technically the same in XR as it has been in digitally enhanced or animated movies and computer games and as these fields have been popular for a long time, there is no shortage of providers available.

VR and AR differ fundamentally in their approach to XR. However, as technology evolves, they start to overlap more and more, which takes us into the world of MR, where virtual and real objects and characters would interact seamlessly. AR approaches real life environments and tries to add helpful augmentations or interfaces to it, while VR creates a new environment altogether according to the needs of the use case. In case of communication and meeting purposes however, both approaches apply equally. Whether in an actual meeting room with AR glasses on, seeing holographic avatars and displays, or in a virtual meeting room, seeing virtual avatars and displays, the function and result is the same. With powerful enough camera equipment, it is possible to combine VR glasses with see-through camera feed to achieve fully opaque virtual objects and avatars with real environments (Varjo, 2021b).

5.3 USER EXPERIENCE IN XR

Norman, Miller, & Henderson (1995) referred to the phrase user experience (UX) as every faucet of an experience of an individual when interacting with a system back in the 1990’s. UX additionally depends on various movements (Rogers, 2012), such as affective design (Jordan, 2002), activity theory (Kuutti, 1996), and usability research (Nielsen, 1994). The authors then continue that in leading UX models usability issues related to effectiveness and efficiency were subsumed as part of the “instrumental” properties of a product. Similarly, usability is critical to UX and that various features of UX are connected to the usability that a product has (Sharples, S., et al., 2007).

The Multi-criteria Assessment of Usability for Virtual Environments (MAUVE) is a taxonomy of criteria and Virtual Environment heuristics that aims to produce an organized way of attaining effective usability and user experience when creating virtual reality user experiences (Stanney, K. M., Mollaghasemi, M., Reeves, L., Breaux, R., & Graeber, D. A. , 2003). Criteria in the MAUVE system include:

a. wayfinding,
b. navigation,
c. object selection and manipulation,
d. visual output,
e. auditory output,
f. haptic output,
g. simulator-sickness,
h. engagement,
i. presence,

j. immersion.

Researchers point out that natural interaction interfaces influence to user experience and it should be designed to accurately identify user requests during interaction and to provide the user with intuitive means of interaction with low cognitive effort (Schafer, D. & Kaufman, D. , 2018). Some researchers have begun to explore the potential of interaction within XR environments through the use of gesture. Chessa and Noceti (2017) reveal that user interaction with virtual content involving human hand gestures has resulted in more successful performance indicators (such as speed, error rate, the natural quality of interaction), compared to a virtual hand avatar. Bai (2016) states that, while interaction with 3D motion-based free-hand movements without the use of markers is more intuitive and natural than 2D touch-based interaction with depth perception, this may create limitations for 3D motion-based interaction.

In the recent thesis, a novel framework for the risk assessment of AR technologies implementation in sociotechnical systems is developed (Bahaei, 2020). The thesis defines the socio-technical system in the AR implementation context to consist of technology: Augmented Reality, Human: AR-extended human and Organisation: AR-related factors. The thesis research questions rise from the fact that new technologies (like XR/AR technologies) that are implemented to enhance human capabilities or extend human functioning may cause distraction or incorrect execution of the required tasks. The research provides a generic framework though the examples stem from automotive domain. The model has been developed to be used during the system development process for eliminating design failures incrementally and iteratively.

Cognitive load is an important factor to consider when designing effective instructions. On the effects of XR to cognitive load, Emin (2019) studied pedagogical effect, instructional design, motivation and interaction interfaces in the training environment. From a pedagogical point of view, XR helps to reduce extraneous cognitive load (distracts working memory from processing new information) and to increase germane cognitive load (deep processing of new information by integrating it with previous learning). As the capacity of working memory is limited, information is retained in the memory for a short time. Long-term memory has an unlimited capacity, with bits of information structured as schematics there. Working memory has a strong relationship with long-term memory as an individual’s expertise develops in a field, the number of interactive elements created by a particular task will decrease as will cognitive load. Cognitive load theory refers to the cognitive processes of the user in the use of technology. The positive contribution of XR to cognitive load in education has been demonstrated in studies. XR contributes to cognitive load with pedagogical effect, instructional design, satisfaction and usability perceptions, interaction interfaces and gender factors. The introduction of XR in education can reduce extraneous cognitive load by positively influencing many sensory channels that lead to the working memory. Research has been conducted on how to use novel AR technology more efficiently, against the rise of new hardware or new interaction features to support XR applications. This implies that traditional task analysis methods do not adequately respond to user needs or may indeed ignore user needs altogether. As such, the cognitive or affective characteristics of the user should be taken into consideration during the design and implementation of interactive systems (Arvanitis, T. N., et al., 2011).

6 VISUALIZATION FOR ADVANCED DATA ANALYSIS

This section discusses several aspects of visualization used for advanced data analysis. Next, are introduced some basic principles of data visualization and interactive visualizations. Then, discussions are provided on data visualization in “traditional” flat displays and visualization in mixed reality environments.

Humans are a visual species and, as such, visualization is a natural way to get a better understanding of data. Cairo (2016, p. 27) defines visualization as “any kind of visual representation of information designed to enable communication, analysis, discovery, exploration, etc.”

In the case of data visualizations, they also serve one or many of these functions. They may help us to explore a dataset, to understand implications of these data, to discover new phenomena, or to communicate our findings to others. Instead of just going over raw data, creating graphical representations allows us to benefit from our capacity to detect visual patterns.

Data visualization is about visual mapping of data. The prototypical form of data visualization is a chart, in which a data magnitude is encoded using shapes, colours or proportions. However, there are several other forms: such as maps that represent geo-located data or network graphs that represent a relationship among entities. As one can imagine, there are plenty of options for visual mapping to choose from when creating a visualization. In an attempt to provide theory to support visualization design, Cleveland & McGill (1984) identified the ten *elementary perceptual tasks* depicted in Figure 16. Most data visualization is a product of using one or many of these properties.

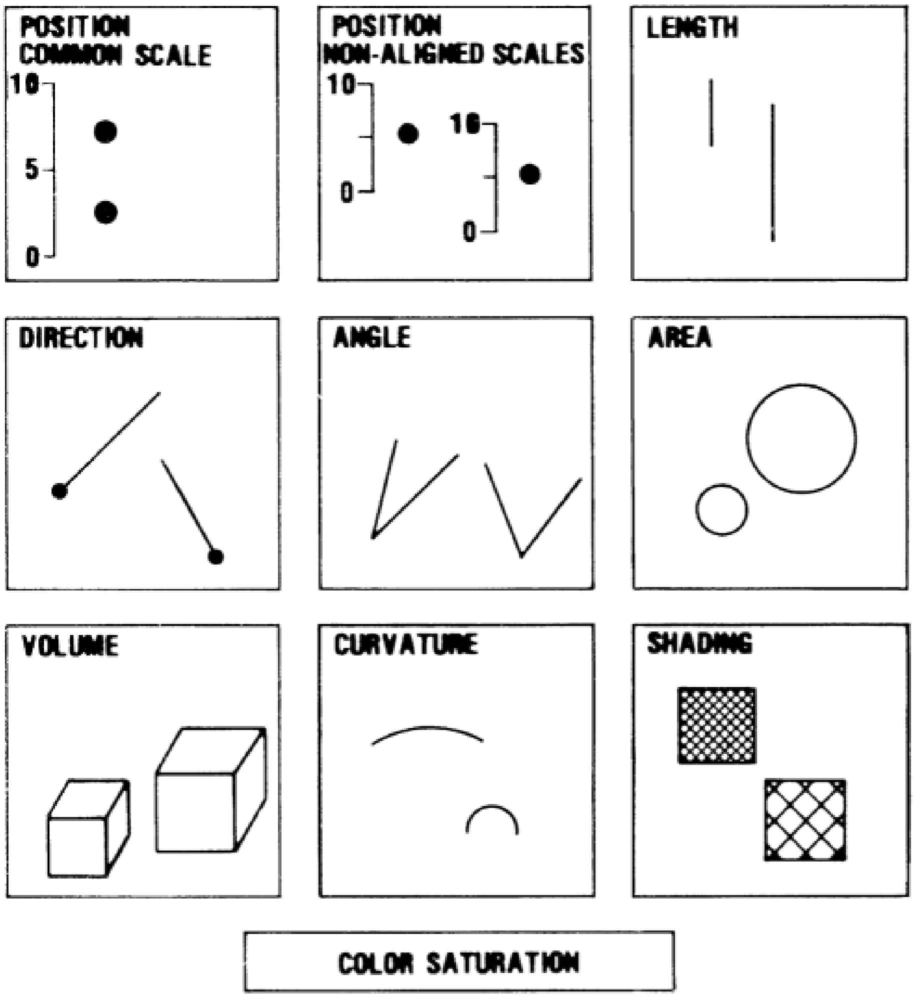

Figure 16: 10 elementary perceptual tasks. (Cleveland & McGill, 1984).

Originally, data visualization was created for paper. This changed with computers, which allow the first interactive data analysis tools. Many data visualizations are now also interactive. Interaction adds one extra layer of complexity and the need to find guidelines to simplify it. The information seeking mantra: “overview first, zoom and filter, then details-on-demand” (Shneiderman, 1996, p. 350) is a good starting point for those designing data analysis systems. This mantra is extended in Shneiderman (1996) with the definition of task by data type taxonomy. Schneiderman identifies seven basic data types: 1-dimensional, 2-dimensional, 3-dimensional, temporal, multidimensional, tree, and network data. For each of these types he discusses also seven interactive tasks: overview, zoom, filter, details-on-demand, relate, history and extract. This taxonomy is a useful reference point to design, evaluate and compare interactive data visualization systems, although it is not the only one. A more recent one is Brehmer & Munzner (2013) who propose a multi-level task typology looking at the why, how and what of visualization interaction. It is also worth taking into account the discussion by Wong (1999) in the early days of data mining as a research topic:

> *"A genuine visual data mining system must not impose knowledge on its users, but instead guide them through the mining process to draw conclusions. Humans should study the visual abstractions and gain insight instead of accepting an automated decision."* (Wong, 1999, p. 20)

After static, and interactive visualizations, there is now experiencing the emergence of data visualization inside immersive environments (see Section XR and Immersive Analytics). Although some experiments were already carried out in the early 90's, e.g. (Bryson & Levit, 1991), it is now when the field of immersive analytics (Dwyer, et al., 2018) is consolidating. On the one hand, the body of knowledge generated by research in non-immersive data visualization needs to be validated for this novel environment. On the other, new concepts will be possible and needed. For example, the concept of visual mapping can also be extended to sensory mapping, as Nesbitt (2000) discusses: data can be mapped as space, visual, sound, or haptics.

6.1 2D/3D DATA VISUALIZATION

A data visualization can go from a very simple chart to an abstract representation. Although some authors historically claim that simplicity is key in this craft, see Tufte (1985). The reality is that sometimes complexity in functionality or aesthetics is needed. Cairo's (2012) visualization wheel represents this concept taking into account different properties of a visualization as dimensions. Depending on its goals, a visualization may fall into a set of values for each dimension represented in the wheel, see Figure 17.

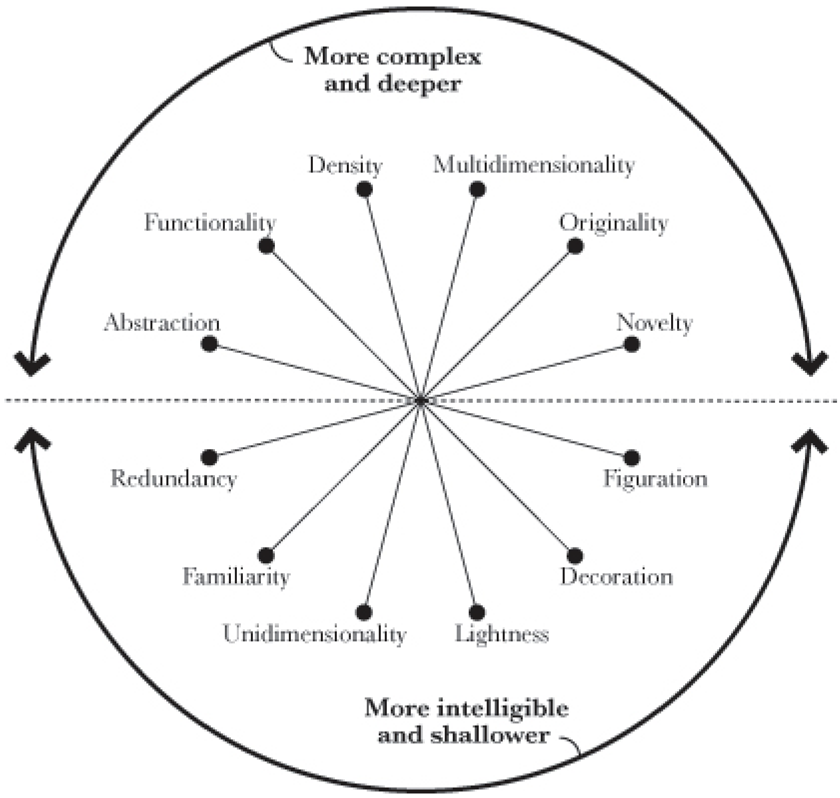

Figure 17: The visualization wheel. (Cairo, Functional Art, The: An introduction to information graphics and visualization, 2012)

Using and understanding tools like the visualization wheel, and the principles accompanying it, are useful guidelines when designing data visualizations. However, they work at a high level of abstraction and are not always practical. There are more concrete classifications, such as Wilke (2019) who divides charts in the following categories:

- Amounts: bars, dots, heatmaps, etc.
- Distributions: histogram, density plot, boxplot, etc.
- Proportions: pie charts, stacked charts, tree maps, etc.
- x-y relationships: scatterplot, bubble chart, line graph, etc.
- Geospatial data: map, cartograms, etc.
- Uncertainty: error bars, confidence strips, etc.

An analogous list accompanies every tool used to create visualizations. And there is a plethora of software tools to create 2D/3D visualizations that practitioners can rely on. Programming frameworks to create interactive data visualizations are also popular, especially JavaScript frameworks to create interactive visualizations for the web. On this front, a few popular alternatives can be enumerated:

- Spreadsheet software, such as Microsoft Excel or Numbers.

- Tableau[26]: a modern data visualization software that can also create interactive visualizations or dashboards.
- MathWorks Matlab[27]: a mathematical computing software, or its open-source equivalent Octave.
- R[28]: a popular programming language and environment for data mining and statistics, being ggplot2 a worth noting library to create visually appealing plots.
- Matplotlib[29]: the most popular plotting library in the programming language Python.
- D3: Data-Driven Documents[30], a library for visualizing data using web standards.
- Plotly[31]: a data visualization library available for JavaScript, but also for Python, R, and Julia.

Users select one or many of these tools depending on their goals, needs and expertise. Some of them require basic technical skills, while some others required advanced knowledge of a programming language and the library to be used.

The tools previously mentioned are general purpose, but mainly focused on creating 2D or 3D charts. When working with graphs (as in network graphs), there are some specialized tools for analysis and visualization, some relevant instances are:

- Networkx[32]: library for Python.
- Gephi[33]: an open-source tool.
- Kineviz GraphXR[34]: a powerful web-based tool, which can also be used in immersive environments.

Researchers have often exploited these, and other tools to create advanced data visualizations for specific domains. The field is broad and has been active for a couple of decades, so instead of analysing individual works, it is worth to first look into the many existing surveys. The survey by Liu, Cui, Wu, & Liu (2014) revisits papers where visualization is applied to diverse domains such as science, business, ballots, education, and more. It categorizes systems in graphs, text, maps, and multivariate. The identify challenges regarding usability, scalability, the use of heterogeneous data, in-situ visualization (as in data streaming), and representation of errors and uncertainty.

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[26] https://www.tableau.com
[27] https://www.mathworks.com
[28] https://www.r-project.org
[29] https://matplotlib.org/
[30] https://www.github.com/d3
[31] https://www.plotly.com
[32] https://networkx.org/
[33] https://gephi.org/
[34] https://www.kineviz.com/

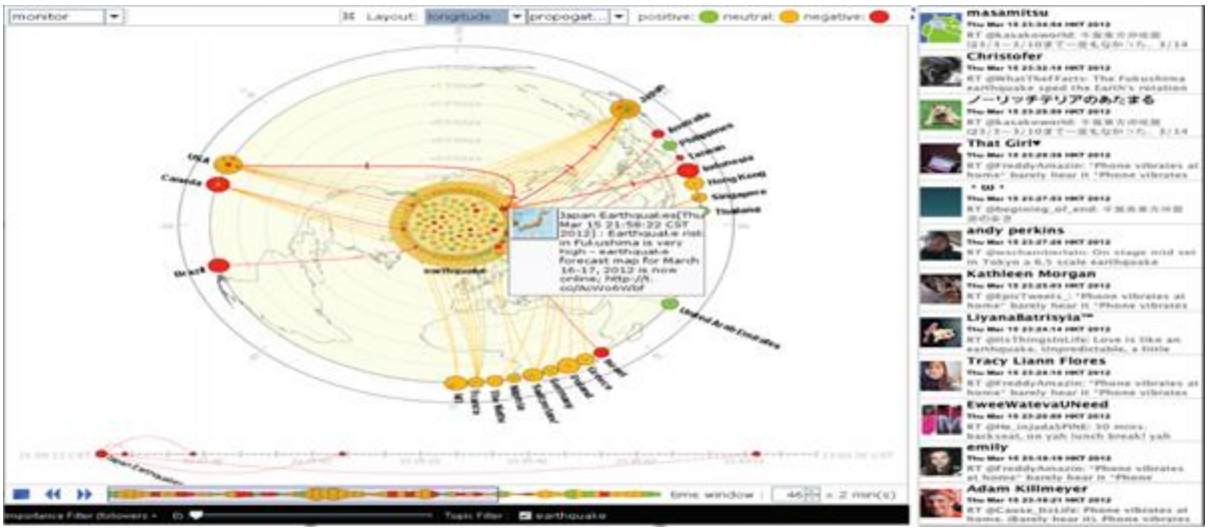

Figure 18: An example of text visualization. Whisper a tool to analyse information diffusion in Twitter. (Cao, et al., 2012)

The area of graph or network visualization has also been of interest for decades now. Herman, Melancon, & Marshal (2000) already talk about many application areas: file hierarchies, organizational charts, taxonomies, web site maps, evolutionary trees, genetic maps, data-flow diagrams, communication networks, and more. The power of visualization in advanced data analytics is key for the analysis of heterogeneous data. Figure 18: An example of text visualization. Whisper a tool to analyse information diffusion in Twitter. Figure 18 shows Whisper (Cao, et al., 2012), a tool to analysis information diffusion in Twitter. It combines text from a social network that is also geolocated. The recent survey from Schöttler, Yang, Pfister, & Bach (2021) discusses geospatial networks, defined as "graphs where nodes and links can be associated with geographic locations".

Although not a tool to create visualizations or a visualization system itself, Vega-Lite (Satyanarayan, Moritz, Wongsuphasawat, & Heer, 2017) is a grammar to describe them, which constitutes a useful abstraction layer for visualization systems.

Lately, there is an increasing interest in using visualization in combination with machine learning techniques, for interactivity, explainability or interpretability (Chatzimparmpas, Martins, Jusufi, & Kerren, 2020).

6.2 XR AND IMMERSIVE ANALYTICS

The advancement in immersive technologies known as extended reality (XR), such as Augmented Reality (AR) and Virtual Reality (VR), has allowed additional avenues to be explored. As well as building upon ICE environments, the new technology has paved the way for immersive analytics.

Immersive analytics is an emerging field described by Dwyer T. et al. (2018) as combining, "data visualisation, visual analytics, virtual reality, computer graphics, and human-computer interaction" with intention of removing the barrier between people, the data, and the tools that are being used for analysis. It has the potential to support the understanding of data, enhance decision making and can be used in a collaborative fashion both locally and remote.

Immersive analytics can utilise a variety of technology either independently or in combination with one another. For example, one solution may use AR in combination with interactive displays, another may use a VR head-mounted display (HMD), and third may use a VR CAVE – a empty space in which the virtual environment is projected onto the walls (see Section 5.1.6). Koehler, Berger, Rajashekar, Wischgoll, & Su (2019) discussed their system DynaCoVE which allows for cross-display interactions between a CAVE projection system and multiple other devices such as laptops. The system is akin to traditional ICE setups, allowing for multiple users to collaborate within a local environment.

Donalek, et al. (2014) discussed the rapid development of virtual reality and the significant reduction in cost that HMDs offer over CAVE-type installations. Additionally, they highlight the portability that HMD systems can allow in comparison to CAVE systems, for example devices can be run from a scientist's laptop rather than a fixed CAVE location. Regardless of the device used, replacing the fixed physical space with an entirely digital environment introduces further potential for collaboration. Multiple users can connect to the same digital environment, both locally and remotely using internet technologies.

Cordeil, et al. (2017) sought to further explore whether HMDs can provide a viable alternative to CAVE installations. Their experiment saw pairs of users working collaboratively to complete a task using either a CAVE or HMD. They then evaluated the effect of each on the user's task performance, collaboration, and overall experience. They tested two 3D network visualization tasks, one involved finding the shortest path between two nodes and the second was counting triangles. Both platforms demonstrated a high accuracy for correct answers from their users, with no considerable difference between the two systems. However, they did discover that HMD participants had increased performance. Specifically, the participants were 40% faster on the shortest path task and 30% faster on counting the triangles. Additionally, they found no significant difference between the two platforms in terms of the user's oral communication or physical engagement. This further supports the claim made by Donalek, et al. (2014) that HMDs are a cost-effective alternative to CAVE systems.

Traditionally, data has been viewed on a 2D screen and navigated using 2D input devices. Navigating a 3D world with these limitations introduces perceptual and navigational conflicts (Herman, Melancon, & Marshal, 2000). The development in immersive analytics, and specifically in HMDs, introduces a new way to view and navigate the data and provides the user with access to data in ways that were previously unachievable.

The immersion and presence that VR environments provide complements visual perception and utilises natural spatial memory (Cliquet, Perreira, Picarougne, Prié, & Vigier, 2017).

Allowing the analyst to place data around the space can create visual links and relationships between multiple datasets. The use of the 3D space has previously suggested that those with a "high spatial ability would use less cognitive efforts in the environment, thus freeing mental power for memorising or remembering the spatial characteristics" (Vindenes, 2017). Providing analysts with the opportunity to organise and structure their data, workflow and thought process is expected to further complement the analysis.

Stuerzlinger, et al. (2018) further discusses the advantages to "a physical instantiation of the 'memory palace'". They highlight that a complex model can split into different spatial locations via compartmentalisation, in both AR and VR. Strong spatial memory can be used to find information easier when associated with a physical space. They further discuss the advantages a virtual space can provide, for example, while performing searches on the data, information can be revealed by highlighting the results yet keeping the data in the same location. This provides the results with context that may be lacking if the surrounding data were to be removed.

Recently Lee, et al. (2021) have explored the use surfaces and spaces within an immersive analytical environment through the development and testing of their prototype system: Free-range Immersive Environment to Support Team-based Analysis (FIESTA). Their research reported positive feedback from participants including improved workspace awareness and commented on ease to share findings with one another.

FIESTA allowed 3D visualisations to be placed anywhere in the environment. Surfaces such as virtual tables were in pre-defined locations and were expected to be used by participants to place visualisations. Instead, it was found participants would create and freely suspend visualisations in convenient locations rather than on top of the tables. A question remains whether this behaviour would continue in a more emergent workspace, where users had more freedom to configure the environment and place their own surfaces, or whether they would continue to suspend visualisations.

In addition, they found participants would organically divide the shared space into approximately equal size territories where they would work individually. Having completed individual tasks, the participants would transition to collaborative work. This was either through observation or through discussion. Participants of FIESTA were all within the same physical space, which may explain why physical distance was maintained in fear of risking collision.

7 GUIDELINES AND OPPORTUNITIES

This section intends to provide guidelines and highlight opportunities that are available for collaborative data analysis XR environments. This section is based on the research that has been analysed in the previous sections but is presented independently to provide a place of reference for readers.

7.1 XR HARDWARE GUIDELINES

The first consideration for developing with XR is which headset to use. If a tethered headset is chosen (Section 5.1.2), then the general recommended requirements for the PC are as follows:

- **Video Card**: NVIDIA GTX 1070 / AMD RX 5700
- **CPU**: Intel Core i5 or AMD equivalent or greater
- **Memory**: 8GB
- **Video Output**: DisplayPort 1.2
- **USB Port**: USB 3.0
- **OS**: Windows 10

These requirements account for HMDs that are not very high resolution or framerate and may need to be adjusted accordingly to match use cases. Some HMDs may remain feasible with lower requirements.

For higher refresh rates (144<) or high resolution (above 2000x2000 per eye) the recommended specification rise to a quad core or eight core processor and graphics card of NVIDIA 2000- or 3000-series, depending on the model. Some models also require display port 1.4 support and up to 32 GB of memory (Lang, How to Tell if Your PC is VR Ready, 2021).High resolution is important for analysing details in 3D as well as reducing cybersickness. Refresh rate is important for smooth motion in video and reducing cybersickness especially in highly mobile video scenes. IPD is important for the optical focus of the picture, which makes it an important factor also in preventing cybersickness. According to studies the mean IPD is around 63mm and most adults have IPD in the range 50 - 75mm in a normal distribution (Dodgson, 2004). Having a larger IPD range makes the device more usable and comfortable for a wider range of users. (Panagiotis Kourtesis, 2019).

7.1.1 AR HARDWARE

For AR hardware the state-of-the-art devices, at the time of writing, are Hololens 2 and Varjo XR-3 with the best features available as of now. They both have spatial mapping, Varjo with LIDAR and Hololens with an unspecific time-of-flight depth sensor. Hololens features a see-through display, allowing natural sight over the real world, while Varjo uses its frontal cameras for “photorealistic” video see-through. While Hololens does not require IPD consideration, Varjo has an automatic IPD adjustment of 59 - 71mm. For virtual objects, Hololens displays them as holograms, whereas Varjo displays opaque objects.

For cheaper options for AR, one could consider VR hardware with camera pass-through, such as Oculus Quest 2, HP Reverb G2 or HTC Vive Pro if the pass-through does not require very high fidelity.

For a high-end AR headset recommendation, Hololens 2 is the choice. Unless opaque objects, LIDAR or full range of virtual continuum are required, Hololens 2 has all the features for AR headset required with half the price, compared to the XR-3. Varjo XR-3 is the choice if some of these extra features are required.

For more details on these headsets, see Appendix A.

7.1.2 VR HARDWARE

For VR hardware the state-of-the-art devices, at the time of writing, are VRgineers XTAL 8K, Pimax 8K X or 5K Super and Varjo VR-3. XTAL 8K and Pimax 8K X have UHD resolution, Pimax 5K Super has QHD resolution and Varjo has bionic display with highest resolution per eye.

The refresh rate is highest with Pimax 5K Super with 160 Hz (180 Hz in experimental mode) followed by Varjo with 90Hz, XTAL 8K with 75Hz with UHD and 120 with QHD and Pimax 8K X with 75Hz (110 Hz experimental mode). For IPD ranges, XTAL has 56-76mm, Pimax 8K X and 5K Super have 55-75mm and Varjo VR-3 has 59-71mm. Feature wise, all the headsets have hand and eye tracking either integrated or as separate modules.

From these high-end VR headsets, if the desire is to maximise resolution per degree, the Varjo VR-3 has the largest resolution and smallest FoV of the high-end headsets. This should decrease cybersickness effectively. The downside is that VR-3 also has the smallest IPD range, so users with very wide or narrow IPD cannot use it effectively. If a large FoV is the priority however, any of the other high-end headsets would be a better choice.

The problem with Pimax 8K is that it has only 75Hz refresh rate, which is rather low and might cause cybersickness. If UHD resolution is not required, the device of choice would then be XTAL or Pimax 5K Super. XTAL would likely be best used with QHD resolution with 120Hz refresh rate, if full resolution is not required as using UHD also lowers the refresh rate to 75Hz. If a very high refresh rate is required, Pimax 5K Super is the choice. It has 160Hz (180Hz experimental) refresh rate, which is high end computer hardware rarely achieves. However, the higher refresh rates than 90Hz cannot be used with the large FoV simultaneously, which reduces the viability of the Pimax 5K Super (VoodooDE VR, 2020).

Cheaper VR options include HP Reverb G2, Valve Index, HTC VIVE Pro Eye and Oculus Quest 2. From these, HP Reverb G2 has the highest resolution, Valve index has the highest refresh rate, HTC VIVE Pro Eye is the only option to have eye tracking and Oculus Quest 2 has the option of untethered use. Resolution of Oculus Quest 2 is close to that of HP Reverb G2, however instead of dual display like the rest of the HMDs mentioned, Quest 2 has a single display configuration. This makes IPD adjustment only support 3 fixed distances, 58, 63 and 68mm, while all the other HMDs have a mechanical IPD slider (Sutrich, 2020). Adjusting the IPD in Quest 2 also affects which pixels are used, which sounds like it makes the resolution slightly lower than advertised (Circuit Stream, 2020). HP Reverb G2 has 60-68mm, Valve Index has 58-70mm and HTC VIVE Pro Eye has 61-72mm IPD ranges.

As mentioned, HP Reverb G2 has the highest resolution of 2160x2160, followed by Oculus Quest 2 with 1832x1920 and Valve Index and HTC VIVE Pro Eye both with 1440x1600. The refresh rate is highest in Valve Index with 144Hz, while all the other HMDs have 90Hz refresh rate.

If a completely untethered experience is required, the choice is Oculus Quest 2, as it is the only modern untethered VR headset. If eye-tracking is required, the only choice is the HTC VIVE Pro Eye. For high resolution, the best are the Quest 2 and Reverb G2, however a comparison shows that the Quest 2 has rather poor colours and contrast, which makes the picture quality, accuracy and immersion lower than Reverb G2 and to some degree even Valve Index, which has a lower resolution (Tyriel Wood - VR tech, 2020; MRTV - MIXED REALITY TV, 2020). So, for high picture quality and resolution, the choice would be Reverb G2.

HTC VIVE Pro Eye has the same resolution as Index, so lower than other headsets mentioned, but it uses OLED PenTile display. This effectively makes it have 1/3 less sub-pixels than the Index, which effectively amounts to a lower resolution. For smooth motion, Valve Index is the choice, as it has the best refresh rate.

It should also be mentioned that Oculus Quest 2 requires a Facebook account with accurate personal information to function. This has been a source of much controversy as Facebook has been criticized in the past of their ways of handling personal data of their users (Patterson, 2020; Flynt, 2020). While people are getting banned from Facebook on account of having fake identities (which is against Facebook terms of service), there has also been reports of banning Facebook accounts seemingly without reason, which effectively prevents the use of Oculus Quest 2 as well (Guinness, 2018; Torres, 2020). This is a factor that needs to be considered, before choosing Quest 2 as a primary interface for a system. To support professional use of Oculus Quest 2, Facebook has however launched Oculus for Business, which prevents the needs for individual Facebook accounts and above-mentioned issues regarding banning.

7.2 OPPORTUNITIES FOR CSCW DATA ANALYSIS IN XR FOR LEAS

There are many opportunities for LEAs using XR in CSCW environments. Visualisations in 3D can provide a new element to analysis, as discussed in Section 6.2. However, there are some recommendations to be made for how the systems are developed in order to capitalise on these opportunities.

7.2.1 CSCW CONSIDERATIONS IN XR

The system should be made to work with AR and VR equipment, so some users can work in the real world, such as a live crime scene, while still being in contact with others that are using VR equipment. This allows many different kinds of physical work environments. Team members in need of real-world desks and equipment should be provided with a dedicated room, equipment, and AR glasses, while people that do not need real world equipment, could work from anywhere with just computer and VR glasses and controllers. The environment could be a real physical office space, which is then replicated into VR space, but effectively everyone sees and acts in the same environment, either virtually or physically. However, if this ends up restricting the possibilities too much, a more open featured VR environment should be created. Special consideration should be made on the headset choice, as tethered headsets often require lighthouses to function properly, which restricts the usage area. Standalone headsets do not have this restriction, but generally have lower screen refresh rate or other trade-offs, which might be a problem for some users with long periods of use as covered in Section 5.1.

The system should also provide a legacy interface for mobile devices or web browsers, as it is possible that outside expert analysis is required at some point, and it cannot be presumed that everyone is residing near the XR collaborators or that they would own a headset. This however should not be a problem as similar interfaces are common in many commercial applications. These interfaces could be also used by executives to monitor the progress of the operation while it is ongoing.

There are numerous conferencing, social networking, and artist applications available on the market, which have many of the features mentioned above already implemented. Technically, some of them, like vSpatial, could even be used for the collaboration part as is, but considering the delicate nature of the work in question by LEAs, the available apps might not fulfil the security requirements. They can however be used as a model and catalogue of features to be implemented (Lang, 34 VR Apps for Remote Work, Education, Training, Design Review, and More, 2020).

7.2.2 AVATARS FOR LEAS

The users should be shown as avatars in the virtual space for others. The avatars should be easily distinguishable and personal, so individuals can be discerned from each other, as individuals often have unique skills and specialities. This also creates tighter team mentality. With specific consideration to LEAs, avatars can take two approaches depending on the requirements:

1. Avatars can closely represent the user. This approach allows all members in the team to see each other and recognise them as being people they know. This lack of

anonymity can provide an element additional security that the people in the room are supposed to be there.

2. Avatars can be unique per user but do not represent the user. This approach gives anonymity to the user which may be required for some LEAs, but by enforcing that each avatar is still unique, it provides an element of recognition and stops the confusion that may occur if multiple people select the same avatar.

7.3 GUIDELINES FOR THE XR ENVIRONMENT

It is important to ensure that the environment has been created for the task at hand. From the research studied within this document, one recommendation for the collaborative data analysis environment would be to work on complex tasks, such as data handling and abstract information visualization, using the same VE, with an identical level of immersion. This will provide more efficient communication and collaboration (Narayan, Waugh, Zhang, Bafna, & Bowman, 2005), and improved user satisfaction (Raja, Bowman, Lucas, & North, 2004).

General recommendations for a collaborative environment would be to provide:

- Shared data exploration;
- Egalitarian acess to data;
- Flexible data immersion;
- Multimodal interaction;
- Seamless;
- Feedback on perfromance and prograss;
- Pointer cues;
- Large display for presenting different data on same space and pace of time (avoid splitting complex information).

It is also recommended to adapt the VE to the purpose of the group and the nature of the task, e.g. briefing, brainstorming, problem solving. Either by offering different predefined spaces or by allowing the users to setup the space. The nature of the tasks can lead to define some predefined spaces with some characteristics. For example, a problem solving may allow six users maximum by default and allows synchronous and asynchronous work with synchronization, whereas a briefing environment may have no maximum number on users and promote synchronous work; brainstorming: twelve user max and promote synchronous work. This is discussed further in Section 3.1.3.

As mentioned in Section 4.2, a mixed environment bring new collaborative interactions while being considered as more usable and preferred by operators of cybersecurity (Kabil A. , 2019; Kabil, Cuppens, Le Compte, Halgand, & Ponchel, 2018). The dimensions found in the study by Kabil (2019) on roles, flexible views, and respecting access rights should be considered in the design of the system to improve collaboration interaction and data analysis, taking into account not only local team members but also inter-organizational collaboration and third party, external collaborators.

Two additional recommendations emerge here:

- the importance of being in adequacy with the inter organization between MS: by implementing feedback synchronized between MS, and the use of mixed reality.
- implementing the system within XR, without rejecting the use of non-immersive technology, like a computer, because it can lead to the rejection of some external, but important users.

7.3.1 COMMUNICATION

One recommendation would be to provide communication tools or dashboard to monitor tasks assignment and progression. According to Casarin, Pacqueriaud, & Bechmann (2018) , which take up some points mentioned before in Section 3.1.3, the tool should provide:

1. Malleability: actors can add, modify, close tasks and objects of the environment;
2. Shared context: place, content, knowledge on other activities;
3. User roles: system need to support variation of the shared context following the actor roles and their rights (Churchill & Snowdon, 1998);
4. Individual activities: the system has to allow to easily switch from individual to shared activities and provide feedback on the impact of individual activities to common work;
5. Embodiment: the system has to provide embodiment or avatars and vocal communication tools at least.

7.3.2 ANALYSIS CONSIDERATIONS

The collaborative analysis environment is designed to be a workspace for the analysts. In other words, it is an extended reality environment for analysing of vast amounts of information quickly and efficiently. It should be usable by users from different member states simultaneously. It should also allow live executive monitoring and communication with outside specialists, while controlling access rights to the different information considered.

The key requirement with the analysis environment is the minimisation of cybersickness during prolonged exposure to XR devices. This means maximising resolution, colour reproduction and refresh rate, while ensuring comfortable locomotion in the system. For interaction methods, hand tracking and controller support should be available for future proofing the system as it is probable that hand gestures become more standardised and tracking algorithms improve in the coming years. For quick input and typing voice commands and dictation and/or dedicated keyboard typers should be considered. For fast 3D modelling photogrammetry can be utilised. For portable meshing, a handheld scanner and/or drone equipped with LIDAR solutions should also be considered.

From the studies explored in Section 3.2, some recommendations have also been extracted of data analysis functionalities within this environment:

- instantly synchronized snapshots;
- highlight information;
- sorting and colorized functionalities;
- integrated non abstract information (pictures, annotation);
- combine navigation style (egocentric and non-egocentric) ;
- filtering and clustering the data.

The suggested collaborative environment should be a multiuser desktop environment, where each user could open application windows at will. The windows should be movable and scalable. This allows the users to scale a large screen for everyone to see, or to have multiple screens of various sizes for their own use. This allows for easy access to many various types of information simultaneously. Users should be able to draw on whiteboards and into the air of the environment in 3D to highlight aspects and draw connections between different pieces of information. The environment should be designed large enough for ample room for everyone to work alone without being distracted by others, but close enough to be able to come do collaborative work with anyone or everyone.

For 3D object integration into the system, a fast method of 3D modelling should be implemented. Topographic maps can be achieved with aerial flights and LIDAR, or from already established archives available (Borneman, 2020; GIS Geography, 2021). 3D objects can be modelled through photogrammetry, 3D scanning or sculpting them from scratch with a software editor (Cribbie, 2017). This could give the analysts a significant advantage in mapping the operation scene and its features in a fast and comprehensive way. 3D object creation software or photogrammetry could be used to recreate indoor scenes and objects for fast analysis. The software method would require a dedicated 3D artist, however.

The system needs to also consider the locomotion method for XR thoroughly, as in a crisis situation, such as may occur in the security domain, elongated sessions are to be expected. Specific types of locomotion are one of the major causes for cybersickness (Saredakis, et al., 2020). The most suitable traditional locomotion methods are actual physical movement in an area allocated to VR or teleportation, as these don't cause discrepancy between sight and other human senses in regards to movement. However, multiuser environment would require a single room without teleportation and free movement, multiple rooms for free movement and teleportation or only teleportation as locomotion methods to prevent collisions with other people in the real world. (Panagiotis Kourtesis, 2019)

Should there be a need for excessive free movement, treadmill solutions should be considered, as these allow unlimited movement, while the user remains positionally stationary in the real world. This effectively limits the required space for a single user and prevents collisions with others in the real world (Section 5.1.3).

7.3.3 BRIEFING CONSIDERATIONS

Having a dedicated briefing environment could be useful for briefing and debriefing the analyst team on situations and progress. This briefing space may be for purely internal communication within the system or with outside sources, such as other organisations. This environment could resemble a conference room with necessary furniture and properties for anything the briefers wish to show, including 3D objects, like topography or physical objects, maps, pictures, documents, and any connections between them. Everybody present in the briefing should be represented by avatars, including the users of non-XR interfaces (web, PC, mobile). The same information should be available within the non-XR interfaces, but possibly in a different way as the 3D environment may not be optimized for traditional displays.

For purely internal communication, the analysis environment could also be used in briefing/debriefing, however in an ongoing operation, the system should allow simultaneous briefing and continued analysis in separate environments. This is required especially when briefing outside sources as some of the information available in analysis environment may not be need-to-know for anyone outside the system at the time. The environments should be interconnected, however, to allow the analysis users to transfer between the two spaces quickly.

7.3.4 INTERACTIONS

The interaction methods used should be fast and accurate. Motion controllers are slow for typing with a virtual keyboard so other methods should be used. The users could use a real keyboard that is calibrated into VR space, like in the application Immersed, to use voice commands and dictation or to have dedicated typist in the team with AR glasses and physical desktop environment. There could be a separate traditional type of desktop interface for the typist too, but it would be beneficial for them to be in the same environment with the VR users or at least see the same environment to be on board with the others and the subject at hand (Cas and Chary VR, 2020).

8 CONCLUSION

This report identified existing research into XR applications, CSCW, and data analysis surrounding the security domain.

Common data mining techniques used within data analysis were initially outlined including entity extraction, cluster analysis, association rule mining, classification techniques and social network analysis (see Section 2). Each of these techniques demonstrate value and merit within data analysis and should be considered for any platforms wanting to develop data analysis.

Data analysis was further explored in the context of Computer Supported Cooperation Work and general collaboration. Aspects such as team configuration, group size, and task structure were noted to influence the quality and quantity of contributions individuals provided during collaborative data analysis and problem solving. Notably research by Anzieu and Martin (1971) suggested that the ideal team size should consist of two to five participants for a specific problem, allowing for sufficient communication to occur.

With support from CSCW, co-location is no longer a requirement for collaboration to occur. Teams can work remotely from one another while maintaining real-time communication and interaction, either working on the task synchronously or asynchronously. These practices can be deployed to allow users to work in shared environments simultaneously or to make individual progress, which the remainder of the team can view at a later date.

Characteristics were identified from previous research outlining what a CSCW system must include to efficiently support collaborative tasks . Characteristics included; shared data exploration allowing for co-located and remote collaboration, egalitarian access to data, the ability to combine results from multiple applications (Cavollo et all. 2019). Additionally, a CSCW which provided feedback to the user was found to increase users participation and performance (Jung, Schneider, & Valacich, 2010). With users of a remote collaborative system generally comprising of teams across multiple locations and differing law enforcement agencies, a sucessful intergration of the previously validated CSCW techniques will likely be essential.

XR has been identified to increase user immersion; improving both memory and social skills in comparison to traditional PC use (Eric Krokos, 2018; Chan, 2020; Gillies, 2018) . This report reviewed current XR technologies and identified the differences between AR, MR, and VR, to understand which would best benefit the development needs of the project. The capabilities of each were assessed looking specifically at tethering, interaction, feedback, and audio. Common metrics were identified including refresh rate, resolution, and field of view. Using the capabilities and metrics, recommendations and guidelines were suggested and can be viewed in section 7.1.

This report reviewed several aspects of visualization used for advanced data analysis. The properties of data visualizations were examined using Cairo's (2012) visualization wheel. It was found that this model works on a high level of abstraction, the use of Wilke (2019) approach, which divides charts into more practical properties such as: amounts (bar, dot, heatmaps, etc), distributions (histogram, density plot, etc) and proportions (pie charts, stacked charts etc). The understanding of these visualisation techniques will allow an XR analysis system to explore innovative ways to display data usually viewed in two dimensions within the immersive environment providing additional ways to view the data.

Data visualisation has previously utilised XR in a format which has become commonly referred to as Immersive Analytics. Whilst CAVE systems had previously explored methods of data visualisation, the emergence of recent HMDs have provided a cost effective and portable solution allowing greater access to this approach than previously seen (Donalek, et al., 2014). The immersion and presence that an HMD headset can provide compliment human traits such visual perception and spatial memory (Cordeil, et al., 2017; Stuerzlinger, et al., 2018), providing analysts unique opportunities to visualise and structure their data. Any future XR analysis systems should build upon the state of the art found in Immersive Analytics and provide new opportunities, especially if being made specifically for LEAs.

Finally, this report provided guidelines for general collaborative data analysis in XR environments, summarising research outcomes discussed in previous sections. Guidelines were provided for procuring the correct XR hardware dependent on the use case. Considerations were suggested for CSCW in XR, before providing final advice on LEA activity within an XR Environment.

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10 APPENDICES

This section contains all the appendices that are referenced throughout this document.

A. DETAILS OF XR DEVICES

An alphabetically ordered table of XR devices is given below. The following information is given:

- **Released**: The release date
- **Price**: Price from the manufacturer or typical price from a popular shop like Amazon
- **Display type**: see-through / closed, LCD/OLED/CLPL and subpixel layout (pentile/RGB)
- **Resolution**: Resolution per eye. Dual display if not stated otherwise
- **Processor**: The model of any embedded processor
- **Platforms**: Advertised software or operating system platforms (very much non-exclusive list)
- **Battery**: Use time with battery or not applicable (N/A) for tethered systems
- **Interaction**: Default interaction methods advertised
- **Sound**: Speakers, mics and audio jack connections
- Other miscellaneous features or notes

All the headsets and their controllers in the list are tracked with 6DoF unless stated otherwise.

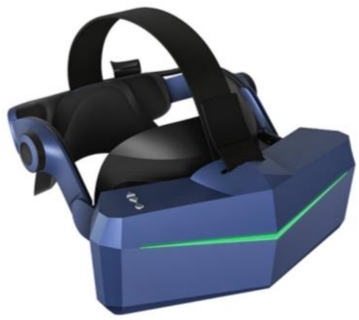
Table 22: List of XR Devices

Device manufacturer and name	Features	Picture
HP Reverb G2	**Released**: 2020 **Price**: 699 EUR (including controllers) **Display type**: closed, LCD **Resolution**: 2160 x 2160 (per eye) **Refresh rate**: 90 Hz **IPD**: 60-68 mm **Processor**: PC (tethered) **Platforms**: SteamVR, Windows mixed reality **Battery**: N/A (tethered) **Interaction**: Controllers **Sound**: Speakers **Miscellaneous**: • Inside-out tracking (Cameras) (Brown, n.d.; HP, 2021)	 (eLive, 2021)

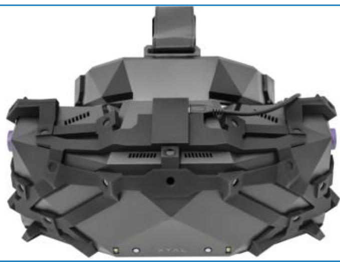
HTC Vive Cosmos Elite	**Released**: 2019 **Price**: 899 USD (with controllers and lighthouses) **Display type**: closed, LCD **Resolution**: 1440 x 1700 (per eye) **Refresh rate**: 90 Hz **IPD**: 61-72 mm **Processor**: PC (tethered) **Platforms**: SteamVR, Viveport **Battery**: N/A (tethered) **Interaction**: Controllers **Sound**: Integrated headphones **Miscellaneous**: • Inside-out tracking (lighthouses) (Brown, n.d.; HTC Corporation, 2021; HTC, 2021)	 (Pro Shop, n.d.)
HTC Vive Pro	**Released**: 2018 **Price**: 1599 USD (with controllers and lighthouses) **Display type**: closed, OLED (pentile) **Resolution**: 1440 x 1600 (per eye) **Refresh rate**: 90 Hz **IPD**: 61-72 mm **Processor**: PC (tethered) **Platforms**: SteamVR, Viveport **Battery**: N/A (tethered) **Interaction**: Controllers **Sound**: Integrated headphones **Miscellaneous**: • Inside-out tracking (with lighthouses) • Eye tracking version available (HTC Vive Pro Eye) (Brown, n.d.; HTC, 2021; HTC Corporation, 2021)	 (Grover, 2021)
Leap Motion Project North Star	**Released**: 2018 **Price**: 245 EUR (not the 3D printed parts) **Display type**: see-through **Resolution**: 1600 x 1440 (per eye) **Refresh rate**: 120 Hz **IPD**: No **Processor**: PC (tethered) **Platforms**: SteamVR, Unity, Esky **Battery**: N/A (tethered) **Interaction**: Hands **Sound**: Nothing by default **Miscellaneous**: • Open source headset design • Hand tracking sensor is proprietary (Ultraleap Leap Motion tracker)	 (Smart Prototyping, 2021a)

	(Leap Motion, 2018; Project North Star, 2021; Smart Prototyping, 2021b)	
Lenovo Mirage VR S3	**Released**: 2020 **Price**: under 450 USD (exact price not given) **Display type**: closed, LCD (single display) **Resolution**: 1920 x 2160 (per eye) **Refresh rate**: 75 Hz **IPD**: Not specified **Processor**: Snapdragon 835 **Platforms**: Lenovo ThinkReality, Runs on Android 8.1 **Battery**: up to 3 hours **Interaction**: integrated controls, hand controller (3DoF) **Sound**: mic, speakers, 3.5 mm jack **Miscellaneous**: • Headset and controller tracking is in 3DoF (Brown, n.d.; Lenovo, 2020; Grahamn, 2020)	 (Grahamn, 2020)
Lenovo ThinkReality A6	**Released**: 2019 **Price**: Unknown **Display type**: see-through **Resolution**: 1920 x 1080 (per eye) **Processor**: Snapdragon 845 (headset), Intel Movidius VPU (compute box) **Platforms**: Lenovo ThinkReality **Battery**: up to 4 hours **Interaction**: hand/voice commands, controller (3DoF) **Sound**: Speakers (surround sound), mics, & 3.5mm jack **Miscellaneous**: • Hand tracking • Eye tracking • Depth sensor • Tethered to separate mobile “compute box” (Brown, n.d.; Lenovo, 2019)	 (Shilov, 2019)
Magic Leap One	**Released**: 2018 **Price**: 2295 USD (includes controller) Display type: see-through **Resolution**: Unknown **Prosessor**: Nvidia Parker SoC **Platforms**: Lumin OS **Battery**: up to 3 hours (tethered to separate compute disk) **Interaction**: controller, hands **Sound**: Speakers (spatial audio), mics, & 3.5mm jack **Miscellaneous**:	 (System Plus Consulting, 2019)

	• Hand tracking • Eye tracking (Brown, n.d.; Magic Leap, 2018)	
Microsoft Hololens 2	**Released**: 2019 **Price**: 3500 USD **Display type**: see-through **Resolution**: 2048 x 1080 (per eye) **Processor**: Snapdragon 850 **Platforms**: Windows Holographic Operating System **Battery**: 2-3 hours (active use) **Interaction**: hand/voice commands **Sound**: Speakers (spatial sound), mics, 3.5mm jack **Miscellaneous**: • Hand tracking • Eye tracking • Spatial mapping • Camera: 8MP stills, 1080p30 video • Inside-out tracking (Microsoft, n.d.)	 (Kościesza, 2020)
Oculus Quest 2	**Released**: 2020 **Price**: 349 EUR (includes controllers) **Display type**: closed, LCD (single display) **Resolution**: 1832 x 1920 (per eye) **Refresh rate**: 90 Hz **IPD**: 58, 63, 68 mm adjustable **Processor**: Snapdragon XR2 **Platforms**: SteamVR, Oculus Home **Battery**: 2-3 hours (active use) **Interaction**: Controllers **Sound**: Speakers & 3.5mm jack **Miscellaneous**: • Hand tracking • Inside-out tracking (cameras) • Capacitive controller buttons • Can be tethered to a PC for more computing power (Brown, n.d.; Oculus, n.d.)	 (Hachman, 2020)
Play station VR	**Released**: 2016 **Price**: 358 EUR (including camera without controllers) **Display type**: Closed, OLED (RGB) **Resolution**: 960 x 1080 (per eye) **Refresh rate**: 120 Hz, 90 Hz **IPD**: software calibrated **Processor**: Play station 4 or 5 **Platforms**: PlayStation **Battery**: N/A (tethered)	 (Republic of Communications, 2019)

	Interaction: PS 4/5 controller, PS Move controllers **Sound**: mic, 3.5mm jack **Miscellaneous**: • Outside-in tracking with PS camera (Brown, n.d.; Sony, 2020; Amazon, n.d.)	
Pimax Vision 5K Super	**Released**: 2020 **Price**: 616 EUR (just the headset) **Display type**: closed, CLPL **Resolution**: 2560 x 1440 (per eye) **Refresh rate**: 160 Hz (180 Hz experimental) **IPD**: 55-75 mm **Processor**: PC (tethered) **Platforms**: SteamVR, Oculus Home **Battery**: N/A (tethered) **Interaction**: Controllers, hands **Sound**: Speakers, mic, 3.5mm jack **Miscellaneous**: • Very broad FoV • Inside-out tracking (Lighthouses) • Eye tracking (separate module) • Hand tracking (separate module) (Brown, n.d.; Pimax, 2021)	 (Pimax, 2021)
Pimax Vision 8K X	**Released**: 2020 **Price**: 1069 EUR (just the headset) **Display type**: closed, CLPL **Resolution**: 3840 x 2160 (per eye) **Refresh rate**: 75 Hz (110 Hz experimental) **IPD**: 55-75 mm **Processor**: PC (tethered) **Platforms**: SteamVR, Oculus Home **Battery**: N/A (tethered) **Interaction**: Controllers, hands **Sound**: Speakers, mic, 3.5mm jack **Miscellaneous**: • Very broad FoV • Inside-out tracking (Lighthouses) • Eye tracking (separate module) • Hand tracking (separate module) (Brown, n.d.; Pimax, 2021)	 (Pimax, 2021)
Samsung Odyssey+	**Released**: 2018 **Price**: 643 EUR (including controllers) **Display type**: closed, OLED (pentile) **Resolution**: 1440 x 1600 (per eye) **Refresh rate**: 90 Hz **IPD**: 60-72 mm **Processor**: PC (tethered) **Platforms**: SteamVR, Windows mixed reality **Battery**: N/A (tethered)	 (Samsung, 2021)

	Interaction: WMR Controllers, Xbox One controller support **Sound**: Integrated headphones, mic **Miscellaneous**: • Inside-out tracking (Cameras) (Brown, n.d.; Samsung, 2021)	
Valve Index	**Released**: 2019 **Price**: 1079 EUR (with controllers and lighthouses) **Display type**: closed, LCD **Resolution**: 1440 x 1600 (per eye) **Refresh rate**: 144 Hz **IPD**: 58-70 mm **Processor**: PC (tethered) **Platforms**: SteamVR **Battery**: N/A (tethered) **Interaction**: Controllers **Sound**: Speakers, mic, 3.5mm jack **Miscellaneous**: • Camera (Stereo 960 x 960) • Inside out tracking (with lighthouses) (Brown, n.d.; Valve, n.d. c; Valve Corporation, 2021)	 (Amazon, n.d.)
Varjo VR-3	**Released**: 2020 **Price**: 3195 EUR (+ licencing starting from 795€, includes just the headset) **Display type**: closed, dual display per eye, focus area: micro-OLED, peripheral area: LCD **Resolution**: 1920 x 1920 (focus area) + 2880 x 2720 (peripheral area) **Refresh rate**: 90 Hz **IPD**: 59-71 mm (automatic adjustment) **Processor**: PC (tethered) **Platforms**: SteamVR **Battery**: N/A (tethered) **Interaction**: Controllers (steam or HTC), hands **Sound**: 3.5mm jack (with mic support) **Miscellaneous**: • Eye tracking • Hand tracking • Inside-out tracking (Lighthouses) (Brown, n.d.; Varjo, 2021a)	 (Varjo, 2020)

Varjo XR-3	**Released**: 2020 **Price**: 5495 EUR (+ licencing starting from 1495€, includes just the headset) **Display type**: closed, dual display per eye, focus area: micro-OLED, peripheral area: LCD **Resolution**: 1920 x 1920 (focus area) + 2880 x 2720 (peripheral area) **Refresh rate**: 90 Hz **IPD**: 59-71 mm (automatic adjustment) **Processor**: PC (tethered) **Platforms**: SteamVR **Battery**: N/A (tethered) **Interaction**: Controllers (steam or HTC), hands **Sound**: 3.5mm jack (with mic support) **Miscellaneous**: • Hand tracking • Inside-out tracking (Lighthouses) • Eye tracking • High quality 12MP video pass-through at 90 Hz • LiDAR (Brown, n.d.; Varjo, 2021a)	 (Varjo, 2020)
VRgineers XTAL 5K	**Released**: 2019 **Price**: 6190 USD (+ licencing if non-personal use) **Display type**: closed, OLED **Resolution**: 2560 x 1440 (per eye) **Refresh rate**: 70 Hz **IPD**: 56-76 mm **Processor**: PC (tethered) **Battery**: N/A (tethered) **Platforms**: SteamVR, ART, OptiTrack, Autodesk VRED **Interaction**: Voice, controllers (HTC Vive), hands **Sound**: Mic, 3.5 mm jack **Miscellaneous**: • Wide FoV • Inside-out tracking (Lighthouses) • Hand tracking • Eye tracking (VRgineers, 2020)	 (VRgineers, 2020)
VRgineers XTAL 8K	**Released**: 2019 **Price**: 7980 USD (+ licencing if non-personal use) **Display type**: closed, LCD **Resolution**: 3840 x 2160 (per eye) **Refresh rate**: 75 Hz @ 4K resolution; 120 Hz @ QHD resolution (per eye)	

	IPD: 56-76 mm **Processor**: PC (tethered) **Battery**: N/A (tethered) **Platforms**: SteamVR, ART, OptiTrack, Autodesk VRED **Interaction**: Voice, controllers (HTC Vive), hands **Sound**: Mic, 3.5 mm jack **Miscellaneous**: • Wide FoV • Inside-out tracking (Lighthouses) • Hand tracking • Eye tracking (VRgineers, 2020)	(VRgineers, 2020)